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Dispersed, self-organizing sensory networks supporting the technological processes

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Jerzy JAGODA [1*], **Mariusz HETMAŃCZYK** [2], **Krzysztof STANKIEWICZ** [1]

Author's affiliations and addresses:

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

[2] Silesian University of Technology, ul. Akademicka 2A, 44-100 Gliwice, Poland

*** Correspondence:**

e-mail: jjagoda@komag.eu

Abstract:

Examples of automation of technological processes for mineral extraction are presented. Aspects related to the diagnostics of machines and devices during operation processes are discussed. Applying the distributed sensor networks to enable designing and manufacturing the machines and devices operated in accordance with the idea of Industry 4.0, the Internet of Things, M2M communication and autonomous behaviour was proposed. The paper presents impact of applying the distributed sensor networks on increasing work safety (multi-redundant communication) and reducing the employment in hazardous areas is presented. Implementation of algorithms based on swarm intelligence to control the routing processes of distributed sensor networks was suggested. Areas of application of distributed sensor networks based on swarm intelligence in other industries (renewable energy sources) are also outlined.

Keywords: sensor networks, swarm intelligence, routing, intrinsic safety

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1. Introduction

Currently, managing the manufacturing process is possible due to information transmitted to supervisors in a real time. This is possible because a network of sensors continuously monitors the condition of machines and equipment involved in the production process. Every smallest part of the process is in the network (Fig. 1) (IIoT Industrial Internet of Things). Information received from the network of sensors enables making decisions affecting the technological process. With the same information, it is possible to immediately observe the effects of the decisions made. This manufacturing process is known as Industry 4.0 (Fig.1)

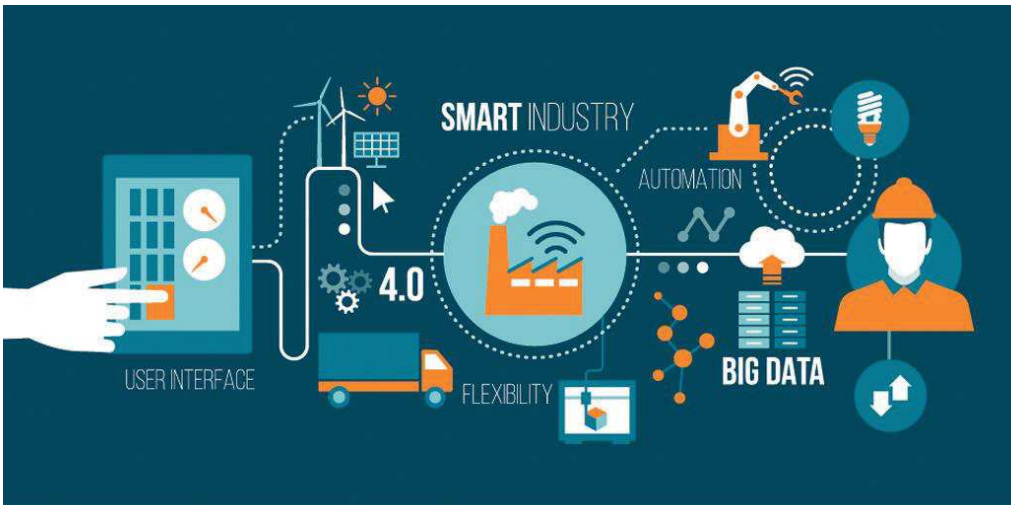

Fig. 1. Industrial Inthernet of Things (IIoT) [1]

The world economy entered the so-called "The fourth industrial revolution" [2]. Digitization of production (Industry 4.0) is one of the processes describing the changes. The concept of Industry 4.0 was introduced in 2011 by professor of physics Henning Kagermann and later transformed into a strategy for the development of the German industry [3]. The idea was to improve the efficiency of manufacturing processes through automation and real-time data exchange [4].

Analyses of the World Economic Forum in cooperation with McKinsey & Company [5] indicate the areas of production processes that changed after the implementation of Industry 4.0 solutions (Fig. 2).

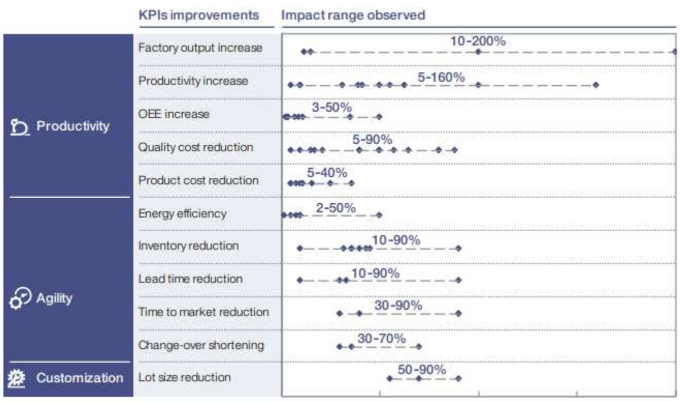

Fig. 2. Impact of Fourth Industrial Revolution use-cases on select KPIs(operational and financial key performance indicators) in lighthouse factories [5]

The analyses indicated 16 production plants in the world that moved from the level of pilot implementations to full integration of technology and implementation of the Industry 4.0 concept. Some plants, due to the application of the Fourth Industrial Revolution, doubled their efficiency, and are able to invest the funds in new technologies and implement solutions of the fourth industrial revolution [5].

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We are at the beginning of implementing Industry 4.0 solutions on the Polish market. The report (Fig. 3) prepared by Computerworld together with ABB shows that only 14% of enterprises have a strategic transformation plan developed. 48% of respondents declared partial implementation of Industry 4.0 solutions. Enterprises that do not intend to introduce any changes related to Industry 4.0 are accounted for as much as 27% of the respondents [6].

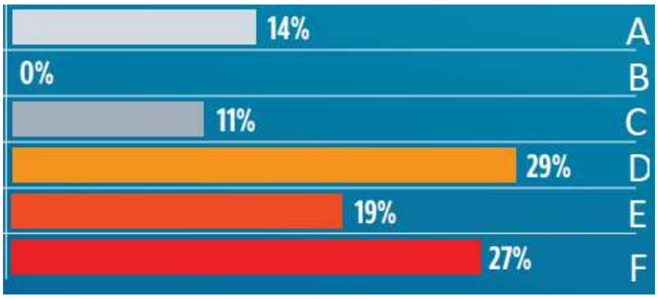

Fig. 3. Research report on the implementation of Industry 4.0 solutions on the Polish market [6]

The appropriate use of technical solutions to improve specific areas of production processes is the challenge for enterprises implementing Industry 4.0 solutions. The further part of the article indicates the areas of hard coal production processes in which it is possible to implement the idea of Industry 4.0.

2. Materials and methods

In today's mining industry, each manufacturing process is digitized. Fig.4 presents the control room of Tauron Mining Group. The control room monitors the status of each mining process, starting from the condition of shearer and powered roof support, through the condition of belt conveyors and ending with the condition of hoist shaft. This information helps in making decisions necessary for the proper functioning of the mining process.

Fig. 4. Tauron's control room [7]

Data for supervisory systems are sent from a network of measuring sensors analyzing the condition of each machine and device as well as the atmosphere at risk of methane and/or coal dust explosion. Sensor networks operate usually in separate diagnostic or automation subsystems of mining processes. Several of the subsystems, in which a network of wireless diagnostic sensors works or it is possible to implement such a network are presented in the article.

The Shield Support Monitoring System (SSMS) is the first of the subsystems presented. The most innovative functions of the SSMS (Fig. 5) include the width measurement of the bridgehead and the monitoring of the powered supports geometry. The most innovative functions of the SSMS (Fig. 5) include the width measurement of the face road and the monitoring of geometry of the powered roof support. These parameters are important for ensuring the stability of the longwall panel and the correct conditions of cooperation between the roof support and the rock mass, and in certain conditions, may affect the possibility to damage certain components of the powered roof support.[8] The system consists of the SSMS-S face road measurement module, SSMS-I inclinometers and the SSMS-C central unit (Fig.5). The system components are wired together within one powered roof support. The SSMS-C central unit receives data from the SSSM-I inclinometers and the SSMS-S module via the modbus, and then wirelessly sends the data to a supervisory network with a "mesh" type topology [9].

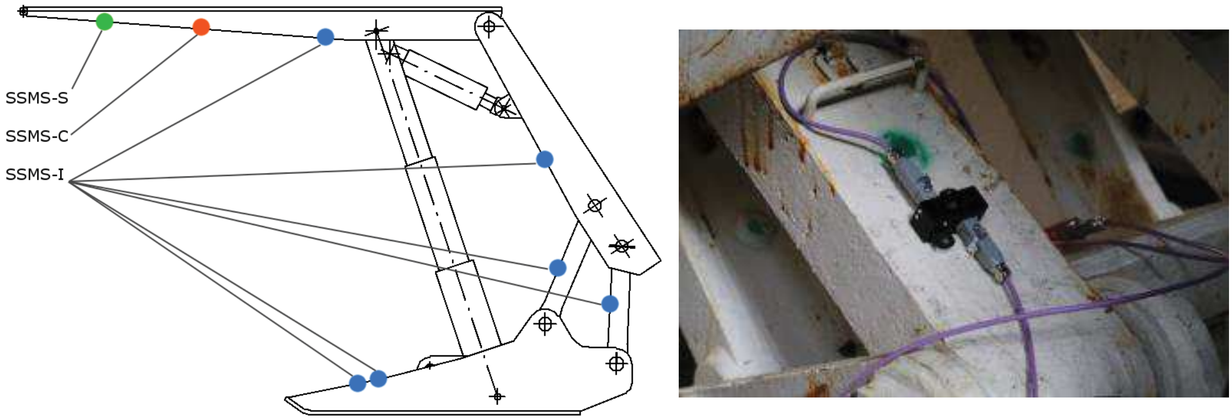

Fig. 5. SSMS elements on the powered roof support. [8]

The system should be fully equipped with wireless communication of the entire sensor network. The routing algorithm for this network, due to its expansion by a large number of nodes, is suggested to be implemented on the basis of an intelligent routing algorithm, which should enable obtaining a stable data throughput despite the increase in the number of network nodes to over a thousand. The expansion of the SSMS sensor network may contribute to the remote operation of the longwall mining process.

The roadheader position measuring system [10], responsible for autonomous roadways development, is another of the presented subsystems. The solution is based on an innovative method using the wave propagation in the roadway. The concept is modelled on the GPS, where 24 satellites located in geostationary orbits are the reference points. In the case of a solution implemented in underground mining plants, the active electronic systems installed on the components of the roadway support will play a role of satellites (Fig. 6). The systems will communicate directly with the transmitting and receiving system installed on the machine's body. The positioning system not only increases safety, but ultimately enables the automation of the drilling process, significantly increasing the efficiency and safety of mining [11]. Expansion of the system with an intelligent sensor network will provide real-time information on the roadheader condition (diagnostics subsystem), and will also provide control over the remote mining process.

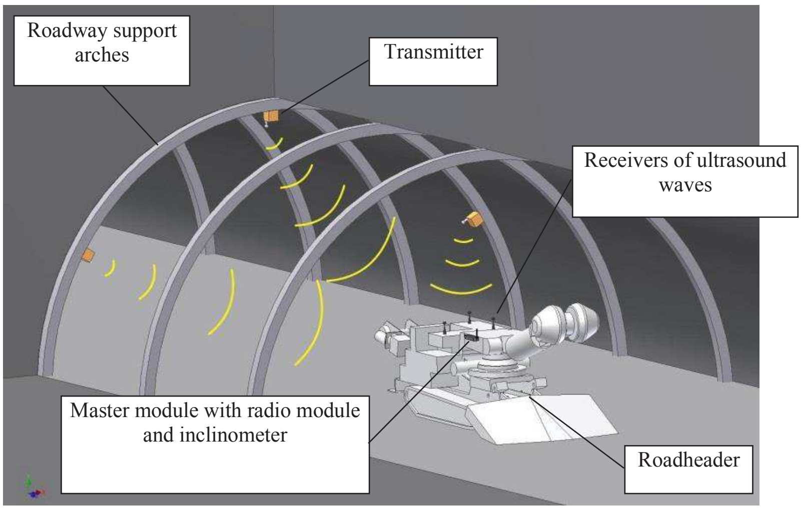

Fig. 6. Roadheader navigation system [11]

In addition to the data on the position and parameters of the roadheader, the sensory networks can also transmit information on condition of the arch support frame (Fig. 7), and more precisely on their load. As part of the international INESI project, the stress in the arch support was measured using draw-wire sensors. Information about the stress can then be transmitted to a sensor network. The applied solution would provide information on condition of the frame of arch support along the entire length of the workings (the length of mine roadways ranges from several hundred meters to several kilometers).

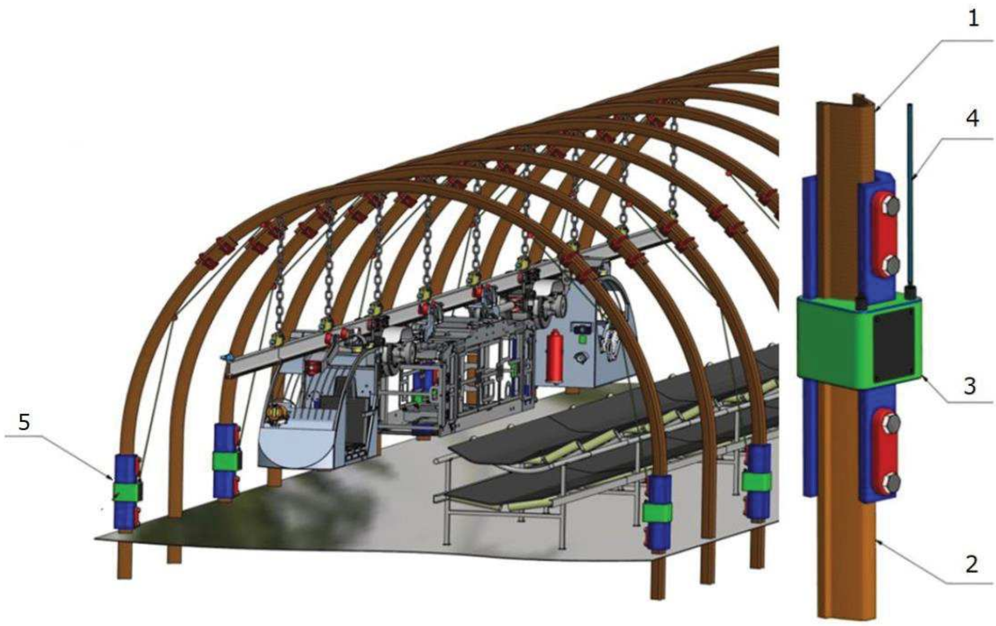

Fig. 7. INESI load monitoring system in arch support: 1 – upper part of wall-side segment; 2 – lower part of wall-side segment; 3 – data-processing module with sensors and data-transferring components; 4 – distance sensor cord; 5 – measuring module [12]

It is also important to monitor the condition of belt conveyors to eliminate the risks associated with their operation in mine workings. Belt conveyors are mainly used to transport the run-of-mine, however, after meeting the relevant regulations, it is also possible to move people. Therefore, it is necessary to ensure the safe operation of the belt conveyor. Sensor networks could transmit information on the temperature and rotational speed of the belt conveyor's supporting rollers. A proposal to implement such a subsystem is presented in Fig. 8.

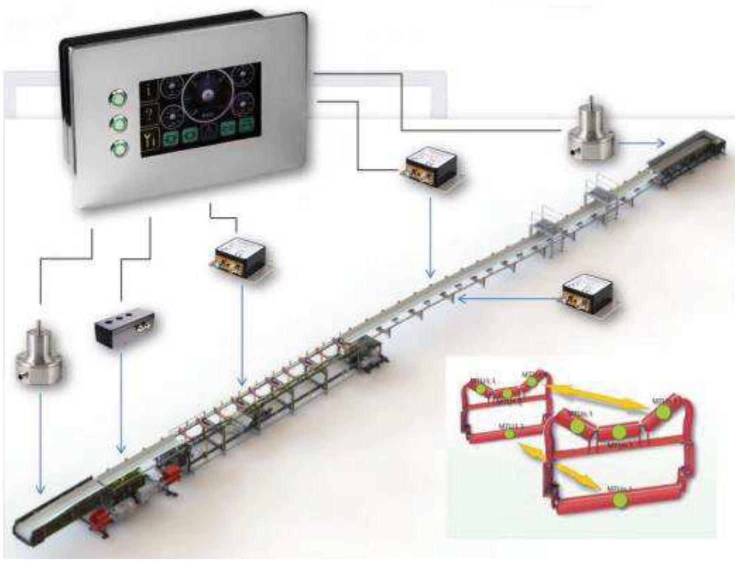

Fig. 8. Monitoring of belt conveyors [13]

The use of sensor networks with intelligent routing algorithms improves technological processes and allows industrial plants to implement the idea of Industry 4.0. Work realised since 2019 in the SUMAD project (whose aim is to analyze the future management of mine heaps, with particular emphasis on geotechnical, environmental, socio-economic challenges as well as sustainable development and long-term management) allowed to identify new fields for application of the intelligent sensor networks. Placement of photovoltaic panels [14] with inteligent control (the idea of the solution is to monitor the parameters of photovoltaic modules, such as: voltage and current intensity, module surface temperature, solar radiation intensity at the module and ambient temperature and humidity) is one of the elements of post-mining heaps management. (Fig. 9 and Fig. 10)

Intelligent controllers of each panel [15] should communicate with each other using radio waves. A grid of a mesh topology is planned. Due to the number of photovoltaic modules installed in power plants, the created wireless network will have a highly complex structure. There are more and more implementations of routing protocols based on artificial intelligence technology and methods in this type of networks [16].

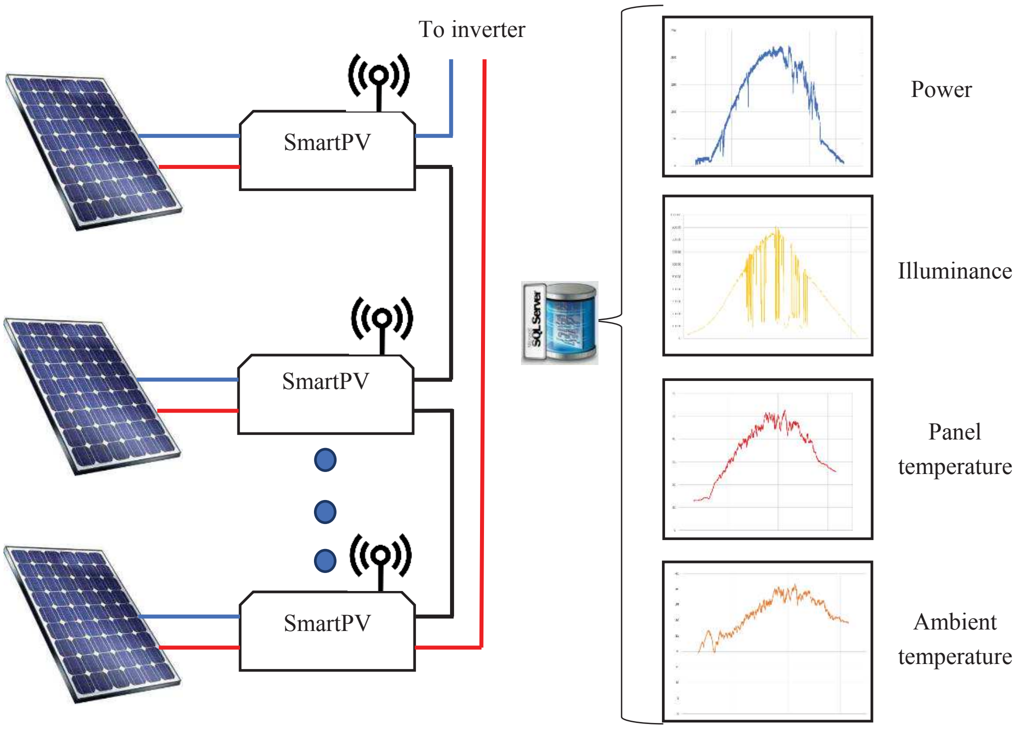

Fig. 9. Intelligent control module for photovoltaic panels [16]

Fig. 10. Intelligent control module for photovoltaic modules [17]

Only the selected subsystem with possibility to expand or implement the Industry 4.0 solutions in a form of intelligent sensor networks are presented. In such extensive networks it is necessary to properly organize information transmission to ensure operational reliability, flexible configuration and operational safety. It is particularly important to ensure the reliable operation of sensor networks operating in conditions of methane and/or coal dust explosion hazard. To meet these requirements, advanced transmission algorithms (routing algorithms) are implemented in sensor networks, making it possible to efficiently manage data flow in an extensive network infrastructure.

3. Results and discussion

The use of sensor networks with intelligent routing algorithms improves technological processes and allows industrial plants to implement the idea of Industry 4.0. Work realised since 2019 in the SUMAD project (whose aim is to analyze the future management of mine heaps, with particular emphasis on geotechnical, environmental, socio-economic challenges as well as sustainable development and long-term management) allowed to identify new fields for application of the intelligent sensor networks. Placement of photovoltaic panels [14] with inteligent control (the idea of the solution is to monitor the parameters of photovoltaic modules, such as: voltage and current intensity, module surface temperature, solar radiation intensity at the module and ambient temperature and humidity) is one of the elements of post-mining heaps management. (Fig. 9 and Fig. 10)

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Routing algorithms in sensory networks are used to ensure optimal delivery of the data packet from the sender to the receiver. Packets can be delivered to the receiver in an optimal way depending on the set following criteria: the highest network capacity, energy savings, packet transmission time, etc.

Routing algorithms used in sensory networks are divided into proactive, reactive and hybrid. In proactive algorithms, the routes between each network node are saved in the so-called routing tables. On the other hand, the reactive algorithms are searching for a route, when it is necessary (at the moment of sending the data packet). This results in no need to occupy the memory of each network node for the routing tables. Unfortunately, longer time for delivery the package to the receiver is the consequence of using such a method. Hybrid algorithms are another types of algorithm used in the routing the sensory networks. In this type of algorithms, selected areas of the network work with the use of proactive algorithms, while their connections are made with the use of reactive algorithms.

Implementation of the presented algorithms to sensory network nodes, operating in the areas of methane and/or coal dust explosion hazard, is associated with meeting the several additional requirements due to the design of each network node. The hardware implementation of a single network node must meet the requirements of the ATEX directive (the power radiated from the transmitting/receiving antenna must be limited to the appropriate values) and the radio system should be of low-energy (nodes are battery-powered or supplied by "energy harvesting").

Taking into account the presented requirements, the selected routing algorithms were analysed. During the literature review, the projects in which simulation tests of reactive and proactive protocols as well as the algorithms working on the basis of swarm intelligence, were distinguished. Some of these projects, which took into account following criteria: packet transmission time, network capacity and energy savings are presented.

Fig. 11 shows the result of simulation tests with use of the reactive AODV protocol, the proactive DSR protocol and the protocol based on the intelligence of the SICROA swarm (the algorithm was prepared on the basis of the ACO ant algorithm). The tests verified the delays generated by each algorithm in relation to the number of network nodes. The test result indicated that the SICROA algorithm generated the smallest delays in transmission of data packets.

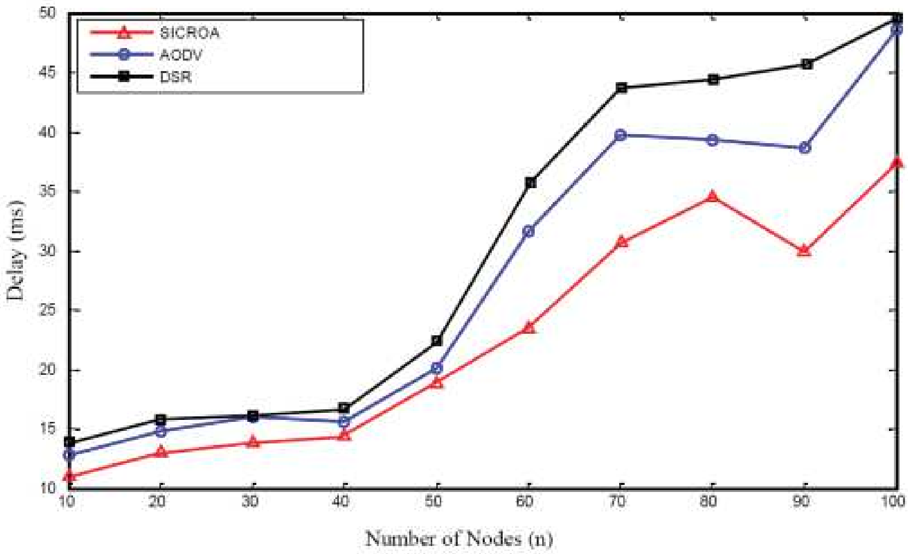

Fig. 11. Latency measurement with respect to node count [18]

Fig. 12 shows the result of simulation tests with use of the reactive AODV protocol and the SSKIR protocol, working on the basis of swarm intelligence (built on the basis of PSO). The tests show that the SSKIR protocol allows to maintain the channel capacity at a higher level than the reactive protocol. Network of a size 500 nodes was tested [18].

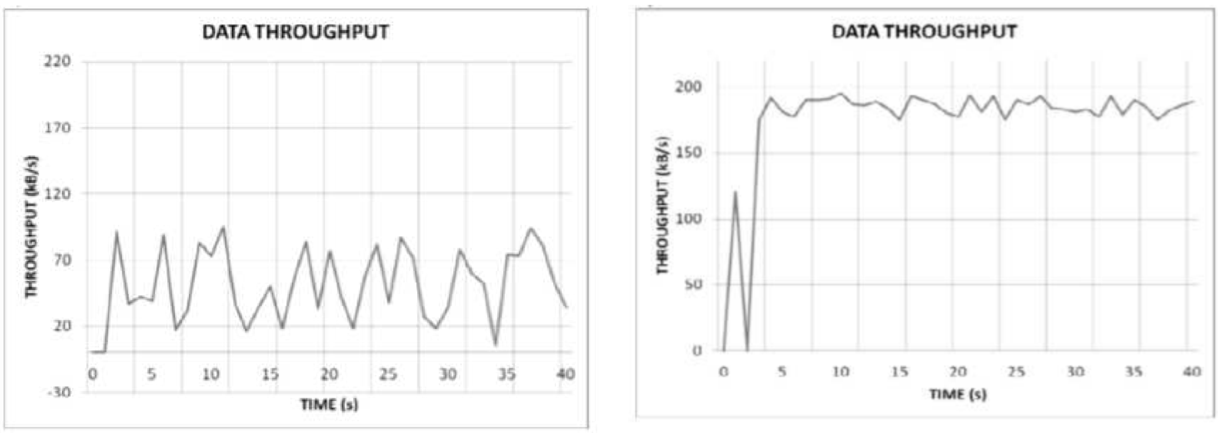

Fig. 12. AODV and SSKIR protocols [18]

Another of the simulation tests (Fig. 13) compared the reactive DSR, AODV algorithms, the proactive DSDV algorithm and the Beehive algorithm working on the basis of swarm intelligence (BI algorithm). The tests showed that the lowest energy consumption of each network node is during the use of the Beehive protocol.

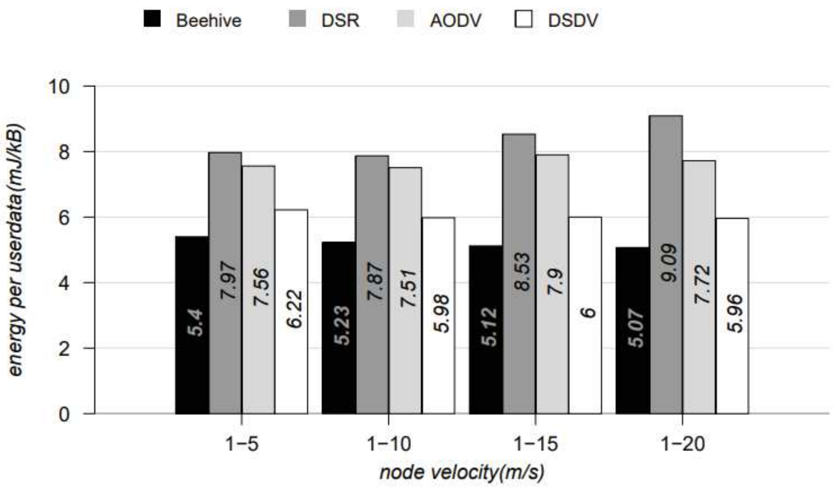

Fig. 13. Energy consumption – Beehive, DSR, AODV, DSDV algorithms [19]

Effective data transmission in sensory networks is very important, in addition, it is necessary to ensure the operational security of each network node (by ensuring the stability of routing protocols).

Algorithms that work with use of machine learning are another of the presented algorithms. Fig. 14 shows the simulation results of routing algorithms before and after the attack on the sensory network (during the simulation process, a learning set with incomplete information about connections between nodes was generated). The analyses show that the use of an algorithm based on machine learning allows to avoid increasing the delay in data transmission despite the attack on a working sensor network.

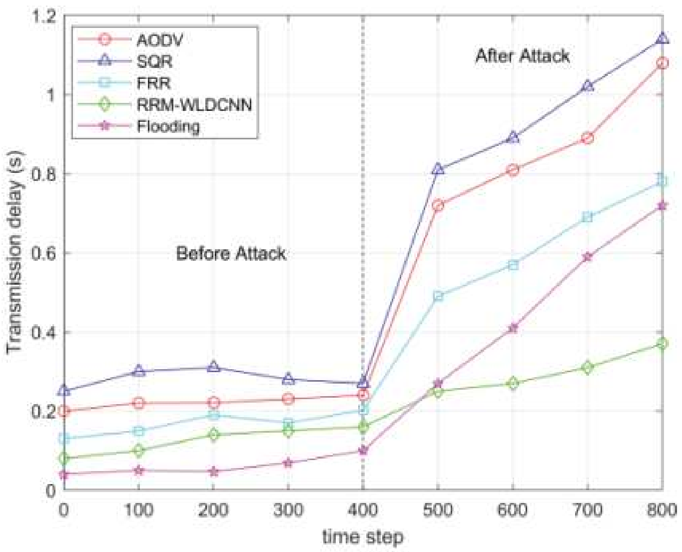

Fig. 14. Simulations with the use of a protocol working with the RRM-WLDCNN machine learning [20]

The analysis of each routing protocol indicate that the highest probability of success of the algorithm implementation in sensory networks operating in a potentially explosive environment are the protocols based on the so-called Swarm Intelligence (SI). These algorithms, regardless of the number of variables in the solutions, adapt to existing constraints and help to solve the optimization problem. The use of these algorithms allows the parameters of data transmission to be maintained at an appropriate level (channel capacity, short time of data reaching the target, high reliability of data transmission). Sensory networks working on the basis of swarm intelligence algorithms are self-organizing and multi-redundant. In addition, if we combine swarm intelligence and machine learning, we can additionally protect the network against deterioration of transmission parameters after attacks that may affect the operation of each network node.

4. Conclusions

The article presents examples of automation of technological processes of mineral extraction. It was suggested to use distributed sensor networks that will enable designing and production of machines and devices in accordance with the idea of Industry 4.0, the Internet of Things, M2M communication and autonomous behaviour. The impact of the use of distributed sensor networks on increasing work safety (multi-redundant communication) and reducing the employment in hazardous areas is presented.

The necessity of appropriate data organization (with the use of routing algorithms) in networks, so extensive as to ensure operational reliability, flexible configuration and operational safety was discussed. Selected simulation tests of sensor network routing algorithms are presented, taking into account the following criteria: packet transmission time, data throughput and energy savings. The analysis of the presented data showed that the algorithms based on the swarm intelligence have the best solution for sensor networks operating in conditions of explosion hazard.

It is necessary to implement the selected routing algorithms in hardware solutions and verifying their operation in real conditions. In the implementation process, it will be necessary to modify the selected algorithms and adapt them to the selected hardware solutions.

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