Cyclic scheduling of multimodal processes in crystalline-like network structures

Grzegorz Bocewicz, Robert Wójcik, Zbigniew Banaszak

Abstract

The paper introduces the concept of a crystalline-like model of a computer communication network (CCN) composed of routers forming a repeating or periodic arrangement. The considered homogenous network assumes the same routers servicing the same number of transmissions form an array. In such a network several isomorphic sub-networks encompassing packet transmission processes serviced by each router, interact each other as to provide a variety of demand-responsive host-server transmission services. In that context, a crystalline-like layout of physically different, however functionally identical, routers provides a homogenous array supporting computer network flows. In turn, packet transmission flows are treated as multimodal processes encompassing arbitrarily given inter-computer communications. Assuming the packets passing their origin-destination routes are synchronized by the same mechanism of packet transmission the problem boils down to a communication processes scheduling. Since concurrent transmission flows are processed along the same presumed routes, hence the schedules sought are cyclic ones. In general case, cycles of multimodal processes depend on CNN’s periodicity. That objective to develop conditions allowing one to calculate the cyclic schedule of whole CCN while taking into account only periodicity of its repeating isomorphic structure.

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Keywords: cyclic scheduling; multimodal networks; constraint programming; structures composition

1. 1. Introduction

Multimodal processes scheduling are found in different application domains such as manufacturing, intercity freight transportation supply chains, multimodal passenger transport networks as well as service domains including...
passenger/cargo transportation systems, data and supply media flows, e.g., cloud computing, overhead power line and computer communication networks.\textsuperscript{1,3,7,8,11,16,17}

In last case, i.e. concerning a computer communication network (CCN), composed of routers, computers, and switches etc., packet transmission flows can be treated as multimodal processes encompassing inter-computer communications.\textsuperscript{5} In that context multimodal processes represent the streams of packet transmitted between source-destination nodes. Since the concurrently executed transmissions sharing the same resources (routers) have to be deadlock-free and of guaranteed capacity the routers synchronization mechanism, play of primary role. In this context the paper discusses a role the computer network structure, and especially its router channels, play in a deadlock-free packet transmission in homogenous computer networks.

It seems to be obvious, that not all the behaviors (including cyclic ones) are reachable under the constraints imposed by the system’s structure. Similar observation concerns the system’s behavior that can be achieved in systems possessing specific structural constraints. In case of computer networks their structures can be modeled by regular or crystalline-like structures, composed of a set of usually similar (isomorphic) substructures. That means, since system constraints determine its behavior, both system structure configuration and desired cyclic schedule have to be considered simultaneously. In that context, our contribution provides a discussion of some conditions guaranteeing solvability of the cyclic processes scheduling in such regular structure computer networks. The main goal regards the conditions determining the relationship among periodicity of a repeating isomorphic substructure and a cycle of a whole network, structure of which encompasses an array of entities. Their examination may replace exhaustive searching for solutions satisfying the required system behavior (the problem considered belongs to a class of NP-hard ones\textsuperscript{1}).

Many models and methods have been considered so far\textsuperscript{10}. Among them, the mathematical programming approach\textsuperscript{1,20}, max-plus algebra\textsuperscript{12}, constraint logic programming\textsuperscript{4,5} evolutionary algorithms\textsuperscript{9}, Petri nets\textsuperscript{19} frameworks belong to the more frequently used. Most of them are oriented at finding of a minimal cycle or maximal throughput while assuming deadlock-free processes flow.

The approaches trying to estimate the cycle time from cyclic processes structure and the synchronization mechanism employed (i.e. mutual exclusion instances) while taking into account deadlock phenomena are quite unique. Note that system periodicity implies its deadlock-freeness. That is the reason why we focus on CCN periodicity. In general case, cycles of multimodal processes depend on CNN’s periodicity. That motivates our main objective concerning conditions allowing one to calculate the cyclic schedule of whole CCN using periodicity of its repeating isomorphic substructure. In that context our main contribution is to propose a new modeling framework enabling to evaluate the cyclic steady state of a given crystalline-like (or mesh-like) structure\textsuperscript{4,5} encompassing the behavior of packet streams flows (see Fig. 1a) in CCN.

The rest of the paper is organized as follows: Section 2 introduces a concept of crystalline-like computer network structure and then provides its representation in terms of systems of concurrently flowing cyclic processes, as well as defines multimodal processes encompassing packet transmission flows. Section 3 provides the problem formulation concerning a way of computer network structure design guaranteeing its presumed, e.g. deadlock-free, behavior. Section discusses the declarative modeling driven approach to multimodal processes scheduling problems. The crystalline-like computer network structure environment is considered, and conditions guaranteeing its cyclic scheduling are developed. Computational experiments and conclusions are presented in Sections 4 and 5, respectively.

2. Concurrent cyclic processes systems

Fig. 1 shows an example of CCN which is composed of routers forming a repeating, i.e. periodic arrangement. The packets are transmitted along two kinds of routes: north-south (blue lines – $mP_{1}$) and east-west (red lines – $mP_{2}$), from six hosts ($H_{1}$– $H_{6}$) to two servers $S_{1}$ and $S_{2}$. These routes, setting the courses of multimodal processes, are composed of fragments of the lines of local packet transmission processes. A network consists of ninth four-port routers\textsuperscript{5} ($1F$ – $9F$) which work in two packet transmission route modes the blue (mode A – routers: $1F$, $3F$, $5F$, $7F$, $9F$) and the red (mode B – routers: $2F$, $4F$, $6F$, $8F$) one, respectively. Each router $iF$, modeled in terms of Concurrent Cyclic Processes Systems (SCCP), is defined by the set of local packet transmission processes ($iP_{1}$, $iP_{2}$,
\(^{1}P_3\) and \(^{1}P_4\) supporting two multimodal processes \(^{1}mP_1,^{1}mP_2\). Similarly transmission mediums are defined by processes \(^{1}P_5\) and \(^{1}P_6\).

Distinguished in each \(i\)-th router \(^{1}F\) two kinds of processes (local and multimodal), are defined in the following way:

- \(^{i}P = \{^{i}P_j | j = 1, \ldots, n\}\) – the set of local processes (representing modes of transmission) described by sequences of operations executed on resources from the set \(R\) (representing transmission modes),
- \(^{i}mP = \{^{i}mP_j | j = 1, \ldots, w\}\) – the set of multimodal processes (representing streams of packets) described by sequences of some sub-sequences from local processes \(^{i}P\).

The operations of multimodal process’s streams require execution of some local processes. For example, operations supporting transmission between resources in \(^{1}mP_1\) (Fig. 1b) require streams of local processes \(^{1}P_2,^{1}P_1,^{1}P_4,^{1}P_6\) respectively. This means the routes of multimodal process are also determined by subsequences of routes of the local processes through which they have to be processed. Note that the resources belonging to these routes are simultaneously shared by both local and multimodal processes. Moreover, it is assumed that both kind of processes

Fig. 1. Computer communication network of routers’ and their SCCP models a), SCCP models of isomorphic substructures b)
are cyclic and act concurrently. Local processes are synchronized by a mutual exclusion protocol, i.e. guaranteeing the only one process simultaneously can be executed on each shared resource. In order to describe the system shown in Fig. 1b) let us introduce the notations:

- \( p_j \) – specifies the route of a local process \( [p_j] \), and its components define the resources used in course of process operations execution, where: \( [p_j] \in R \)

- \( R = \{ R_1, R_2, \ldots, R_c, \ldots, R_m \} \) – denotes the set of resources used for the \( k \)-th operation in the \( j \)-th local process of router \( [p_j] \); in the rest of the paper, the \( k \)-th operation executed on the resource \( [p_j] \) will be denoted by \( [p_j]_i \).

- Dispatching rules determining an order in which local processes can access the resource working in the mode \( A \), are following:
  - the resources used in course of process operations execution, where:
  - the set of resources, and variables characterizing the start time of the operation
  - the route of multimodal processes.

where:

- \( \theta = \{ \theta^0, \theta^1 \} \) – the set of priority dispatching rules \( \{ \sigma^0_1, \sigma^0_2, \ldots, \sigma^0_i, \ldots, \sigma^0_m \} \), where \( \sigma^0_i = \{ S^0_{c,1}, S^0_{c,2}, \ldots, S^0_{c,j}, \ldots, S^0_{c,l}(p) \} \) is the sequence components of which determine an order in which the processes (local or multimodal for \( l = 1 \)) can be executed on the resource \( R_c \), \( i^1 \in P \), \( i^0 \in mP \).

Dispatching rules determine the order in which local processes can access the resource \( R_c \) in the router \( F \) working in the mode \( A \), are following:\n
\( \sigma^0_0 = \{ \sigma^0_1, \sigma^0_2, \ldots, \sigma^0_i, \ldots, \sigma^0_m \} \), \( \sigma^0_0 = \{ \sigma^0_1, \sigma^0_2, \ldots, \sigma^0_i, \ldots, \sigma^0_m \} \) for \( i = 1, 2, 3, 4 \) (see Fig. 1b). In turn, dispatching rules for the router \( F \) working in the mode \( B \) are following:

\( \sigma^0_0 = \{ \sigma^0_1, \sigma^0_2, \ldots, \sigma^0_i, \ldots, \sigma^0_m \} \), \( \sigma^0_0 = \{ \sigma^0_1, \sigma^0_2, \ldots, \sigma^0_i, \ldots, \sigma^0_m \} \) for \( i = 2, 4, 6, 8 \) Fig. 1b).

CCN from Fig. 1. An example of a crystalline-like structure \( SC \), composed of several isomorphic subnetworks encompassing packet transmission processes serviced along distinguished routes, e.g. mode A (routers: \( F, F, F, F, F, F \)) and mode B (routers: \( F, F, F, F, F, F \)):

\[
SC = \bigoplus_{i=1}^l (SC)
\]

where: \( SC = \{ [R, SL], SM \} \) – the isomorphic substructure, \( [R] \) – the set of resources, \( SL = \{ [P, U, T, \theta^0] \} \) – characterizes the structure of local processes in \( SC \), \( O \) – the set of local processes, \( T \) – the set of local process operations, \( \theta^0 \) – the set of dispatching priority rules.

\( SM = \{ mP, mII, mT, \theta^0 \} \) – characterizes the structure of multimodal processes in \( SC \), \( mP \) – the set of multimodal processes, \( mII \) – the set of multimodal processes routes, \( mT \) – the set of multimodal processes operation times.

\( \Theta_{l} \) – a number of isomorphic subclasses belonging to \( SC \).

\( \Theta_{l} = \{ SC \} \) – means a way the isomorphic substructures are composed due to the operator \( \Theta \) of structures composition. The composition of two structures \( SC \) and \( SC \) connected mutually shared resources \( R, B \) such that \( R \cap B \neq \emptyset \), i.e. \( SC \cap BSC = SC \), is the structure \( SC \) defined by:

\( R = [A \cup B \cap SC \} \)

\( U = A \cup B \}

\( T = A \cap B \} \)

\( \Theta \)
Problem of crystalline-like SCCP

In above mentioned context our main problem concerns an adjustment of SCCP parameters as to obtain its cyclic behavior:

Problem of crystalline-like SCCP’s cyclic scheduling

Given: The structure $SC$ (1) of the SCCP where operation times $^iT$, $^iMT$ and dispatching rules $^i\theta$, $i = 1 \ldots lc$ are unknown.

Question: What values of $^iT$, $^iMT$ and $^i\theta$ ($i = 1 \ldots lc$) guarantee the SCCP cyclic (deadlock free) behavior $X'$ (3)?

Considered problem belongs to the class of the synthesis (inverse) problems$^4$ where, parameters guaranteeing the cyclic behavior of SCCP are sought. In proposed approach the selection of parameters $^iT$, $^iMT$ and $^i\theta$ can be carried out for each isomorphic substructure $^iSC$ independently. That means, the problem boils down to the following question: Does there exist a set of parameters $^iT$, $^iMT$ and $^i\theta$ of the given isomorphic substructure $^iSC$, guaranteeing the cyclic behavior of the whole SCCP? In other words, our main objective is to provide conditions allowing to calculate the cyclic schedule of a given SCCP based on the periodicity of its elementary isomorphic structure.

Let us show that knowledge about the schedule $X'$ of the single substructure $^iSC$ enables to calculate $^iT$, $^iMT$, $^i\theta$ values, as well as the cyclic schedule $X'$. In considered case, see Fig. 1, substructures $^iSC$ of routers servicing packet transmission in modes A and B, respectively, generate the same behaviors. That means, behaviors (encompassing cyclic schedules) of two distinguished substructures, see Fig. 1b) determine the behavior of the whole structure $SC$. However, in order to guarantee that operations executed according to $X'$ do not lead to deadlocks and collisions [4, 6], the resources sharing subsequent substructures $^iSC$ (e.g. $^iR_6$, $^i+3R_6$, $^iR_5$, $^i+1R_5$) have to be unified as to provide connections between common resources, see structure $^{ab}SC$ on Fig. 2. In this kind of structures, i.e., representing interconnected isomorphic substructures, so called elementary structures, resources: $^{ab}R_5$, $^{ab}R_5'$, $^{ab}R_6$, $^{ab}R_6'$, representing $^iR_6$, $^i+3R_6$, $^iR_5$, $^i+1R_5$ ($i = 1 \ldots 9$) in $SC$ from Fig. 1 are unified. In other words, an elementary structure $^{ab}SC$ (consisting substructures $^{ab}SC$, $^{ab}SC$ of both modes) is a model of isomorphic substructures (mode A and B) interconnected each other alternately along horizontal and vertical lines - see Fig. 2. The behavior of $^{ab}SC$ determines the behaviors of each isomorphic substructures. Taking into account such top-down perspective, the
cyclic schedule $a^bX'$ (consisting of schedules $a^aX'$ and $b^aX'$) imposed by the structure $a^bSC$, implies cyclic schedules 
$i^aX'$, for $i^SC$, $i = 1..9$, as well.

That means that in order to determine parameters of each isomorphic substructure $i^SC$ the parameters of an elementary structure $a^bSC$ should be found at first. In turn, in order to find the values of sought dispatching rules $a^b\theta$ and operation times $a^bT$, $a^b mT$, guaranteeing reachability of the cyclic schedule $a^bX'$, the following constraint satisfaction problem \[18\] has to be solved:

$$PS'_a = \left( \left\{ \left( a^bT', a^bX', a^b\alpha', \left\{ \left( D_T, D_x, D_\theta, D_a \right) \right\} \right\}, \left\{ C_L, C_M, C_D \right\} \right\} \right)$$

where: $a^bT'$, $a^bX'$, $a^b\alpha'$ – decision variables, $a^bT' = (a^bT, a^b mT)$ – sequence of operation times of structure $a^bSC$ (Fig. 2), $a^bX' = (a^aX, a^b mX)$ – cyclic schedule of structure $a^bSC$, $a^b\theta = \{ a^b\theta^0, a^b\theta^1 \}$ – the set of priority dispatching, $a^b\alpha' = (a^b\alpha, a^b m\alpha)$ – periodicity of local/multimodal processes executions, $D_T, D_x, D_\theta, D_a$ – domains determining admissible value of decision variables: $D_T: a^b mT_{j,k}, a^bL_{j,k} \in \mathbb{N}$; $D_x: a^bX_{j,k}, a^bL_{j,k} \in \mathbb{Z}$; $D_a: a^b\alpha, a^b m\alpha \in \mathbb{N}$; $\{ C_L, C_M, C_D \}$ – the set of constraints $C_L$ and $C_M$ describing SCCP behavior, $C_L$ – constraints determining cyclic steady state of local processes, i.e. their cyclic schedule \[4\], $C_M$ – constraints determining multimodal processes behavior \[4\], $C_D$ – constraints that guarantee the smooth (deadlock-free and collision-free) implementation of the processes operation executed on mutual resources $(a^bR_5, a^bR_5', a^bR_6, a^bR_6')$. The solution of the problem \(4\) is the schedule $a^bX'$ following all the constraints from the given set $\{ C_L, C_M, C_D \}$. That means, if such schedule exists for the elementary structure $a^bSC$, then it is possible to smoothly execute the operations of processes occurring in all isomorphic substructures $(i)SC$.

The constraints $C_L, C_M$ guarantee that in the elementary structure $a^bSC$ from Fig. 2 the processes will be executed in a cyclic and deadlock-free manner. These constraints, however, cannot ensure the lack of interferences between the operations executed in neighboring substructure processes: $a^SC, b^SC$, (resources $a^bR_5, a^bR_5', a^bR_6, a^bR_6'$). In order to avoid interferences of this kind, additional constraints $C_D$ are introduced, which describe the relationships between the process operations of the composed structures. For that purpose the principle of substructures composition is applied. The resulting cyclic schedule $a^bX'$ can be obtained as composition of the schedules $a^aX'$ and $b^aX'$: $a^bX' = a^aX' \cup b^aX'$ if the following conditions hold:

(a) the period of schedule $a^aX'$ is equal to the total multiple of the periodicity of schedule $b^aX'$: $a^a m\alpha MOD b^a m\alpha = 0$ and $a^a \alpha MOD b^a \alpha = 0$,
the operations of common resources (e.g. $abR_2, abR_5', abR_6, abR_6'$) are executed without mutual interferences, i.e. in the schedules $a'X', b'X'$ there are cyclically repeatable time windows that make it possible to execute the process operations of both substructures $aSC, bSC$.

2. Formally, the constraints that guarantee the lack of interferences while executing the process operations on mutual resources are defined in the following way.

3. In order to guarantee the smooth process implementation on the resource $R_k$ the extension of the conventional constraints of non-superimposition of time intervals is used [2, 13, 14]. The two operations $a_{o_{l,j}}, b_{o_{q,r}}$ do not interfere (on the mutually shared resource $R_k$) if the operation $a_{o_{l,j}}$ begins (at the moment $a_{x_{l,j}}$) after the release (with the delay $\Delta t$) of the resource by the operation $b_{o_{q,r}}$ (at the moment $b_{x_{q,r}}$ of the subsequent operation initiation) and releases the resource (at the moment $a_{x_{l,j}}$ of the subsequent operation initiation) before the beginning of the next execution of the operation $b_{o_{q,r}}$ (at the moment $b_{x_{q,r}} + b\alpha$). The collision-free execution of the local process operations is possible if the constraint below is satisfied:

4. $\forall a_{x_{l,j}} \in aX, \forall b_{x_{q,r}} \in bX, \forall R_k \in Rk\{a_{x_{l,j}} \geq b_{x_{q,r}} + k' \cdot b\alpha + \Delta t \land a_{x_{l,j}} + k' \cdot a\alpha + \Delta t \leq b_{x_{q,r}} + b\alpha\}$

5. $\forall \left[(b_{x_{q,r}} \geq a_{x_{l,j}}, k' \cdot a\alpha + \Delta t) \land (b_{x_{q,r}} + k' \cdot b\alpha + \Delta t \leq b_{x_{q,}} + b\alpha)\right]$ (5)

6. where: $j' = (j + 1) \mod I_x(i)$, $r' = (r + 1) \mod I_r(q)$.

7. $k' = \{0 \text{ when } j + 1 > I_x(i) \} \land k'' = \{0 \text{ when } r + 1 > I_r(q) \}$, $1 \text{ when } j + 1 \leq I_x(i)$.

8. $a\alpha / b\alpha$ – periodicity of schedule $aX' / bX'$; $I_x(i) / I_r(q)$ – length of process route $aP_i / bP_q$.

9. $a_{x_{l,j}} / b_{x_{q,r}}$ – initiation moments of the operation $a_{o_{l,j}} / b_{o_{q,r}}$ of the structure $aSC / bSC; a_{x_{l,j}} / b_{x_{q,r}}$ – initiation moments of operation executed after $a_{o_{l,j}} / b_{o_{q,r}}$.

Satisfying the constraint (5) means that on every mutually shared resource of the substructures $aSC, bSC$ the local processes are executed alternately, i.e. they pass each other. In similar way the constraints for multimodal processes are defined. Such constraints can be treated as a sufficient conditions to guarantee a cyclic behavior of structure $SC$ (1) composed of isomorphic substructures $lSC$.

4. Computational experiments

Presented approach can be seen as an alternative to ones presented in [20]. It enables to recognize the cyclic behavior (encompassed by the cyclic schedule $X'$ (3)) of the crystalline-like structure $SC$ based on the behavior of elementary structure. For example the recognition of SCCP behavior from Fig. 1 follows from evaluation of the elementary structure $abSC$ parameters (i.e. the composition of substructures $aSC, bSC$, see Fig. 2). Therefore the problem $PS'_{ab}$ (4) has to be solved.

In case of constraints $C_2$ it is necessary to guarantee a collision-free execution of processes operations $aP_1, bP_6$ (on the resource $abR_2, abP_6, bP_1$ (on the resource $abR_5'$, $aP_5, bP_2$ (on the resource $abR_5'$, $aP_5, bP_5$ (on the resource $abR_5$). These constraints are formulated due to (5). The problem $PS'_{ab}$, formulated in this manner, can be then implemented and solved in the constraint programming environment OzMozart (CPU Intel Core 2 Duo 3GHz RAM 4 GB). The first admissible solution was obtained in less than one second.

The result of the problem solution for the structure from Fig. 2 is illustrated as a cyclic schedule from Fig. 3. In considered case the dispatching rules $ab\theta$ and the operation times $abT'$ of routers corresponding to the modes A and B, see Fig 1b) are known. That means only rules and operation times of resources $abR_5', abR_5, abR_6, abR_6', abR_7, bR_7, aR_8, bR_8$, as well as initiation moments of all operations $abX'$ are sought. If the operation times $abT'$ and initiation moments $abX'$ have such values as those in Fig. 3 and the dispatching rules as those in Tab. 1, then in the structure $abSC$ a cyclic behavior is reachable.
According to (4) the final schedule (containing the schedules \( a^X \), \( b^X \)) can be treated as pattern to create the schedule \( X' \) (\( a^X \) is a pattern for \( i^X \), \( i = 1,3,5,7,9 \) as well as \( b^X \) is a pattern for \( i^X \), \( i = 2,4,6,8 \)). The schedule \( X' \) being a multiple composition of the schedules \( i^X \) is presented in Fig. 4. It is evident that the composition of schedules \( i^X \) of all the substructures \( i^SC \) does not lead to interferences in the execution of the operation – the schedules \( i^X \) on the resources \( i^R \), \( i^R + i^R \), \( i^R \) and \( i^R + i^R \).

Referring back to CCN presented in Fig. 1, the obtained schedule should be treated as an illustration of packet transmission flows between the hosts and servers. It should be emphasized that time of transmissions realized along blue (red route) route takes 106 u.t. (104 u.t.). The periods of local and multimodal processes are equal to: \( i\alpha = 9, i\ma = 18 \) u.t., respectively.

Presented experiment shows how to use proposed approach to evaluate the behavior of crystalline-like structure. Total computation time required is less than 2 seconds. In opposite to other approaches\(^5,20\), the schedule \( ab^{X'} \) can be used to evaluate the schedule \( X' \) of structure \( SC \) (Fig. 1) with any size (with any numbers of routers). The only limitation follows from the size of an elementary structure which cannot exceed 40 operations.\(^4\)

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Table 1. Dispatching rules for the structure \( abSC \) from Fig. 2

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<tr>
<th>dispatching rules for local processes</th>
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Legend: \( P_i \) – execution of process’s \( i^P \) operation \( P_j \) – suspension of process’s \( i^P \) \( m^P \) – execution of process’s \( i^m^P \) operation

Fig. 3. The cyclic schedule \( ab^{X'} \) of the structure \( abSC \)
A declarative modeling approach to multimodal processes cyclic scheduling in crystalline-like CCN environment is considered. In such a regular network, i.e. composed of isomorphic substructures, the packet transmission flow is realized along arbitrarily determined origin-destination routes. The routes considered consist of routers synchronizing packet transmission flows while using the similar structure of local processes control mechanism. Since a problem of concurrent cyclic processes scheduling can be seen as a blocking job-shop one (where the jobs might block the resources), i.e. as a NP-hard problem\(^{15}\), hence the considered case of packet transmission also belongs to that class of problems. The solution proposed assumes that schedules of packet transmission flows match-up the given routes. The relevant sufficient conditions guaranteeing such a match-up exists were provided. The behavior of the crystalline-like structures composed on the base of principle of substructures composition, i.e. assuming that structures are composed of the elementary isomorphic substructures, manifests behaviors of

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**Legend:**
- \( \text{\textcolor{blue}{\textcircled{\text{P}}}} \) – execution of process’s \( \text{\textcircled{\text{P}}}_j \) operation
- \( \text{\textcolor{red}{\textcircled{\text{s}}}} \) – suspension of process’s \( \text{\textcircled{\text{P}}}_j \) operation
- \( \text{\textcolor{green}{\textcircled{\text{m}}}} \) – execution of process’s \( \text{\textcircled{\text{m}}P}_j \) operation

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Fig. 4. The cyclic schedule \( \chi' \) representing the packet transmission in a part (taking into account routers: \( ^1F, ^2F, ^3F \)) of CCN from Fig. 1

5. Conclusions

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elementary structure. Since each isomorphic structure generates cyclic schedule which match-up with the schedules generated by adjacent isomorphic structures, hence the behavior of the whole crystalline-like structure is also cyclic. Consequently, cyclic behavior of the crystalline-like structure can be easily evaluated from the behaviors of its elementary component structures. This kind of approach allows to reduce the computational complexity of considered problem.

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