Discrete Optimization Based Rail Passengers Safety and Comfort Communication System Configuration Design

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Abstract. This paper presents rail passengers safety and comfort communication system configuration design proposal. The objective is to integrate four communication modules in the vehicle: general communication, wireless technology relevant to project implementation, data transmission to the Control Centre and passenger access point module. For each module three or four available solutions were proposed and analyzed. Then, each solution has been evaluated by experts under different criteria: functionality, upgradeability and implementation costs. Basing on obtained results, we propose to present configuration design of the system as multi-objectives discrete optimization process. Proposed solution leads to optimal system configuration.

Keywords: Communications systems · Multi-criteria optimization · Optimal system configuration design · Configuration management

1 Introduction

Passenger safety is the most important objective for operators and providers of railway services, manufacturers and carriers. It is therefore a basic factor for assessing its performance and determines its efficiency, as well as the broader criterion of transport service quality [1–5, 16, 18]. Monitoring the state of rail safety in Poland is maintained by the Office of Rail Transport, Chalubinskiego Street 4, 00-928 Warsaw. Within the framework of the statutory tasks the office prepares quarterly reports summarizing the state of rail safety. Last analysis show that the number of three types of events is growing [6]: collisions of trains, the derailment of trains and fires of railway vehicles. These conditions justify starting work on a system which helps to reduce the negative effects of railway incidents. Design experiences of ENTE company indicates that it is possible to develop an integrated system in terms of on the following aspects:

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1. trains collision detection,
2. driver monitoring,
3. fire and potential causes of fire detection

Within the project the concept of a prototype of Integrated System Supporting Information Management of Railway Passenger Traffic has been proposed [7]. The concept is presented in Fig. 1 and consists:

1. the traffic data taken from a railway vehicle,
2. warnings of possible dangers during the journey,
3. transmission the data in case of disasters.

The prototype is based on multilayer distributed architecture, which provides the expected scalability of the whole solution. The integration of modules within information management system under different assumptions (excluding communication configuration) has been considered earlier in our works [8, 13, 14]. In this paper the goal is to configure four communication modules optimally considering the below factors:

1. general communication architecture to be used in a vehicle,
2. wireless technologies relevant to project implementation,
3. links implementing for data transmission to the Control Centre,
4. passenger - access point module in a vehicle.

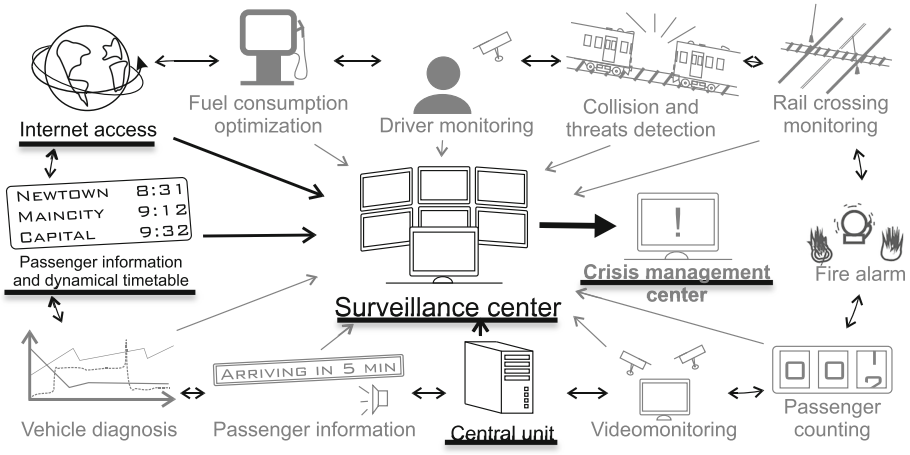

Fig. 1. The concept of integrated system supporting information management of railway passenger traffic. Analyzed items highlighted

1.1 Motivation and Contribution

Basing on expert assessments we propose to present configuration design of the communication system as discrete optimization problem. In Sect. 2 the basic features and functionality of the recommended solutions for each communication module in the system are presented. In Sect. 3 problem of configuration design of the system as two-objectives discrete static optimization problem is formulated and solved. In Sect. 4 optimal system configuration is presented. Finally, results are concluded.

2 Basic Features and Functionality of the Recommended Solutions for Each Communication Module

As a part of the work associated with the development of the conceptual framework for each module, three or four different methods of its implementation has been analyzed, taking into account their architecture, technology, functionality and implementation costs. Each of these methods has been evaluated by independent experts under two evaluation criteria: criterion 1 - functionality, criterion 2 - costs.

Table 1. Passenger - access point module in a vehicle

Method	Architecture	Technology	Functionality	Other	Costs	Functionality
1	IrDa	Wireless	Small range of up to 3 m/low optical power, point-to-point communication	Used for short distances, need for direct vision	1	1
2	Bluetooth	Wireless	The relatively small range point-to-multipoint	Use for approx. 5 m, low signal strength	2	3
3	Wi-Fi	Wireless	Acceptable range point-to-multipoint	Good coverage of rooms and other spaces	3	4

Assessments used the following rating: 1 - very low, 2 - average, 3 - high, 4 - very high. The optimal choice of module implementation method based on analysis result is summarized in presented tables. In Table 1 three methods with corresponding ratings of Passenger - access point module in a vehicle implementations are presented.

In Table 2 four methods with corresponding ratings of general communication architecture to be used in a vehicle are presented. In Table 3 three methods with corresponding ratings of wireless technologies relevant to project implementation are presented. Finally, in Table 4 four methods with corresponding ratings of links implementing for data transmission to the Control Centre are presented.

Table 2. General communication architecture to be used in a vehicle

Method	Architecture	Technology	Functionality	Other	Costs	Functionality
1	RS-232	Wire	Low range	Up to 15 m	4	1
2	RS-485	Wire	Long range, noise resistance	High cost of converters, limited bandwidth	3	2
3	Optical fiber	Wire	Long range	Complexity of the arrangement, the high cost of converters	4	3
4	Ethernet	Wire	Open standard, no interference	Simplicity, standard accessibility, large and sufficient bandwidth	1	4

Table 3. Wireless technologies relevant to project implementation

Method	Architecture	Technology	Functionality	Other	Costs
1	WiMax	Wireless	The network under development	No cover the whole area, the system under development	1
2	GSM-R	Wireless	Standard dedicated for use only in railways	Large organizational costs, not widespread network	2
3	GSM	Wireless	Standard	General availability, drop-down, gradual increase system capacity	4

Table 4. Methods of links implementing for data transmission to the Control Centre

Method	Architecture	Technology	Functionality	Other	Costs
1	Leased lines/Frame relay	Wire	Network operating phase	High costs	1
2	Polish telecommunication	Wire	Standard	High costs, general availability	2
3	Internet	Wire/wireless		Costs depend on operator	3
4	GPRS	Wireless	Standard	Low costs	4

3 Problem of Configuration Design of the System as Discrete Optimization Problem

In this section multi-objective optimization problem is presented. The concern is the minimization of a vector of objectives F(x) that can be the subject of a number of constraints or bounds [9–15, 17]. Denoting that n is a number of decision variables, k is a number of criteria, m is a number of inequality constraints and p is a number of equality constraints, we have $x = [x_1, x_2, \ldots, x_n]^T$, and:

$$F(x) = [f_1(x), f_2(x), \ldots, f_k(x)]^T, \tag{1}$$

$$g_i(x) \leq 0, \text{ for } i = 1, 2, \ldots m, \tag{2}$$

$$h_i(\mathrm{x}) = 0, \text{ for } i = 1, 2, \ldots p. \tag{3}$$

Due to the fact that $F(x)$ is a vector, if any of the components of $F(x)$ are competing, there is no unique solution to this problem. Then the concept of non-inferiority (also called Pareto optimality) must be used to characterize the objectives. It is assumed that non-inferior solution (Pareto optimal solution) is one in which an improvement in one objective requires a degradation of another. To describe the concept of non-inferior solutions, introduce the set of all possible solutions that satisfy constraints, such as the project budget, available technologies, etc. It is called set of feasible solutions that satisfies constraints (2) and (3). This allows to find all values of different objectives included in the objectives vector. If, for example, one takes two objectives minimization problem, for each feasible solution one can determine values for the two objectives and illustrate them in two-dimensional space, as shown in Fig. 2.

There are many methods of selecting a particular solution from the set of Pareto solutions (e.g. [12]). This weighted sum method is based on transformation of the multiple criteria problem to the problem of single-criteria, where each component of objectives vector describes the impact of this criterion for the final solution. The impact depends of the weight value w_i, $i = 1, 2\ldots k$. This leads to the following problem objective formulation:

$$\underset{x \in \Omega}{Min} F(x) = \sum_{i=1}^{k} w_i f_i(x) \tag{4}$$

It is assumed that solving multi-objective maximization problem result indicates each module implementation method. The problem is built on the basis on values in Table 5 that summarizes data from Tables 1, 2, 3 and 4. Assume:

- i – module index, $i = 1, 2, \ldots.4$;
- j – criterion index, $j = 1, 2$;
- k – method index, $k = 1, 2, 3$;

then $x_{i,j,k}$ – denotes value taken from Table 5, e.g. $x_{4,2,2} = 2$.

Table 5. Data for optimization

Method	Costs	Functionality
I. Passenger - access point module in a vehicle		
1	1	1
2	2	3
3	3	4
II. General communication architecture to be used in a vehicle		
1	4	1
2	3	2
3	4	3
4	1	4
III. Wireless technologies relevant to project implementation		
1	4	1
2	3	2
3	1	4
IV. Methods of links implementing for data transmission to the Control Centre		
1	4	1
2	4	2
3	3	3
4	1	4

Set of all $x_{i,j,k}$ forms the space of feasible solutions $\Omega = \left\{x_{i,j,k} \in \mathbb{Z}^n : 1, 2, 3, 4, 5\right\}$ for all admissible *i, j, k*. Objectives of the problem to be maximized are overall evaluation of criteria, i.e.:

$f_1\ (x)$ – is the first objective defined as a sum of all modules criterion 1 values depending on the method, i.e.:

$$f_1(x) = \sum_{i=1}^{4} x_{i,1,k}; \quad i = 1, 2, \ldots 4; \quad k = 1, 2, 3, (4); \tag{5}$$

$f_2\ (x)$ - is the second objective defined as a sum of all modules criterion 2 values depending on the method, i.e.:

$$f_2(x) = \sum_{i=1}^{4} x_{i,2,k}; \quad i = 1, 2, \ldots 4; \quad k = 1, 2, 3, (4); \tag{6}$$

Optimization the two-component vector of objective functions would give the solution for the problem given:

$$\mathrm{F(x)} = (\mathrm{f_1(x)},\ \mathrm{f_2(x)}). \tag{7}$$

Admissible solutions are presented in Fig. 2, where Pareto solutions are indicated by red circles. The number of possible variants (L), i.e. set of admissible solutions, based on the number of modules built and possible system configurations can be easily determined:

$$L = 3 * 4 * 3 * 4 = 144. \tag{8}$$

Two-criteria optimization problem was formulated as a minimization problem, so if: Max F(x) = − (Min (− F(x)) and the goal is to maximize functionality (criterion 1) and minimize the cost (criterion 2), one can assume following objective function:

$$\text{Min} \leftarrow \text{F}'(\text{x}) = (-\text{f}_1(\text{x}),\ \text{f}_2(\text{x})). \tag{9}$$

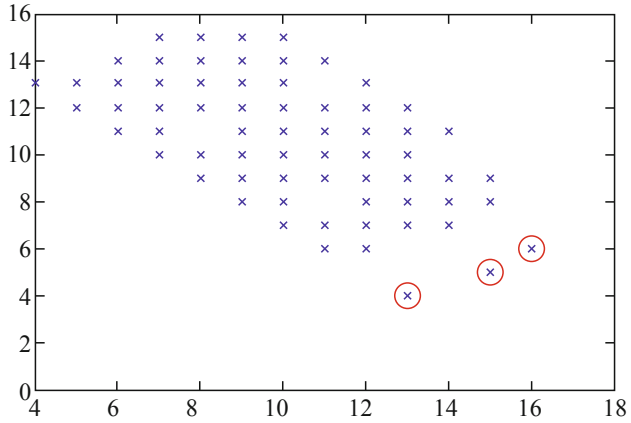

Fig. 2. Set of admissible solutions and Pareto solutions (in circles). Vertical axis denotes variant costs, horizontal axis denotes variant functionality

Basing on formula (9) objective function is transformed to one-objective optimization problem:

$$\text{Min} \leftarrow \text{F}''(\text{x}) = -\text{w}_1 * \text{f}_1(\text{x}) + \text{w}_2 * \text{f}_2(\text{x}). \tag{10}$$

Example. Let No. 1 of possible variant (admissible) solution will be the choice of method 1 for each of the built modules. Therefore, on the basis of the Table 5, one can built Table 6 with exemplary admissible solutions and corresponding values of objective functions. The values of each objective function for admissible solution No. 1 (first row in Table 6) data from Table 6 are presented below:

$$f_1(x) = 1 + 4 + 4 + 4 = 13,$$
$$f_2(x) = 1 + 1 + 1 + 1 = 4.$$

Optimal configuration design problem has been solved in three cases:

Case 1: $w_1 = 1$, $w_2 = 1$. Each criterion is equally important. The optimal solution is a variant of No. 144, the minimum value of $F''(144) = -10$.

Case 2: $w_1 = 0$, $w_2 = 1$. Border case, where optimization problem is reduced to costs. The optimal solution is a variant of No. 48, the minimal value of $F''(48) = 4$.

Case 3: $w_1 = 1$, $w_2 = 0$. Border case, where optimization problem is reduced to functionalities. The optimal solution is a variant of No. 144, the minimal value of $F''(144) = -9$.

Table 6. Exemplary admissible solutions and corresponding values of objective functions

Module	I			II			III			IV			$f_2(x)$	$f_1(x)$
No	method	costs	Functionality	Method	costs	Functionality	method	Costs	functionality	Method	Costs	functionality	Sum fo costs	Sum of functionalities
1	1	1	1	1	4	1	1	4	1	1	4	1	13	4
2	1	1	1	1	4	1	1	4	1	2	4	2	13	5
etc.														
144	1	1	1	1	4	1	1	4	1	4	1	4	10	7

Optimal modules configurations are presented in Table 7.

Table 7. Optimal modules configurations

Module	I			II			III			IV			$f_2(x)$	$f_1(x)$
No	method	costs	Functionality	Method	costs	functionality	Method	Costs	functionality	Method	Costs	functionality	Sum fo costs	Sum of functionalities
Case 1 = Case 3	3	3	4	4	1	4	3	1	4	4	1	4	6	16
Case 2	1	1	1	4	1	4	3	1	4	4	1	4	4	13

4 Optimal System Configuration

The scheme resulting from the multi-criteria optimization for passenger communication analysis - the access point in the vehicle is shown in Fig. 3.

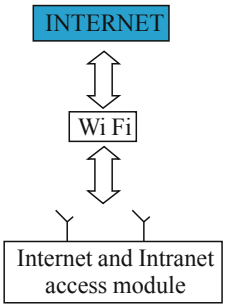

Fig. 3. Architecture recommendation according to variant I after passenger communication analysis - access point in the vehicle (source in Polish: project documentation)

Based on the analysis from the previous chapter of multicriterial optimization, a solution based on an Ethernet network in the context of architecture for use in a vehicle was chosen. The architecture resulting from the optimization will be implemented using UTP cat. 5 and UTP cat. 7 for the backbone of the network. Critical points will be the transitions between vehicle combinations in case of more than one composition. All connections between individual modules in the wired area will be made as shown in Fig. 4.

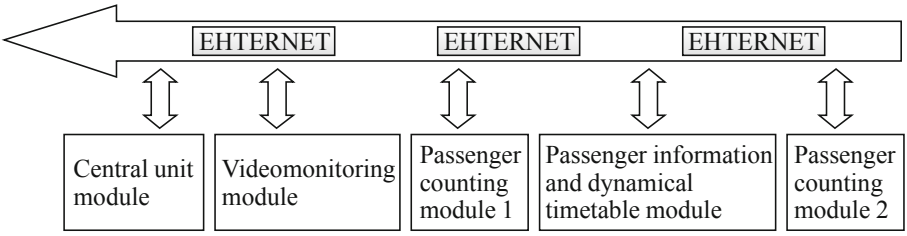

Fig. 4. Architecture recommendation according to variant II after the analysis of architecture for use in the vehicle (source in Polish: project documentation)

Considering the choice of the variant resulting from the analysis of wireless technologies relevant from the point of view of the project implementation, the GSM network was chosen, which allows the functionality of the central unit modules to be implemented. It will be equipped with a GSM module and enable communication and data transfer via the GSM/UMTS network. If the GSM/UMTS network coverage is missing, the data will be saved in the "black box" and transmitted to the server after receiving the coverage. The functionality of the Supervision Center module, such as displaying on the maps in the dispatch center, the current position of each vehicle will be implemented via the GSM network. The functionality of the vehicle diagnostics module will also be implemented through the GSM network, based on reading the controller's operating parameters and sending them, via the GSM network, to the Supervisory Center on an ongoing basis (Fig. 5).

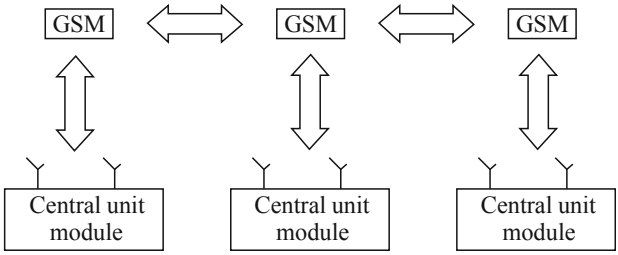

Fig. 5. Recommendation of wireless technologies important from the point of view of project implementation (source in Polish: project documentation)

A data link based on GPRS packet data transmission will be used for data transmission (Fig. 6). It results from the bi-objective optimization in the aspect of the analysis of links in terms of transmission to the Supervisory Center. This link will enable the functionality of the fire signaling module consisting in sending information about alarms occurring in the vehicle to the Supervisory Center module. Then, activation of the fire alarm sensor will automatically change the monitoring system monitoring in the vehicle's cabin and send the information and photos of the threatened area to the Monitoring Center module without delay. In terms of the basic functionality of the collision and threat detection module, a packet-based data transmission link will enable sending important information to the Crisis Management Center (i.e. immediate delivery of information on the geographical location and size of the disaster to the appropriate services). The signal will first reach the Surveillance Center and then to the Crisis Management Center. Information and photographs of the threatened area will also be sent to the Surveillance Center without delay. The content of information sent in the GPRS packet will be: data on the speed of the vehicle at the time of the disaster, data on the number of passengers at the time of the disaster, exact geographical location of the vehicle at the time of the disaster, recording of camera images and conversations in the driver's cab just before the disaster. This amount of data will be enabled by a packet-based GPRS data transmission connection, where access to the APN of the mobile operator will be a prerequisite. APN is the IP address of the backbone network element that allows routing of packets between the operator's network and the external packet network.

The collision and accident detection module after collision detection and determination of the impact force and bank angle will enable immediate transmission of information to the Supervisory Center (Fig. 7).

The level crossing monitoring module will allow automatic detection of cases of improper behavior driving motor vehicles on level crossings through continuous analysis of the area and registration of incorrect situations. The GPRS connection selected as a result of the optimization of variant No. IV will allow sending information about the event (i.e. the intrusion of the vehicle on the railway crossing with closed tall boots or active traffic lights) to the Supervision Center. A photo material will be sent to the registration of the registration number of the vehicle which entered passing. The general architecture of the recommended solution are presented in Figs. 8 and 9.

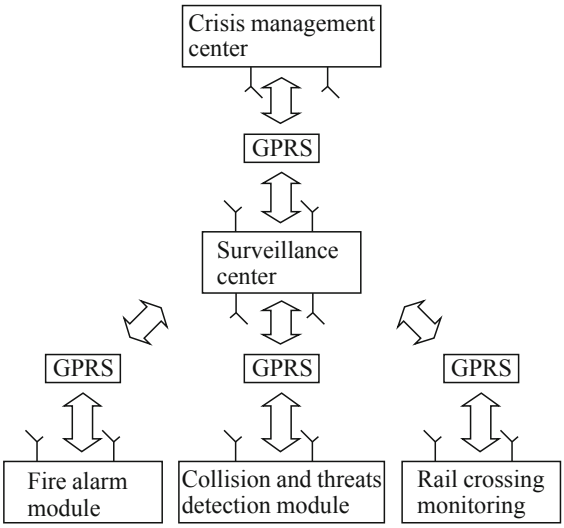

Fig. 6. Recommendation of links in terms of transmission to the Supervision Center - option IV (source in Polish: project documentation)

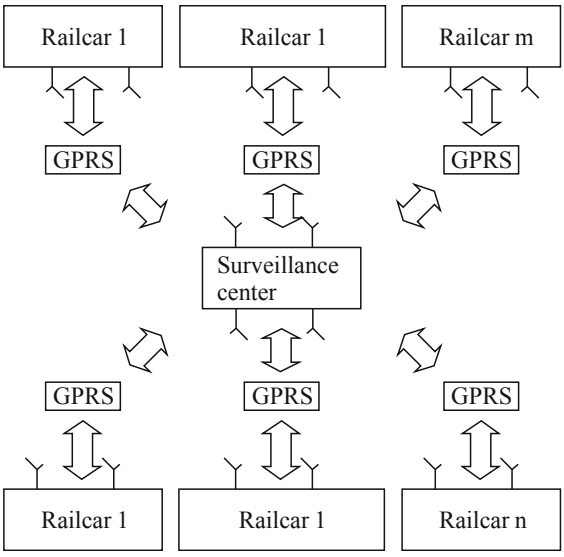

Fig. 7. Mutual communication between vehicles after the area analysis stage (source in Polish: project documentation)

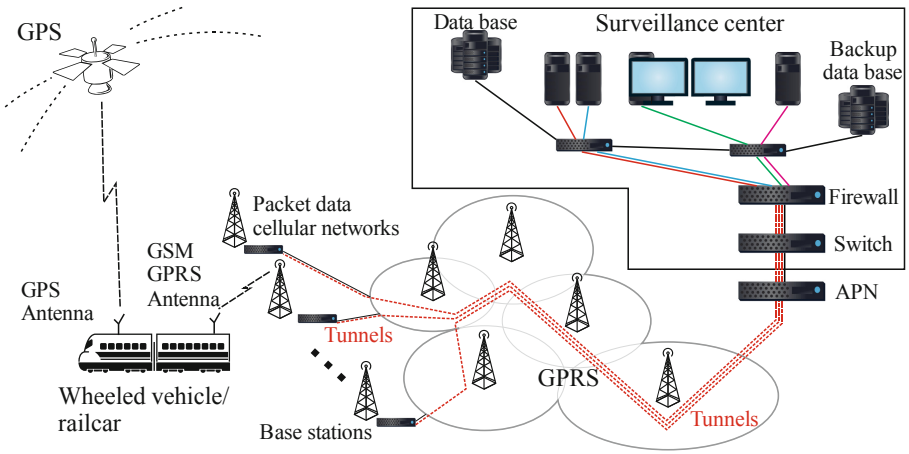

Fig. 8. Diagram of individual system components (source in Polish: project documentation)

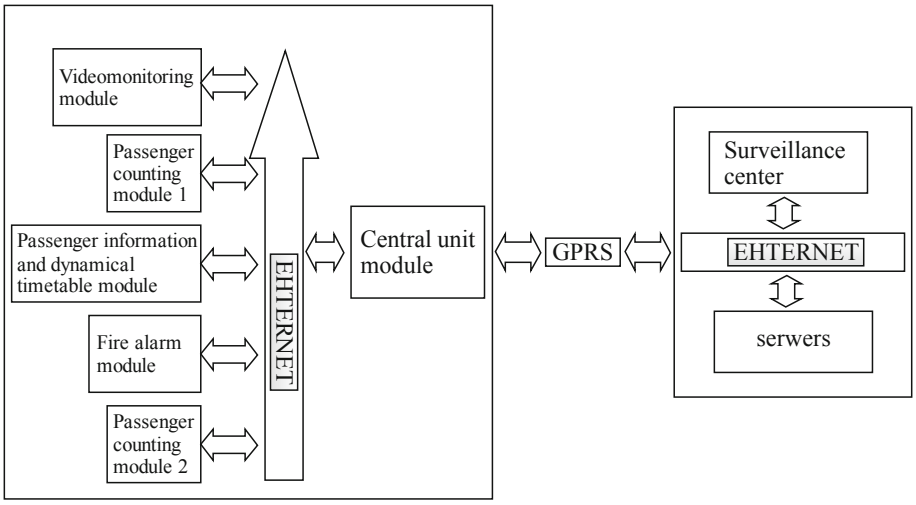

Fig. 9. System topology (source in Polish: project documentation)

5 Conclusion

The paper presents the design of rail passengers safety and comfort communication system as multi-objective optimization problem The system is an integration of four modules: general communication architecture to be used in a vehicle, wireless technologies relevant to project implementation, links implementing for data transmission to the Control Centre and Passenger - access point module in a vehicle into one coherent solution. For each module three or four different construction methods were proposed and considered. Then, each method has been evaluated under different

criteria: functionality, upgradeability and implementation costs. Basing on obtained results, we propose to present configuration design problem of the system as optimization problem. Solution of the problem leads to different optimal system configurations, depending on priorities assigned to objectives.

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