Energy-efficient Managing of Data Transmission in Socio-Cyberphysical System at Critical Facility

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Abstract. This paper describes information management exchange processes in data transmission network of a socio-cyberphysical system of a critical facility, ensuring secure data transmission. The lock-free routing approach, developed on the basis of this model, includes a number of methods, the implementation of which allows to meet reliability requirements as when designing of an energy-efficient data transmission network of a socio-cyberphysical system on a critical facility from scratch, as when modifying an already existing one. A composite efficiency measure gain is presented here, as well practical suggestions concerning practical application of the developed methods are given.

1. Introduction

Current trends in modern critical facility (CF) security system development are tightly coupled with processes of their automation and integration, which also concern all the other systems for lifecycle and workflow management in such facilities. Following the logic of such integration, it’s further appropriately creating comprehensive security systems with extensive functional capabilities, allowing to automate management of all the others critical facility systems [1]. It’s necessary to note, that efficient CF management requires enough information of its purpose, tasks, current state, as well of present external factors, influencing it [2]. These data are acquired using monitoring capabilities, transmission and processing of relevant data with control devices (measurement units, sensors), communication channels, routers and computing devices, which are the main parts of a CF management system [3, 4].

Currently during CF management system establishment, the following technologies are actively used: smart scheduling and control solutions, Big Data, Internet of Things, Data Mining, etc., already partially approved in action, when used in systems and networks of Industry 4.0 standard [5, 6]. The research data, comprised in the network perspective of M. Kallon, D. Lo, B. Latur, object-oriented ontology of Bogost YA., KHarman G., Brajyanata L., Morton T. and new digital universe ontology of Volfram S., TSyuze K., Fredkin E. show, that by digital data transmission there’s no principally important, who produces and consumes some traffic, and which entity is given an ID: a physical system, a subsystem, a technical device, a thing, a human, a smart algorithm or an event of some kind [7]. Consequently, this all enables us to treat CF management systems as socio-cyberphysical systems (SCPS). Such systems are based on an integral hardware and software platform, which essentially is an automated control system with multi-layered networking structure, which has a centralized LAN-based control unit and contains managing controllers, ingress controllers, communication lines and...
peripheral devices for information harvesting and processing. This information can be ingested from various threat-detection devices (sensors). Such systems can also be employed to manage various automation means in security and vital systems of CF [8, 9].

The essence of Information Exchange Processes (IEP), being run during CF management, consists in implementation of an (operational) workflow, concerned with transmission and input of (partial) messages from sender to receiver. The interactions between participants are performed here using resource separation or via control signal exchange [10, 11].

Analysis of routing algorithms, employed in modern data transmission networks (DTN) showed, that majority of them are intended for routing using source address, what greatly increases the size of routing tables [8]. Due to this shortcoming, such routing approach poorly suits for DTN SCPS CFs [12].

Conversely, increased reliability is one of the key premises of DTN SCPS CF design, as any malfunction or failure of the system can cause severe consequences. The required reliability of the modern DTNs required reliability is ensured by introduction of redundant components and line reservation [13]. That’s why it appears urgent to develop a DTN SCPS CF design approach, which would allow high reliability of data transmission.

2. Problem Formulation

DTN SCPS CF topology is most appropriately to represent as a directed graph $G = (V, E)$, including a finite set of vertices (nodes) $V$ (we denote the number of vertices as $|V|$), and a set of directed arcs (edges) without loops $E \subset V \times V$ (we denote the number of arcs as $|E|$), such as $(v_i, v_j) \notin E$ for any $v_i \in V$ [14]. Considering, that in DTN SCPS CF communication lines are usually bidirectional, we can postulate, that if $(v_i, v_j) \in E$ is a directed arc, then the arc $(v_j, v_i) \in E$ is also a directed one. We denote the set of the graph vertices, adjacent to the vertex $v_i$ as $\text{Adj}(v_i) = \{v_k \in V | (v_i, v_k) \in E\}$.

Designing modern DTN SCPS CFs it’s necessary to take into account, that message transmission builds solely on their destination addresses; as a rule, the source address of the transmitted message isn’t used in such cases. By routing the sender address maps according to the routing table maps to one or several forwarding operations [15]. Any given receiver in the network can have several different routing graphs, but for practical purposes let’s suppose, that for any vertex $v_i \neq v_j$: $\omega_{G_v}(v_i) \geq 1$ and $\omega_{G_v}(v_j) = 0$ holds true.

Particularly relevant during design are such routing graphs, that allow increasing DTN SCPS CF reliability, providing the following condition for every node. Routing, fully compliant to this condition, is called lock-free and requires loop elimination (acyclic routing graphs). Every vertex of a lock-free routing graph provides at least two ways to receiver node, so if one outbound communication line fails, one of remaining lines comes into action, without recalculation of routing tables [16].

To increase reliability of links between adjacent vertices, we can take $O_1$ vertices, for which $\omega_{G_v}(v_i) = 1$ and appropriately allow for them to have routing loops, consisting of two directed arcs each, obligatory blocking them in normal working mode. We’ll treat such a bidirectional arc $v_i v_j$ in routing graph $G_{v_i} = (V, E)$, where this arc meets $(v_i, v_k) \in E$ and $(v_k, v_i) \in E$ conditions, as a reserve arc. The arc is a reserve one only within a certain routing graph and can be used in default mode, when leading to other receiver nodes.

To define lock-free routing, let’s consider the following conditions. Suppose, $G = (V, E)$ is a DTN SCPS CF topology. Then for a receiver node $v_j \in V$ we take as a lock-free routing graph a directed
subgraph of \( G - G_{v_i} = (V, E') \), including all its vertices \((E' \in E)\) and meeting the following conditions:

1. 1) \( \forall v_i \in V : v_i \rightarrow g v_j \) – accessibility of the receiver node from any other nodes;

2. 2) \( \forall v_i \in V - \{v_j\} : \omega_g (v_i) \geq 2 \) – necessary out-degree not less than 2 for every node except the receiver node;

3. 3) \( \forall v_i \in V - \{v_j\} \forall v_k \in V - \{v_i, v_j\} : v_k \rightarrow g v_j \) – receiver node accessibility from the other nodes in case of deleting any other node except the receiver;

4. 4) \( \forall v_i \in V - \{v_j\} \exists v_k \in V :(v_i, v_k) \in E u (v_k, v_j) \not\in E \) – requirement of at least one non-reserve outbound arc for every vertex other than receiver;

5. 5) \( v_i \rightarrow g v_k \land v_k \rightarrow g v_j \Rightarrow v_{ij} \in E \) – by mutual accessibility of vertices \( v_i \) and \( v_k \) in graph \( G \) they are adjacent, and a reserve arc works as a connection between them.

Hence, the criteria of the lock-free routing are the following [16]:

1. The routing graph is chosen as such, when it meets the criteria of lock-free routing to the certain receiver within the given network topology;

2. If it is impossible within the topology of the given network to meet the lock-free criteria to the certain receiver, the graph with minimum reserve arc number is used for routing, as it maximally qualitatively approaches to the lock-free routing graph.

Evidently, lock-free routing graphs can’t be constructed for every network topology and for any receivers. Hence it seems important to study criteria, properties and design approaches of DTN SCPS CF, compatible with lock-free routing.

3. Information Exchange Model in Data Transmission Network of a Socio-cyberphysical System OF a Critical Facility

As a mathematical model of IEP management in DTN SCPS CF it’s appropriate to use a streaming one, as it allows to account for simultaneous interactions of multiple information sources and receivers and is the most objective tool to improve DTN performance by data exchange to discover internal parallelism [3, 11].

Consider a network, consisting of \(|V|\) nodes, connected with directed lines \( e \in E \) with \( C_e \) throughput each. In this case the physical topology of the DTN SCPS CF under consideration can be described by a graph \( G = (V, E, C) \).

Messaging traffic from SPCS sensors, belonging to various classes of \( s \) service (CoS) \( s \in S \), which possesses a certain attribute set, specifying priority levels for the SPCS messages, transmitted by (groups of same-type) sensors [9].

Let \( v_i \) be the source vertex and \( v_j \) be the traffic receiver vertex. We denote the pair of nodes \((v_i, v_j)\) as \( \sigma_{ij} \left( i, j = 1, |V|, \space i \not= j; \space v_i, v_j \in V \right) \).

For the specified vertex pair \( \sigma_{ij} \) the traffic stream \( f_{\sigma_{ij}} \) of the CoS \( s \) can be transmitted via network by different routes; hence it’s important to define the appropriate route \( r_{\sigma_{ij}, s}^x \), which is used to deliver
some part of the output stream of the CoS $s$ to the receiver vertex $v_j$. The aggregate traffic $f_{\sigma_{ij,k}}^k$ of the multiple valid routes, going through each $e$ line, cannot exceed the throughput capacity of this line.

The aggregate stream $f_{esv_i}$ of the CoS $s$, going through the $e$ line, can be defined for all routes, going out of the $v_i$ vertex, as follows:

$$f_{esv_i} = \sum_{j=1}^{|V|} \sum_{k} f_{\sigma_{ij,k}}^k, e \in \{r_{\sigma_{ij,k}}^k\}, \forall j,$$

(1)

where $\{r_{\sigma_{ij,k}}^k\}$ – a set of valid routes $r_{\sigma_{ij,k}}^k$, going through the $e$ line.

In such case the aggregate traffic CoS $s$ stream from all the nodes $v_i \in V$, going through the $e$ line, is calculated as follows:

$$f_{es} = \sum_{i=1}^{\|V\|} f_{esv_i} = \sum_{i=1}^{\|V\|} \sum_{j=1}^{\|V\|} \sum_{k} f_{\sigma_{ij,k}}^k, e \in \{r_{\sigma_{ij,k}}^k\},$$

(2)

and maximum stream, allowable to go through the $e$ branch of the partial traffic of the CoS $s$

$$f_{es}^* = C_e \rho_e^s,$$

(3)

where $\rho_e^s$ – maximum allowable load factor, determining the throughput fraction of the $e$ line, which is consumed by the partial traffic of the CoS $s$.

For the streams of the CoS $s$ and for the streams of even higher priority the aggregate allowable line $e$ load factor is defined as follows:

$$R_{eg}^s = \sum_{g=1}^{s} \rho_{eg}^s,$$

(4)

where $g$ – the id number of the CoS $s$ in the set $S$ (the highest priority has the CoS with index number $g = 1$).

The maximum throughput $F_{e}^*$ of the $e$ line, treated as maximum allowable CoS $s$ stream and the ones with higher priority, is defined by $R_{eg}^s$ factor:

$$F_{e}^* = \sum_{g=1}^{s} f_{eg}^*, e \in R_{eg}^s.$$

(5)

The prerequisite to exclude locks on every line $e \in E$ in the network under consideration is the following:

$$F_{e}^\Sigma = \sum_{g=1}^{s} f_{eg}^*.$$

(6)

The prerequisite to exclude locks on every line $e \in E$ in the network under consideration is the following:

$$F_{e}^\Sigma \leq F_{e}^*.$$

(7)
Hence, if the condition (7) is met, further reliability increase of DTN SCPS CF due to greater number of possible paths among nodes; but simultaneously the cost function grows, required to build such a network [17]. To resolve this contradiction more thorough research is needed.

4. Method for Providing Lock-free Routing in Designing a Data Network of a Socio-Cyber-Physical System of a Critical Facility

Method for providing lock-free routing in designing DTN SCPS CF includes following steps [16].

4.1. Analysis of the source data and the construction of the graph corresponding to the processes of information exchange

As the source data for the design of DTN SCPS CF compatible with non-blocking routing, we define the following:

1) representation of network topology (directed or undirected graph).
2) network topology, given as a graph and including:

- set of graph vertices (nodes) \( V = \{v_i; i = 1, ||V||\} \);
- set of graph edges (arcs) \( E = \{e_l; l = 1, ||E||\} \).

4.2. Analysis of the initial topology of network for compatibility with lock-free routing

Preceding the direct design process of the DTN SCPS CF. The method of analyzing the initial topology of the DTN SCPS CF for compatibility with lock-free routing allows to set the possibility of reaching from specific vertices any other network vertices in two or more ways, independent the nodes and edges used (matching the conditions of lock-free routing).

![Diagram](image1)

**Figure 1.** Routing graphs: a) Source graph G; b) The result of the implementation of the first step of the method (graph \( G' \)); The result of the implementation of the second step of the methodology (graph \( G'' \)).

Let the initial topology of the DTN SCPS CF is given in the form of an undirected graph \( G = (V, E) \), which must be checked for compliance with the conditions of unlocking routing (figure 1, a).

**Step 1.** Convert a graph \( G \) to a graph \( G' \) by the rule: for all adjacent pairs of triangles \( \Delta v_k v_m v_n \in G \) and \( \Delta v_m v_n v_q \in G \) (where \( v_m v_n \in \Delta v_k v_m v_n \) and \( v_m v_n \in \Delta v_m v_n v_q \)) represent the vertices \( v_m \) and \( v_n \) in the form of a pair of vertices \( (v_{m1}, v_{m2}) \) and \( (v_{n1}, v_{n2}) \), connected by virtual edges \( v_{m1} v_{m2} \) and \( v_{n1} v_{n2} \).
and \( v_{n1}v_{n2} \), as well as edges \( v_{m1}v_{n1} \) and \( v_{m2}v_{n2} \). The obtained graph is denoted as \( G' = (V', E') \) (figure 1, b).

**Step 2.** Transform graph \( G' \) into graph \( G'' \) according to the following rule: substitute the triangles like \( \Delta v_i v_j v_l \in G' \) present in the graph with respective abstract vertices \( v_i, v_j, v_l \), obligatory retaining connections with all the neighboring vertices (figure 1, c).

**Step 3.** If the graph \( G'' \), obtained in effect of the second method step implementation, is a connected one, i.e., any two of its vertices are connected with sequential pairs of parallel edges, then this graph provides for lock-free routing. If the resulting graph \( G'' \) after all transformations is an unconnected one, necessary guidelines are articulated, concerning possible modifications of the initial DTN SCPS CF topology to meet the provisions of lock-free routing; alternatively, a network is designed, maximally close to lock-free routing topology.

In effect of implementation of this methodology it is possible to judge on compatibility or incompatibility of the initial DTN SCPS CF topology with lock-free routing.

4.3. **Designing DTN SCPS CF in the case of specifying of the initial network topology as a directed graph**

In this case lock-free routing graph construction is made according to lock-free routing iterative optimization methodology. Thereby the following constraints are defined. When implementing the methodology, the following constraints are specified:

1) For all vertices \( v_i \) of the directed routing graph \( G_{v_i} \) it is necessary to ensure the out-degree \( \omega_{G_{v_i}}(v_i) = 2 \);

2) Reserve arcs are allowed only if it is impossible to meet lock-free routing conditions without them.

Having implemented the first methodology step within routing graph \( G_{v_j} \) we obtain only direct arcs in it. Having deleted the redundant arcs (step 2), we obtain by each vertex, except receiver, one or two outbound arcs. When implementing step 3 each vertex \( O1 \) acquires one additional arc (if it is possible). In step 4 we iterate over arcs in graph \( G_{v_i} \) in such way, that the out-degree of every arc remains unchanged together with obligatory decrease of reserve arc number and path length. The number of iterations, required at the last step is greater, than on all previous steps in total.

The lock-free routing graph \( G_{v_j} \) appears as result of methodology implementation, [16] and the computational complexity of this routing algorithm for all receiver nodes, estimated this way, is \( O\left(|V|^3|E|^4\right) \).

4.4 **Designing lock-free DTN SCPS CF in the case of defining of initial network topology as an undirected graph**

In this case lock-free routing graph is constructed according to one of lock-free routing template-oriented methodologies, specifically: based on minimum viable template set or using additional templates.

Routing graph template is generally defined as a subgraph, containing at least one vertex with one outbound arc, used as a primary element when constructing \( G_{v_j} \) graph [18]. At the outset of this implementation approach the routing graph \( G_{v_j} \) contains a single receiver node. Further the vertices,
adjacent to graph $G_{v_j}$, are added to it within a certain template and add up together with the outbound arcs to a new routing graph.

Research shows, that any lock-free routing graph can be represented as a set of routing templates [18]: $T1$ – multidirectional template "from one to many", $T2$ – multidirectional rectangular template with a reserve arc, $T3$ – unidirectional triangular template with a reserve arc, $T4$ – unidirectional template with an outbound arc, $T5$ – composite multidirectional template with a reserve arc, $T6$ – composite unidirectional template with a reserve arc (figure 2).

Figure 2. Routing templates.

Minimum viable templates to construct a lock-free routing graph are T1-T4, on which the lock-free routing methodology is based, consisting in the following.

If the network topology under consideration principally allows for a lock-free routing graph, then at the first step of the methodology implementation only one template may be used, specifically T3 (if it is impossible to add the T3 template at the first implementation step, it is concluded, that the network is incompatible with lock-free routing). However, if it is compatible with lock-free routing, on any following implementation steps it is recommended to employ preferentially T1 or T2 routing templates. T4 is appropriate to use only in extreme cases, if routing graph cannot be constructed using any other templates.

Consequently, at initial methodology implementation steps an incomplete routing graph $G'_{v_j}$ includes a single receiver vertex $v_j$. Until the graph $G'_{v_j}$ will not include all the vertices, belonging to $V$ set, the required routing template is searched within the ring around $G'_{v_j}$ and then added to the graph. Thereby after each implementation step the incomplete routing graph $G'_{v_j}$ is transformed, so the ring around it also changes.

Methodology of lock-free routing provision, based on employment of additional templates, adheres to the same patterns, which are implemented within the previous methodology: first the routing graph $G'_{v_j}$ is constructed, and because of additional routing templates T5 and T6, used here, allows to minimize possibility of T4 usage. Depending on network topology, only two routing templates may be added on the first step: T3 and T4. Should it be impossible to add the routing template T3 at the first step, the network being designed will be incompatible with lock-free routing. Consequently, to construct a lock-free routing graph, first at all it is required to use routing template T3 at the first step. At any next steps it is recommended to employ routing template T1 in any case, and should it be not feasible – T2, T3, T5, T6 and T4 in extreme cases (the templates are ranked in order of preference).

Both methodologies result in lock-free routing graph construction.

4.5. Double-check of the designed network topology for compatibility with lock-free routing
Using the discussed above network topology analysis approach.

4.6. Estimation of reliability and cost-efficiency of the designed DTN SCPS CF in practice
When implementing the proposed methodology.
Within this model the probability of flawless operation of the $l$-th system element is treated as a logical variable $e_l$ and calculated as follows:

$$P_l(t) = e^{-\lambda_l T}, \quad (8)$$

where $\lambda_l$ – failure rate of $l$-th system element, $T$ – its time in use.

Algebraic logic function $y(e_1, ..., e_n)$, being a logical function of system description based on probabilistic connectivity criterion, considering at least one operational path, can be formulated as follows:

$$y(e_1, ..., e_n) = \bigcup_{k=1}^{K} \bigcap_{\sigma \in D_{\sigma_k}} e_{\sigma} = \bigcup_{k=1}^{K} \bigcap_{l \in D_{\sigma_k}} e_l, \quad (9)$$

where $k = 1, ..., K$ – the ordinary number of successful operational path of the system; $r_{\sigma_k} = \bigcap_{l \in D_{\sigma_k}} e_l$ – shortest path; $D_{\sigma_k}$ – set of variables $e_l$, included into $k$-th path, provided the following:

1) possible values of the logical variable $e_i$: $e_i = \begin{cases} 1, & \text{if } l \text{-th element is operational } P_l(t) = 1, \text{ at } T \to \infty, \\ 0, & \text{if } l \text{-th element is not operational } P_l(t) = 0, \text{ at } T \to \infty; \end{cases}$

2) possible values of the function $y(e_1, ..., e_n)$:

$$y(e_1, ..., e_n) = \begin{cases} 1, & \text{if the system is operational,} \\ 0, & \text{if the system is not operational.} \end{cases}$$

The physical significance of the process in question isn’t lost irrespective the fact, when the qualitative parameter is substituted with a logical binary variable – at outset of the research or at it is end.

For analytical description of the system structure, represented by the graph, a transition matrix $|C_{ij}|$ is used, being a rectangular matrix, whose elements can take only three fixed values, defining the degree of connection for vertices $v_i$ and $v_j$.

$$|C_{ij}| = \begin{cases} e_i, & \text{if } i \text{-th the vertex of the graph is logically related to } j \text{-th;} \\ 0, & \text{if the vertices } v_i \text{ and } v_j \text{ are not related;} \\ 1, & \text{if } v_i = v_j. \end{cases}$$

To estimate reliability of DTN SCPS CF depending on the research task, concerning path capacity, it is required to construct system operability function (SOF), obtained via raising of the transition matrix logic $|C_{ij}|$ to power $n - 1$, according to algebraic rules, where $n$ – maximum number of elements in the network structure. Then SOF should be transformed from disjunctive normal form (DNF) into orthogonal disjunctive normal form (ODNF).
Performing sequential operations on $k$ and substituting all the logical variables with their probabilistic values $P\{y(e_1,e_2,\ldots,e_n)=1\}$, we can define:

$$P_c = P\{y(e_1,e_2,\ldots,e_n)=1\} = \sum_{i=1}^{L} P\{Q_i=1\},$$  \hspace{1cm} (10)

where $Q_i$ – orthogonal members of the logical function $y(e_1,\ldots,e_n)=\bigcup_{k=1}^{K} r_{\sigma_k} = \bigcup_{i=1}^{L} Q_i$.

As result of the estimation, based on known $e_i$ values and using probabilistic connectivity criterion on at least one operational path, we define the reliability score of a two-pole network $P_c$ as follows:

$$P_c = P_{e_{a_1}} = P\left\{y(e_1,\ldots,e_n)=\bigcup_{k=1}^{K} r_{\sigma_k} = \bigcup_{i\in D_{\sigma_k}} e_i = 1\right\}.$$  \hspace{1cm} (11)

Thereby meeting a structure monotonicity condition is a logical constraint here. Reliability criterion of the DTN SCPS CF being designed is:

$$P_c^* = \sum_{m=1}^{M} g_m \cdot P_{e_{a_m}} \rightarrow \text{max}, \hspace{1cm} (12)$$

where $g_m$ – significance (specific weight) of the $m$-th two-pole network ($\sum_{m=1}^{M} g_m = 1$); $M$ – total number of two-pole networks.

To estimate practical economic efficiency of network resources of the designed DTN SCPS CF consider the cost function of the network channel throughputs:

$$D = \sum_{l=1}^{|L|} d(C_{e_l}) = \sum_{l=1}^{|L|} d_{e_l} C_{e_l},$$  \hspace{1cm} (13)

where $d_{e_l}$ – cost value per throughput unit of $l$-th channel (cost coefficient), arbitrarily changing depending on specific parameter of the channel and linearly depending on its throughput.

Using Lagrangian method and defining added value $D^+$ as

$$D^+ = D - \sum_{l=1}^{|L|} F_{e_l} d_{e_l},$$  \hspace{1cm} (14)

where $F_{e_l}$ – total estimated stream, going through $e_l$ branch, we find the most efficient solution of the throughput selection problem:

$$C_{e_l} = F_{e_l} + \left(\frac{D^+}{d_{e_l}}\right) \sqrt{\frac{\sum_{l=1}^{|L|} F_{e_l} d_{e_l}}{\sum_{l=1}^{|L|} \sqrt{F_{e_l} d_{e_l}}}}.$$  \hspace{1cm} (15)

A natural constraint in this case is meeting a condition for cost function of DTN SCPS CF construction:
\[ \sum_{i=1}^{[n]} d_{i} C_{i} \leq D_{\text{max}}. \] (16)

Therefore, to ensure efficient management of information exchange processes in DTN SCPS CF, it must comply with requirements, regarding throughput (7), reliability (12) and cost (16), whereas the networks as such should be based on lock-free routing graphs (meet conditions of lock-free routing).

5. Comparison of Methodologies of Data Transmission Network Design

Comparative analysis of different design methodology in practice, regarding various network topologies, shows, that for the majority topologies considered, both template-oriented methodologies ensure construction of equal routing graphs [12, 16].

So, for an example topology from a tentative DTN SCPS CF, represented on figure 3, reliability and cost efficiency estimate was made upon the following parameters: number of nodes O1, number of reserve arcs (Npq), probability of robust DTN performance in case of failure of one node (Pv1), probability of robust DTN performance in case of failure of two nodes (Pv2), probability of robust DTN performance in case of failure of one edge (Pe1), probability of robust DTN performance in case of failure of two edges (Pe2), probability of robust DTN performance in case of simultaneous failure of one node and one edge (Pve), DTN construction cost (D) (Table 1).

![Figure 3. A topology fragment from a tentative DTN SCPS CF.](image)

| Design methodology                                   | Efficiency | O1 | Npq | Pv1, % | Pv2, % | Pe1, % | Pe2, % | Pve, % | D, y.e. |
|------------------------------------------------------|------------|----|-----|--------|--------|--------|--------|--------|--------|
| based on minimum required number of templates       |            | 0  | 11  | 100    | 100    | 99.647 | 100    | 99.757 | 99.67  | 93500  |
| based on use of additional templates                |            | 0  | 11  | 100    | 100    | 99.647 | 100    | 99.757 | 99.67  | 93500  |
| based on modified Dijkstra's algorithm              |            | 16 | 0   | 99.697 | 98.838 | 99.46  | 98.565 | 98.757 | 98.757 | 92930  |

Taking into account similarity of the values of these parameters for considered methodologies, it is reasonable to estimate the effectiveness of the DTN SCPS CFs functioning process based on parameter system \( \vec{Y} = (O1, Npq, P_{e1}, P_{e2}, P_{v1}, P_{v2}, P_{ve}, D)^T \) with the subsequent formulation of a generalized vector optimality criterion:

\[ I_{\text{opt}}(\vec{Y}) = \sum_{n=1}^{N} \left( I_{n}(\vec{Y}) - I_{n}^{*} \right)^2, \] (17)
where \( n_I \) – normalized value of \( n \) optimality criterions (table 1); \( n^* \) – extreme (ideal) values of \( n \) optimality criterions (requirements from the DTN SCPS CF administrators).

**Table 2.** Values of composite efficiency

| Composite efficiency | Design methodology based on minimum required number of templates | use of additional templates | modified Dijkstra’s algorithm |
|----------------------|---------------------------------------------------------------|-----------------------------|-------------------------------|
| \( I^2 (Y) \)       | 1.03                                                          | 1.03                        | 6.32                          |

Comparative analysis of composite efficiency showed, that design methods, based on the use of templates are significantly more favorable in contrast to the existing counterpart [9, 16]. Both templating methodologies provide lock-free traffic for any network, compatible with lock-free DTN SCPS CF routing. That said, of the two template methodologies, specifically the methodology based on the minimum required number of templates seems more preferable due to much lower implementation complexity.

### 6. Conclusion

Practical significance of the results, presented in this paper, consists in potential applicability of the proposed estimation methodology to judge on compatibility of the networks in use with lock-free routing and design of new DTN SCPS CF, according to lock-free routing criterion. The results of this research are recommended to employ preparing guidelines and process specifications, concerning information exchange in DTN SCPS CF, as well during improvement of modular structures for data mining and processing [19].

The DTN SCPS CF design approaches, developed within the presented methodology, are intended to substitute traffic types currently in use based on shortest path search algorithm (modified Dijkstra algorithm), respecting information on channel state.

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