Analysis of the Optimization Problem of the Cyber-Physical Objects Distribution

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Abstract. The article discusses the movement of one and a group of cyber-physical objects in the form of a telecommunication system with queues or a queuing system. Their interaction in the group and the exchange of information between them with minimal delays and the highest speed are described. The conditions of optimal interaction are shown, the analysis of the distribution functions of applications depending on the number of objects in the group is carried out.

Keywords: Cyber-physical objects, Queuing system, Group Interaction, Telecommunication system.

1 Introduction

An important role in the successful implementation of modern information technologies within a particular subject area is played and will be played by the relevant unified information space. In general, under these spaces is understood a set of data and knowledge, organized in a special way and built with the use of database systems, file storage and technologies for their use, as well as information and telecommunication systems and networks that operate according to general rules and provide information interaction and access to consumers geographically distributed information resources of organizations and enterprises involved in improving the information system. In connection with the emergence and widespread implementation in practice of cyber-physical and mobile robotic systems, as well as the need to organize individual and group management of them, the issues of formation of unified information spaces that ensure effective interaction of these systems are of particular relevance [1].

Cyber-physical systems – a new technological paradigm that combines various information and telecommunication systems from the standpoint of isolation and integration into a single whole layer of physical elements and their information displays. Along with the Internet of things, BigData technologies and pervasive sensor networks, cyber-physical systems form the technology platform for Industry 4.0 [2, 3]. In view of the pervasive spread of cyber-physical systems, developers of specialized software and hardware solutions are searching for unified approaches that would simplify the development of various solutions in the field of cyber-physical systems and reduce the cost of creating specialized control and monitoring systems. In addition, the existence of a unified approach will simplify the problems associated with scaling, which will arise with the further expansion of the considered systems [4].

2 Models of cyber-physical objects

The cyber-physical approach allows to consider information aspects of communication and interaction of objects of management among themselves and with an external environment. The cyber-physical model describes the processes of formation or antientropy, i.e. organized movement of objects of reality taking into account information influences. CPhS is a much more general concept for the terms «robot» and «artificial intelligence», representing in some cases the integration of the two concepts. In the general case of cyber-physical object – the object that is data-driven.

Each robot is a cyber-physical object that corrects its state, reacting to the impact of the surrounding physical and information environment. Due to the widespread introduction of digital technology for the collection, storage, processing and transmission of robot data, any modern robotic object exists exclusively in digital reality. Each physical object surrounding the robot is represented in its memory in the form of digital information. If something cannot be measured and recorded, it simply does not exist for a robot [5].

The concept of CPhS is comprehensive. Under certain conditions, a significant part of the phenomena of the modern world can be called CPhS.

According to the format of devices, CPhS can include global «systems of systems», their individual components, sensors and measuring instruments, objects of any size and scale.

CPhS includes both hardware and computing parts. Each of these components, in turn, can interact with most modern technologies.

The term «CPhS» can be used both to describe a particular device and to describe a system or concept (implying the integration of a computational component into a physical process).

The model of infocommunication system assumes division of interaction space into three levels (domains), each of which is connected with groups of objects of the General nature – physical, information (cybernetic) and cognitive. These objects represent the entities of the respective domains – physical (PhD), information (ID) and cognitive (CD). Appropriate interfaces are implemented at domain boundaries to allow interaction between system elements. Each element of the system has a finite ordered set of States that define the element's own thesaurus.

CPhS and CPhO exist in cyberspace, which is a fundamentally new environment of confrontation between competing States, not being geographical, but being international.

At the heart of any cyberphysical system is the model of the cyberphysical atom (CPhA). The atom is the smallest indivisible element of the system. Accordingly, the CPhA describes one entity of the physical domain and its corresponding cybernetic part. Both of these entities form a single complex that exists in PhD and ID.

The transition from the physical domain to the information domain is realized with the help of various devices-sensors (sensor). The reverse transition is performed by actuating devices (actor).

CPhA must be considered to formally describe the behavior or state of an individual cyber-physical object, for example, if the system operator aims to analyze an individual object operating within the system. However, the cyber-physical network is traditionally represented as a network of interacting CPhOs, in which case the CPhA will be the basis for further, more complex abstractions.

The CPhT is based on the topological description of the CPhA network. CPhT defines the graph of the cyber-physical atom network. The main descriptor of CPhT is a connectivity matrix.

Cybernetic or information exchange is implemented through various protocols and its features are described by the information communication operator of the «cyber-object – cyber-object» type.

CWTS together with the CPhA set are theoretically capable of fully describing any cyber-physical network, but a few more abstractions may be required for ease of simulation. The following model describes a cyber physical cluster (AS). This model shows its useful properties in the problems of scaling CPhO networks. If it is required to operate with a significant number of cyber-physical atoms and cyber-physical typology, when whole constellations of CPhA and segments of the general cyber-physical typology need to be considered as a single entity, it is advisable to use CPhC. Accordingly, the complex network of a cyber-physical object can be simplified to describe a connection between several cyber-physical clusters.

Although any CPhS can be described in terms of a cyber-physical topology or using Bazis CPhT, this approach does not allow to reflect genetic relationships in cyber-physical network as well as the process of evolutionary transitions, sub-processes, etc. at the same time, such information is essential as the selection of classes and instances of classes will allow you to install respective Parallels in the thesaurus of the monitoring subsystem and to structure the process of presenting information to the operator. Thus, to describe the hereditary relationships within the CPhS, we will use the cyber-physical hierarchy.

Cyber-physical hierarchy completes the set of models used to describe CPhS. However, further research aimed at modeling CPhS may lead to the need to create additional classes of models.

3 Dynamics of the behavior of a cyber-physical object

The movement of CPhO in three-dimensional space, interaction in the group and the exchange of information between them with minimal delays and the highest speed can be described as a telecommunications system with queues or Queuing system.

Each CPhO is a node of the network capable of being at rest or moving according to a given algorithm.

If we assume that one CPhO is the master, and the rest are static in space , then the movement of the leading CPhO during the interaction $s = t_0 \cdot v$, where t_0 – the time of interaction with one node of the network, v – its speed of movement. For correct description it is necessary that $\frac{t_0 \cdot v}{R} \to 0$, where R - radius of coverage area.

If $v > 0$ and $t_0 > 0$, then the connection at the boundary of the circle by radius R is lost (figure 1).

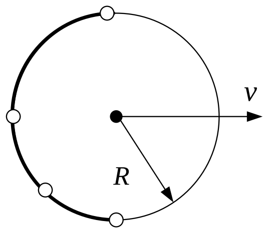

Fig.1. Unserved nodes on the zone boundary at $v > 0$

With a known time spent in the service area of the node is determined by the boundary of the area in which the node is guaranteed to be serviced at a known speed of the leading CPhO. With minimal maintenance time t_0, the distance to the zone boundary is equal to (figure 2):

$$S_c = t_0 \cdot v$$

At interaction of a set of nodes CPhO can be considered as Queuing system on which input applications arrive, in a certain priority [6].

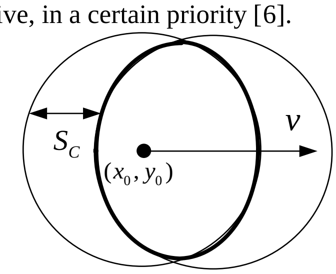

Fig. 2. Service Area of CPhO at $v > 0$

Nodes that are not serviced will be refused. The flow rate is determined by the value R, the number of nodes in the service area and the speed of the leading CPhO.

Time is spent on servicing each request, during which the node must be in the zone R (figure 3).

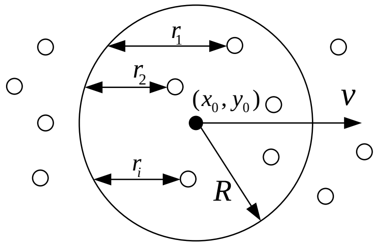

Fig. 3. CPhO Interaction with network nodes

Depending on the determination of the coordinates of the nodes, two service cases are possible. If the coordinates of the nodes are known, then a deterministic flow of requests enters the system. In this case, the optimal operation will be according to a certain service rule.

If the coordinates of the nodes are not known, then a random stream of requests enters the system. In this case, you need to know the probability of denial of service from the system settings.

For the first case, the number of nodes interactcing with the leading CPhO is equal to:

$$k_{MAX} = \left[\frac{R}{v \cdot t_0} \right]$$

where is the k – number of interacting nodes.

The number of nodes depends on the time spent in the interaction area and location in space (figure 4).

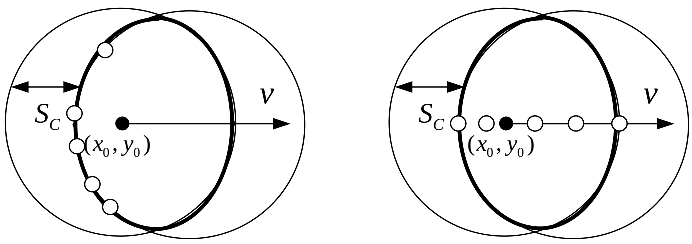

Fig. 4. Examples of node placement in the service area

Let there be a node in the service k area, and the time spent in it is equal to:

$$t_i = \frac{r_i}{v}$$

where is the r_i – distance from the node to the boundary of the i -st node.

It takes time to maintain each node t_0. When you select the interaction sequence in which the number of servicec nodes is maximum, the initial point in time $t_1 = 0$ and one node is serviced at the same time. Then the start time of the j node is equal to $t_j = (j-1) \cdot t_0$.

To solve the problem, you need to determine the order of service nodes, which would be served their maximum number.

In the second case, when the coordinates of the nodes are unknown, the following restrictions are required:

– the number of static nodes is constant and represents a Poisson field,

– the leading CPhO moves rectilinearly at a constant speed,

– the interaction zone has the area of a circle with a radius R .

We define the distribution function for the incoming flow of applications. To do this, consider the CPhO service area at time 0 and at time t.

During the time t the system will receive those applications (nodes) that are in the area shown in figure 5.

According to the properties of the Poisson field, the probability that in some region is n the number of nodes is determined by the Poisson distribution and depends only on the area of this area.

The probability that in the S will be m knots, equal

$$P_m = \frac{a^m}{m!} e^{-a}$$

where $a = \rho \cdot S(t)$

ρ – is the number of nodes per unit area;

$S(t)$ – the area of the region.

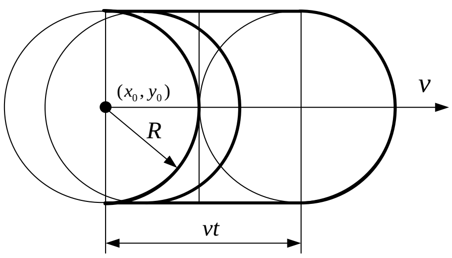

Fig. 5. Probability of hit n nodes in the region S

$$P_m(t) = \frac{(\rho \cdot S(t))^m}{m!} e^{-\rho \cdot S(t)}$$

The area of a given area is

$$S(t) = 2R \cdot vt$$

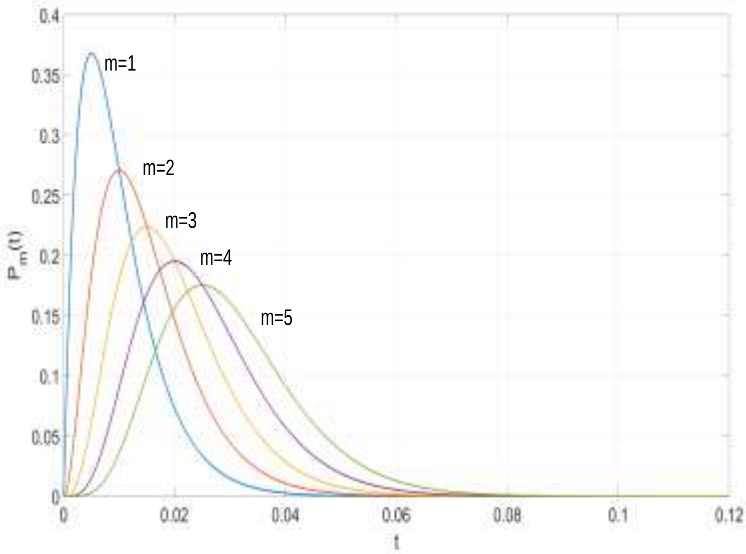

Fig. 6. Distribution Function of the number of applications $m = 1...5$

The flow rate, i.e. the average number of applications per unit of time, will then be:

$$\lambda = \rho \cdot 2R \cdot v$$

Consider a random variable T – the time interval between two adjacent events in the stream – and find its distribution function:

$$F(t) = P(T < t)$$

The probability that the time interval is long t m applications will be received, equal to:

$$P(T \geq t) = 1 - F(t)$$

$$P(T \geq t) = p_0(t) = e^{-\rho 2Rvt}$$

The distribution function of the time interval between applications has the following form (figure 7):

$$F(t) = 1 - e^{-\rho 2Rvt}$$

Thus, the input of the system receives a stream, the time intervals between applications in which are distributed with an average value:

$$\bar{a} = \frac{1}{\rho \cdot 2R \cdot v}$$

and dispersion:

$$\sigma_a^2 = \frac{1}{4(\rho 2Rv)^2}$$

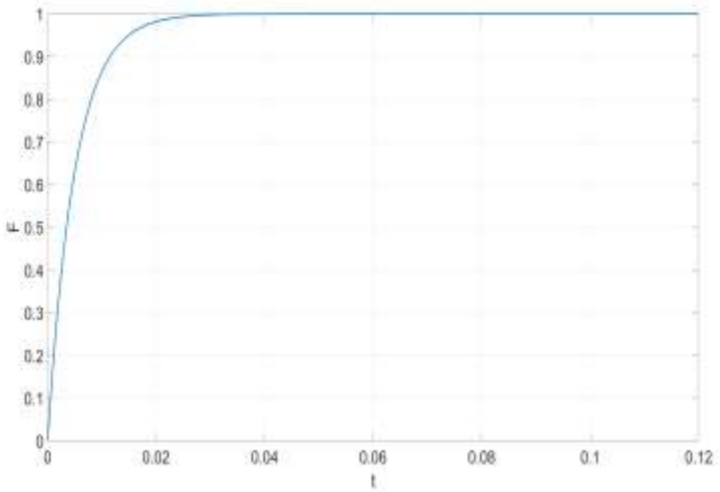

Fig. 7. Time interval distribution Function between applications

If the time of stay of the node in the interaction zone is not limited, then:

$$P = \frac{1-\rho}{1-\rho^{\frac{2}{C_a^2+C_b^2}K+1}}\rho^{\frac{2}{C_a^2+C_b^2}K+1}$$

where $$\rho = \frac{\lambda}{\mu} = \lambda \cdot t_0$$

C_a – coefficient of variation of the time interval between applications;

C_b – coefficient of variation of service time;

K – number of waiting places in the queue.

In this instance $C_a = 1,\ C_b = 0$, with this in mind

$$P = \frac{1-\rho}{1-\rho^{2K+1}}\rho^{2K}$$

4 Dynamics of the behavior of a group of cyber-physical objects

When considering the problem of data collection from nodes located on a large territory, it is advisable to consider the possibility of using a group of CPhO.

The CPhO group can be represented as a queuing system [7].

The flow of requests (messages) coming to the node of each of the CPhOs, γ_i it has the properties of the simplest flow of applications.

Host message output i with probability r_{ij} fed to the input node j.

With probability $1-\sum_{j=1}^{n} r_{ij}$ applications leave the node i and are directed to the external environment.

Service time on the route section t it consists of the time of transmission of the message on the channel τ and the standby time of the ready state ψ channels that are random.

Channel state change is a random process that occurs under the influence of a variety of independent factors, such as input and output from the communication zone, due to a random deviation from a given trajectory, the impact of interference from transmitting devices located on other elements of the system, etc. With a sufficiently large number of such independent events, the channel readiness intervals will have a distribution close to exponential.

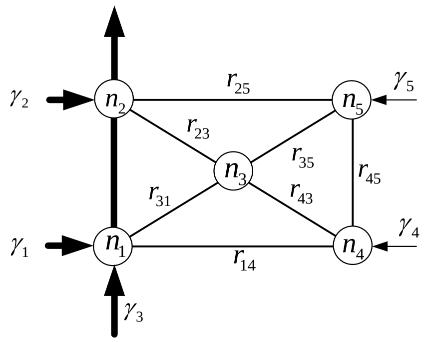

Fig. 8. Data delivery route model between source (s) and receiver (t)

As shown in [8], the average delivery time in such a network can be estimated as:

$$\bar{T} = \sum_{j=1}^{M} \frac{\lambda_j}{\gamma} T_j$$

where M - number of channels in the network;

n – number of nodes in the network;

$T_j = \dfrac{1}{\mu_j - \lambda_j}$ – delay on the j -th channel;

$\gamma = \sum_{i=1}^{n} \gamma_i$ – total network traffic;

λ_j – total traffic in the j -th channel;

$\mu_j = \frac{1}{\overline{t_j}}$ – service intensity in the j -th channel;

Delivery times for a particular network route can be estimated using Jackson network properties. It is known that each of the nodes of such a network can be considered as an independent Queuing system M/M/1, and the entire route-as a sequence of independent Queuing systems M/M/1.

The function of distribution of time of delivery of the message on a route in such system can be described by distribution of Erlang. By $\lambda_i = \lambda$ and $\mu_i = \mu$ $\overline{t_i} = \overline{t} = 1$ $i = 1,\ldots,m$, with an average of $m \cdot \overline{t}$, which is the average delivery time of the message along the route $\theta_k = m_k \cdot \overline{t}$, where m_k – number of channels in k -m route.

$$S(x,m) = \frac{m \cdot \mu \cdot (m \cdot \mu \cdot x)^{m-1}}{(m-1)!} e^{-m \cdot \mu \cdot x}$$

The order m in this case corresponds to the number of transitions, assuming that the message transmission time on each of them is the same.

The approximation of the network in question by the Jackson network is probably the more accurate the larger n and the closer the service time distribution is to the exponential distribution. With a relatively small number of nodes and a small number of routes, network properties can differ significantly from Jackson network properties. In such a case, the route model can be described as a multiphase g/G/1 system. Obtaining a delivery time allocation function in this case can be very difficult.

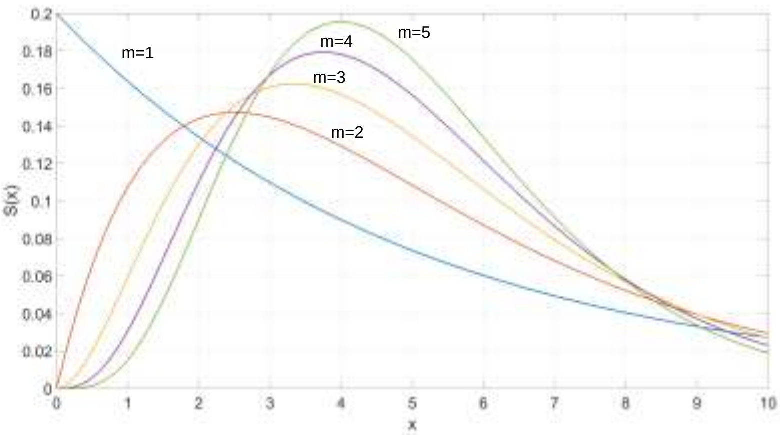

Fig. 9. Probability Density of delivery time along a route length of $m = 1,2,3,4,5$ transitions

However, an approximate estimate of the average delivery time in the j-th channel of the route is possible, as shown in [9]:

$$\tilde{T}_j \approx \frac{\rho_j \cdot \overline{t}_j}{2(1-\rho_j)} \left(\frac{\sigma_{a_j}^2 + \sigma_{t_j}^2}{\overline{t}_j^2} \right) \left(\frac{\overline{t}_j^2 + \sigma_{t_j}^2}{a_j^2 + \sigma_{t_j}^2} \right)$$

where $\rho_j = \lambda_j \overline{t_j}$

$\sigma_{a_j}^2$ – dispersion of intervals between messages;

$\sigma_{t_j}^2$ – the variance of service time in j-th channel;

$\overline{t}_j$ – service time in channel j;

$a_j = \dfrac{1}{\lambda_j}$ – the average value of the interval between messages in the j-th channel.

Then the delivery time on the route will be equal to:

$$\theta_k = \sum_{j=1}^{m_k} \tilde{T}_j$$

where m_k – number of channels in the k-th route.

The probability of connectivity can be defined as the probability of hitting a sphere of a given radius. From the properties of the Poisson field, this probability is:

$$P_{\geq 1} = 1 - e^{-a}$$

where $a = V \cdot \rho$ the expectation of the number of points in a sphere.

$V = \dfrac{4}{3}\pi \cdot x^3$ – the volume of the sphere of radius x;

ρ – node density (number of nodes per cubic meter).

Then the dependence of the probability of connectivity on the density and radius of the network node is equal to:

$$P = 1 - e^{-\frac{4}{3}\pi \cdot x^3 \cdot \rho}$$

If the boundary is a plane, then the volume in which communication with a neighboring node is possible is half that for a node located near the center of the considered area.

5 Conclusion

The above analysis shows that in the case where the location of network nodes can be described by the Poisson field, the model of interaction between the CPhO and the ground control point can be described by the model of a Queuing system with a combined service discipline (expectation and losses), which receives the simplest flow of applications. With a random distribution of nodes, to describe the quality of service of nodes (probability of losses) is required to evaluate the coefficients of variation of time intervals between requests (the moments of ingress nodes in range RPO) and service time application (time of transmission).

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