Journal of Machine Construction and Maintenance
QUARTERLY
ISSN 1232-9312 2/2019(113)

p. 105–111

Krzysztof STANKIEWICZ *
Institute of Mining Technology KOMAG, Gliwice, Poland
* Corresponding author: kstankiewicz@komag.eu

SMART MINING COMMUNICATION SYSTEMS

Key words: sensors, communication, network, data.

Abstract: Polish industry stands at the threshold of the 4th Industrial Revolution, whose core is data collected from manufacturing and exploitation processes. The number of the devices that are capable of communication increases exponentially. These facts imply a constant evolution of automated systems, intelligent data analysis, and methods for their reliable and efficient transmission. The current rapid development of communication technologies mainly focuses at the transmission of digital data. Digital data is most often sent within separated hardware segments of business management structures, for the control and monitoring of machines, devices, and processes. At the lowest levels, fieldbuses prevail, from which data is aggregated and transmitted, often by Ethernet protocols, to the level of enterprise branch servers. Then branches connect to the central structures using encrypted tunnels created within the Internet. The whole structure is exposed to a number of threats related to the presence of typical failures, disruptions, as well as actions leading to the data mismatch or transmission failures. A similar state of needs and threats in the field of acquisition and transmission of digital data occurs in Polish mining. The problem of the complexity of communication structures, including sensory networks and battery-powered wireless sensors, becomes a part of mining technology and the processing of raw materials. Development processes of sensory networks are mainly focused on its reliability, followed by performance. For this reason, as well as bearing in mind the reduction of the costs of building the communication infrastructure, networks with mesh topology develop, which are characterized by high transmission reliability due to its multi-redundant structure. This article describes the development of one of the latest communication protocols SSKIR, intended for use in mesh networks.

Inteligentne górnicze systemy komunikacyjne

Słowa kluczowe: sensory, sieć, komunikacja, dane.

Streszczenie: Polski przemysł stoi u progu 4 Rewolucji Przemysłowej, której trzon stanowią dane pochodzące z procesów wytwórczych i eksploatacyjnych. Liczba urządzeń zdolnych do komunikacji rośnie wykładniczo. Fakty te implikują stałą ewolucję systemów zautomatyzowanej, inteligentnej analizy danych i metod ich niezawodnej oraz wydajnej transmisji. Obecny, gwałtowny rozwój technik komunikacyjnych dotyczy przede wszystkim transmisji danych cyfrowych. Dane cyfrowe przesyłane są najczęściej w ramach wyraźnie wyróżnionych segmentów sprzętowych struktur kierowania przedsiębiorstwem, sterowania i monitorowania maszyn, urządzeń oraz procesów. Na najniższych poziomach dominują magistrale polowe, z których dane są agregowane i przesyłane, często protokołami ethernetowymi, na poziom serwerów oddziałów przedsiębiorstwa. Następnie oddziały łączą się ze strukturami centralnymi za pomocą szyfrowanych tuneli tworzonych w ramach sieci Internet. Struktura ta narażona jest na szereg zagrożeń związanych z obecnością typowych awarii, zakłóceń, jak i celowych działań prowadzących do zawłaszczenia danych lub unieruchomienia transmisji. Podobny stan potrzeb i zagrożeń w zakresie akwizycji i transmisji danych cyfrowych sygnalizuje polskie górnictwo. W ramach procesów wydobywczych i przeróbczych surowców skalnych coraz częściej napotyka się na problem złożonych struktur komunikacyjnych, w tym sieci sensorycznych obejmujących czujniki bezprzewodowe zasilane bateryjnie. W ramach sieci sensorycznych główny nacisk kładziony jest na jej niezawodność, a w dalszej kolejności na wydajność. Z tego powodu, oraz mając na uwadze redukcję kosztów budowy infrastruktury komunikacyjnej, rozwija się sieci o topologii kratownicowej (ang. mesh), charakteryzujące się wysoką niezawodnością transmisji dzięki strukturze multiredundantnej. W niniejszym artykule opisano rozwój jednego z najnowszych protokołów komunikacyjnych SSKIR, przeznaczonego do zastosowań w sieciach kratownicowych.

Introduction

The most important way to increase the efficiency of coal mining, while maintaining the safety of crews, is to include Polish mining in the idea of Industry 4.0. Research into key sectors of the German and European economy has shown [3] that progress is possible through digital transformation, whose basic factors are digital data, automation, communications, and digital access of consumers.

The broadly understood Polish underground mining industry is beginning to transform itself within the idea of the Mining 4.0 programme, which means the development of such areas as the Internet of Things, mechatronics, telematics, and product distribution.

The first area, the Internet of Things (IoT), is aimed at including all devices into the network of intelligent management, both from the local manufacturer's level and from the external supplier/manufacturer/service provider of machines and devices. From the point of view of security and economy, it is important to combine production processes [11] with business processes [14] through appropriate software. On the basis of the collected data, their evaluation, inference, and suggestions of solutions are made. Thanks to the connection with economics, it is possible to obtain measurable information about the conducted production and business processes [16].

The second area, mechatronics, combines elements of mechanics, electronics, control and computer science, and it is used, among others, to design modern machines and equipment for automation and robotics. According to the definition adopted by the International Federation for the Theory of Machines and Mechanism, mechatronics is a "synergistic combination of precision mechanics, electronic control and system thinking in the design of products and production processes" [10]. It should be stated that this area has been developed for several years by scientists and manufacturers of products working for the mining industry. The fact that mechatronics in mining is already well established is also confirmed by that education in the field of mechatronics is one of the requirements for qualifications in the area of professional training of a person who is supervising underground activities of a mining plant with mechanical specialization in the field of underground machines and equipment.

Telematics is understood as [12] structural solutions, in which electronic information acquisition and processing are integral elements of the telecommunications system and technical solutions integrating universal telecommunications and IT systems. Telematics basically defines new telecommunication functions connected with the field of IT, which, in mining, means specialized ICT systems integrating telecommunications with IT used in these systems [13].

The last of the areas, product distribution, is oriented towards the final customer, while the distribution itself is an element of logistic activities in the company [17]. The character of this area is best explained by one of many definitions, which states that the purpose of distribution is to provide customers with products in appropriate quality, in the appropriate time and place, in the most convenient forms and conditions of making purchases, as well as at the lowest possible costs of bringing them from production to intermediate and final customers [10].

1. State-of-the-art smart mining communication systems

The rock and coal, surrounding a coal mine roadway, act as relatively low-loss dielectric media in the frequencies of range 200–4,000 MHz and a dielectric constant of 5–10. Under these conditions, a reasonable hypothesis is that the transmission takes the form of wave propagation, since the wavelength of ultra-high-frequency (UHF) waves are smaller than the roadway dimensions. An electromagnetic wave traveling along a roadway in a dielectric medium can propagate in any one of a number of allowed waveguide modes. All of these modes are modes with losses, because any part of the wave that impinges on the roadway wall is partly refracted into the surrounding dielectric and partly reflected back into the waveguide. The reflected part propagates away from the waveguide and represents a power loss. The overall loss in the strength of the signal, in a straight roadway, is the sum of propagation loss and the insertion loss of the transmitting and receiving antennas. It has been found that the total loss is minimal in the range of 400–1000 MHz, depending on the desired communication distance. Hence, the UHF communication system is used in straight roadway for line-of-sight communication [1].

In the present market, there are many mining systems of wired and wireless communication, which must function under the harsh conditions described above. Most of them do not have smart features, understood as the ability to adapt and learn, which increases the resistance to failures and interference. Mining telecommunications networks are mainly used for analogue and digital voice communication, text communication, identification, positioning, and the aggregation of data coming from machinery and equipment during longwall and excavation operations. Mining communication networks are mostly created with the use of classical bus and star topologies as their assembly. The main communication routes are commonly made with the use of a fibre optic medium. However, there are relatively many networks with copper medium in use, the core of which is inefficient serial communication based on the RS485 protocol.

As the hierarchy of communication becomes lower and lower, innovative solutions of fieldbus class networks, including networks intended for data acquisition from extensive sensory structures, are more and more frequently encountered. In this context, the solutions developed in recent years should be listed:

1. EH-PressCATER (Fig. 1) – a smart wireless network of pressure sensors with mesh topology produced by Elgór-Hansen Sp. z o.o., characterized by the following features:
   - anti-explosion structure according to the PN-EN 60079-25,
   - wireless control & communication – no troublesome wiring,
   - robustness to damage of communication nodes due to adaptation and redundancy,
   - pressure control inside pillars, props, and on inflow or outflow trunk lines,
   - minimum one year work period on one battery,
   - registration of the pressure course with the measurement frequency & result with a refreshing rate of 1 second,
   - possible remote parameterization of the RPSI sensors adjustments from the computer,
   - data/measurement archiving in the SQL database,
   - open architecture,
   - possible expansion of the wireless pressure sensor network,
   - making data available to other visualization systems using standard transmission protocols & generation of reports.

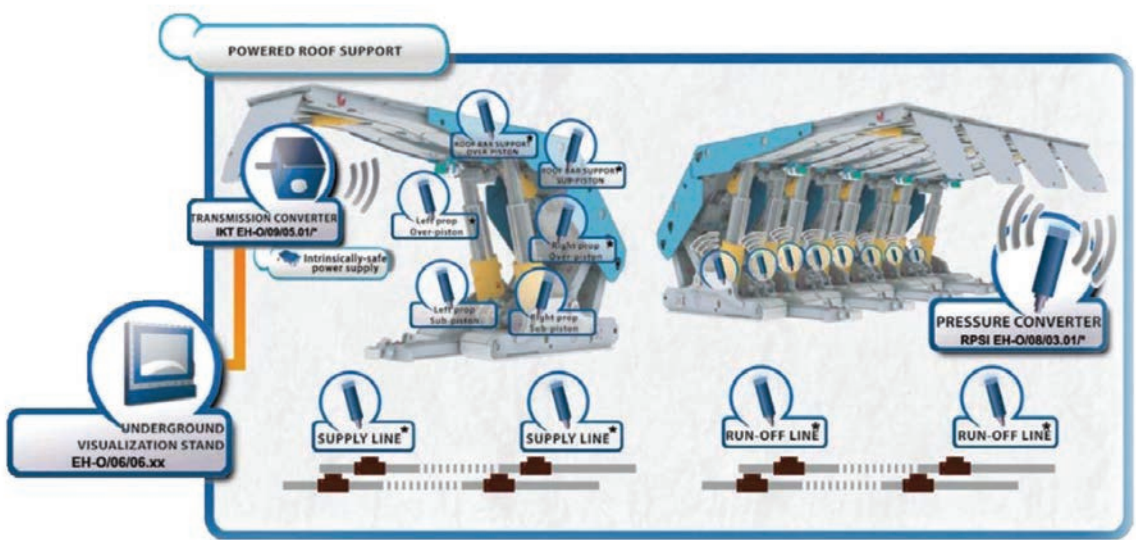

Fig. 1. EH-PressCATER wireless monitoring system [5]

2. DPS11 – mine smart telemonitoring system (Fig. 2) produced by ZAM-SERVICE s.r.o.. The DPS11 Mine Data Transfer System is a modular system for two-way transfer of data, visualization and control the mines technology and air monitoring in the SCADA standard. DPS11 use for the data transfer between the mine sections comprised of data concentrators fitted with terminal monitoring sensors or DKD11--ABVconcentrators and the surface section comprised of modems and a server to process, store and visualise the data. The DPS11 provides communication and power supply to peripheries connected to the system. The system ensures the transfer of data with information referring to, for example, the methane concentrations measured, the levels of analogous signals, statuses of binary inputs, binary outputs, and voltage outputs.

The system also includes a state-of-the-art solution of communication cable RFK-01 which integrates WiFi access points and RFID readers in its structure (Fig. 3).

3. Since 2012, ITG KOMAG has been developing the concept of a protocol of self-organizing communication structure, named SSKIR [9], which is based on one of artificial intelligence technologies, "swarm intelligence," which is a direct implementation of phenomena and behaviour observed in nature among organisms living in large groups. Their behaviour, to some extent, can be transferred to the operation of routing protocols. The system structures developed by humans (irrespectively to real implementation), using the swarm algorithm, have high possibilities for adaptation and high operational reliability. In 1987,

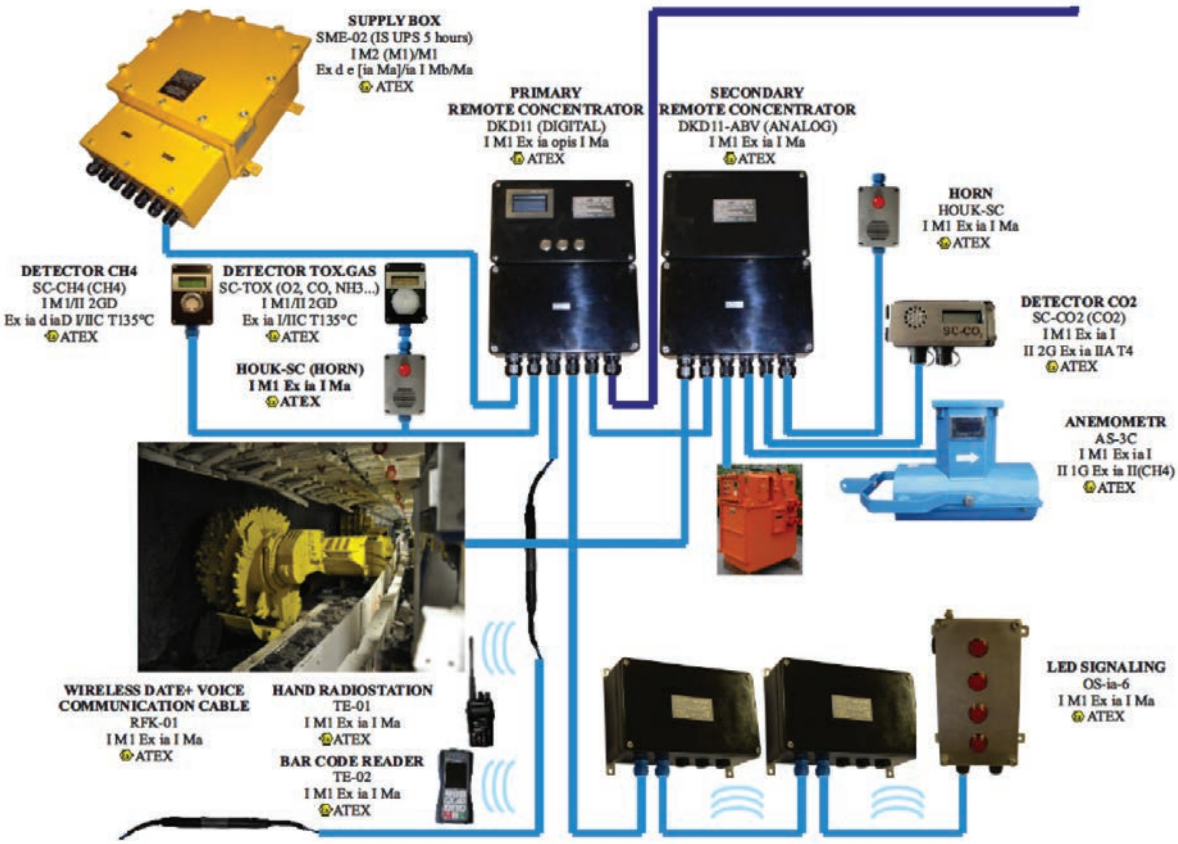

Fig. 2. DPS11 mine telemonitoring system diagram [15]

Fig. 3. RFK-01 communication cable

during the SIGGRAPH conference, a programmer, Craig Reynolds, in the paper entitled "Flocks, Herds, and Schools: A Distributed Behavioural Model," suggested three basic rules of self-organization based on observed groups of animals, as follows [7]:

- Collision avoidance is control eliminating a local concentration of individuals. Collision avoidance eliminates accumulation of hardware and decision structures.
- Flock centring are actions towards the average behaviour of local groups of individuals.
- Velocity matching are actions towards the average objective of local groups of individuals. Velocity matching enables the individual to adapt its actions to other individuals from its local group.

Based on the above rules, the creation of a communication system made of a sensor network in which routing is based on a swarm algorithm was suggested [8]. Each data frame transferred by the Measure Transmission Unit (MTU) is marked by a quality coefficient W_p specifying the transmission priority referring to the effectiveness of data transmission to the main transceiver stations. This coefficient can take a value that conforms to one of connections or path metrics [2, 4].

2. Smart mining wireless communication system based on the SSKIR protocol

The solution of sensory network proposed by ITG KOMAG is based on wireless network nodes working at the frequency of 2.4 GHz. The advantage of this solution is the short distance between the nodes (under 10m), and thus negligible problems with power loss and wave reflections in the mine roadways. The presented communication system will also be implanted in the SSMS longwall support geometry monitoring system [6].

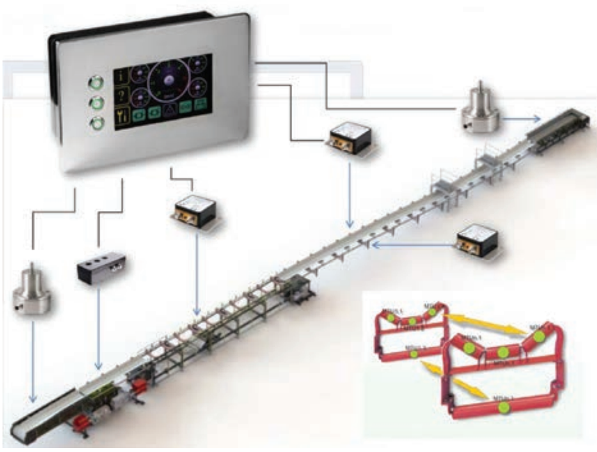

Fig. 4. Example of implementation of the SSKIR protocol in sensory network of belt conveyor rollers [8]

As mentioned above, the W_P coefficient can take a value that conforms to one of connections or path metrics; therefore, transmission speed and the number of hops of transmitted frames containing the following measurement data is based on data propagation times:

- Expected Transmission Count (ETX) is a metric that is widely used in mesh networks. ETX is the metric specifying the number of expected transmissions, which is indispensable when sending data to the next node without errors. The number varies from 1 to infinity. An ETX metric equal to 1 indicates a perfect data transmission path, and an ETX approaching infinity represents the connection that is not functioning.
- Expected Transmission Time (ETT) is an extension of ETX metrics, since it takes into consideration the difference in the speed of data transmission. The ETT of connection l is defined as an expected duration of the successful transmission of a data package in connection 1. The importance of p path is defined as a sum of the ETT of all possible connections along the given path. The relationship between ETT and ETX can be expressed as follows:

$$ETT_l = ETX_l \frac{s}{b_1} \tag{1}$$

where b_l – is a speed of transmission of information in connection l, s – is a size of transmitted package.

- Hop count is the most often used routing metric in the existing routing protocols, such as DSR (Dynamic Source Routing), AODV (Ad Hoc On-Demand Distance Vector), or DSDV (Destination-Sequenced Distance Vector). Hop count is the routing measure used to measure a distance between transmitting and receiving stations counting the hops. The next hop can be a receiving station or device intermediating in the exchange of information. The protocol using the Hop count metric determines the route with the lowest number of hops between transmitting and receiving stations.
- Weighted Cumulative ETT (WCETT) is a metric that includes both the quality of a connection (losses, throughput) and the number of hops. Thus, we can reach a compromise between delay and throughput.

$$WCETT(p) = 1 - \beta \cdot \sum_{l \in p} ETT_l + \beta \cdot \max_{1 \le j \le k} X_j \tag{2}$$

where β – is a set parameter from the range $0 \le \beta \le 1$. Higher values of β give priority to paths using many channels and its lower values give priority to shorter paths, $\max_{1'' j'' k} X_j$ – counts the maximal time of appearance of the same channel in a given path.

- MIC is metric that improves the operation of WCETT by solving its isotonicity and inability of detecting the collisions. MIC metrics of p path can be defined as follows:

$$MIC(p) = \frac{1}{N \cdot \min(ETT)} \sum_{linkij \in p} IRU_{ij} \sum_{nodei \in p} CSC_i \tag{3}$$

where N – is a number of all nodes in the network, *min(ETT)* – is the lowest ETT in the network and it can be determined on the basis of the lowest speed of data transmission in radio charts.

Additionally, the following principles resulting from swarm phenomena are assigned to each data package so that the system can react to changes in a node structure (failures, nodes displacement):

1. The package matches its speed to the packages moving in paths of higher W_P coefficient.
2. The package uses the path parallel to the optimal route (of highest known W_P value), if its W_P decreases.
3. The package uses the optimal path (of higher known W_P value), if the W_P coefficient of the current route decreases.
4. The package avoids transmission through the nodes that are marked as damaged.
5. The package can leave the present path, if the main transceiver station is found.

Local data, which is indispensable for the realization of tasks resulting from the above principles, are calculated and stored in nodes. There is no need to create a master routing table. The use of these rules causes that the group of MTUs creating the transmission connection automatically develops the structure of reliable transmission routes while neglecting the damaged units. The data frame in the SSKIR protocol is defined by four additional values:

- Its own unique MTU identification number,
- *X* and *Y* coordinates defining the occupied position in the solution space of the communication path structure,
- The priority factor in the communication path of which the frame is an element,
- The baud rate for the *X* and *Y* dimensions, i.e. *vX* and *vY*.

The neighbours of frames with the number of a given MTU are called other frames that are in the MTU transmission range, i.e. those that are in a sufficiently short distance *d* and simultaneously in the field of view, defined by the value of virtual angle *r*. In order to check whether a given frame *e* of coordinates *e.X* and *e.Y* respectively, is a neighbour of MTU *b* of coordinates *b.X* and *b.Y*, it is necessary to check first whether the element is in a sufficiently short distance.

$$\sqrt{(e.X-b.X)^2+(e.Y-b.Y)}<d \quad (4)$$

If the inequality is not met, then the next rules are not checked, because a given frame from the MTU *e* is certainly not a neighbour of frames from the MTU *b*. If the inequality is met, it is checked if the frame is in the virtual viewing angle *r* by determining the angle r_1 under which the frame moves virtually:

$$r_1=\arctan\left(\frac{b.vY}{b.vX}\right) \quad (5)$$

and the virtual angle r_2 of the segment connecting the MTU *b* frame with the MTU *e* frame:

$$r_2=\arctan\left(\frac{e.Y-b.Y}{e.X-b.X}\right) \quad (6)$$

assuming that $b.vX\neq 0$ and $e.X\text{-}b.X\neq 0$. Then the absolute value of the angle difference is calculated and the inequality checked:

$$|r_1-r_2|<r \quad (7)$$

If the unevenness is met, then the frames come from neighbouring MTU. Next, the first rule is applied, and each frame adjusts its path to frames from neighbouring MTU. One must calculate the average speed v_{avg} of all frames from the neighbouring MTU (separately for the *vX* and *vY* components) and then modify the frame transmission speed, taking into account the path priority factor, the current speed, and the calculated average, according to the following formulae:

$$\begin{aligned} b.vX &= b.vX+\left(W_p\cdot\left(vX_{avg}-b.vX\right)\right)\\ b.vY &= b.vY+\left(W_p\cdot\left(vY_{avg}-b.vY\right)\right)\end{aligned} \quad (8)$$

To apply the second rule, the average number of frame jumps in the d_{avg} transmission path should be calculated in relation to frames from neighbouring MTU, and then the frame transmission speed should be modified in relation to neighbouring MTU. Formulae (9) are the result of the triangular similarity claim. The frame's position in the transmission path, whose speed is modified *b* and the position of the neighbour *e*, is used:

$$\begin{aligned} d &= \sqrt{(e.X-b.X)^2+(e.Y-b.Y)}\\ b.vX &= b.vX+\frac{(e.X-b.X)\cdot\left(d-d_{avg}\right)}{d}\\ b.vY &= b.vY+\frac{(e.Y-b.Y)\cdot\left(d-d_{avg}\right)}{d}\end{aligned} \quad (9)$$

The third rule shows that, when a frame in a path with a lower priority coefficient tries to carry out the transmission, competing with a frame with a higher priority, it should avoid it by modifying its speed. Formulae (10) also use the triangular similarity claim. Let *b* be a lower priority frame competing with a frame from the neighbouring MTU, with a higher priority *e*. In regard to the above rule, the following formulae should be applied:

$$\begin{aligned} d &= \sqrt{(e.X-b.X)^2+(e.Y-b.Y)}\\ b.vX &= b.vX+\left(\frac{\left(e.X-b.X\right)\cdot d_{\min}}{d}-\left(e.X-b.X\right)\right)\\ b.vY &= b.vY+\left(\frac{\left(e.Y-b.Y\right)\cdot d_{\min}}{d}-\left(e.Y-b.Y\right)\right)\end{aligned} \quad (10)$$

where d_{min} is a preset minimum number of jumps in the transmission path, which should not be exceeded by the transmitted frame. The last two rules are introduced to the system by modifying the fourth rule based on the dependencies (10). It should be noted that each frame can move with a certain maximum speed imposed by the physical system. In simulations, this speed should be limited and the following entered:

- Limitations resulting from the presence of MTU in the emergency or start-up state (elements that frames should avoid creating transmission paths), and
- Attractors in the form of main receiving and transmitting stations.

Summary

Control and monitoring systems, capable of adaptation and learning, are used in industrial practice on a larger scale. The Internet of Things (IoT) techniques and direct communication M2M (Machine to Machine) have an impact on the structure and functionality of control systems used in machines, shaping the idea of Industry 4.0.

Smart wireless communication systems based on the mesh topology are beginning to appear on the mining market. These systems are characterized by a high degree of reliability, scalability, and low energy consumption.

The method of the self-organization of the communication system based on a swarm algorithm enables an implementation of the state-of-the-art and effective routing technology in the networks of mesh topology, including those used in underground mines, especially in diagnostic and monitoring systems, as well as for the protection of machines. Sub-assemblies of the networks equipped with MTU nodes can be treated as components of a measuring swarm. It is particularly important for operational safety in underground mines due to the reliability of mesh networks.

References

1. Bandyopadhyay L.K., Chaulya S.K., Mishra P.K.: *Wireless Communication in Underground Mines: RFID-based Sensor Networking*. Springer, 2010.
2. Basagni S., Conti M., Giordano S., Stojmenovic I.: *Mobile Ad Hoc Networking*. New Jersey: IEEE Press, 2004.
3. Roland Berger Strategy Consultants, BDI: *The digital transformation of industry*. [Online]. 2015. [Accessed 30 April 2019]. Available from: https://www.rolandberger.com/publications/publication_pdf/roland_berger_digital_transformation_of_industry_20150315.pdf
4. Boukerchea A., Turgutb B., Aydinc N., Mohammad A.Z., Bölönid L., Turgut D.: Routing protocols in ad hoc networks: A survey. *Computer networks*, 2011, 55(13), pp. 3032–3080.
5. Elgór-Hansen: *Pressure monitoring system for roof-supports*. [Online]. 2019. [Accessed 30 April 2019]. Available from: https://elgorhansen.com/en/offer/pressure-monitoring-system-for-roof-supports
6. PRASS III: *Main website*. [Online]. 2019. [Accessed 30 April 2019]. Available from: http://prass3.komag.eu/
7. Reynolds C.W.: Flocks, Herds, and Schools: A Distributed Behavioral Model. *Computer Graphics*, 1987, 21(4), pp. 25–34.
8. Stankiewicz K.: Mining control systems and distributed automation. *Journal of Machine Construction and Maintenance,* 2018, 2(109), pp. 117–122.
9. Stankiewicz K.: A self-organizing communication system based on the swarm algorithm. Presented at the *International Conference Mechatronics: Ideas for Industrial Applications,* Gdańsk (Poland), 11–13 May 2015.
10. Sztucki T.: *Marketing przedsiębiorcy i menedżera*. Warszawa: Agencja Wydawnicza Placet, 2000 [in Polish].
11. Trenczek S.: Kierunki rozwoju infrastruktury systemowej zasilania, informatyki technicznej i automatyki. *Mechanizacja i Automatyzacja Górnictwa*, 2009, 9, pp. 9–15 [in Polish].
12. Wydro K.B.: Telematyka – znaczenie i definicje terminu. *Telekomunikacja i techniki informacyjne*, 2005, 1–2, pp. 116–127.
13. Wojaczek A.: Telematyka w podziemnych zakładach górniczych. *Mining – Informatics, Automation and Electrical*, 2017, 7, pp. 27–34 [in Polish].
14. Żeliński J.: *Co to jest proces biznesowy*. [Online]. 2012. [Accessed 30 April 2019]. Available from: https://it-consulting.pl/autoinstalator/wordpress/2012/09/28/business-process-manifesto
15. ZAM-SERVICE: *DPS 11 Mine Telemonitoring System*. [Online]. 2009. [Accessed 30 April 2019]. Available from: http://www.zam.cz/KATALOG_DULNI/EN/DPS-11_EN_V140116.pdf
16. Zawiła-Niedźwiecki J.: *Zarządzanie ryzykiem operacyjnym w zapewnianiu ciągłości działania organizacji*. Kraków: Wyd. Edu-Libri, 2013 [in Polish].
17. Witkowski J.: *Rodzaje działań w zakresie strategii logistycznej przedsiębiorstwa*. Wrocław: AE we Wrocławiu, 1995 [in Polish].

This article appeared in its printed version in Journal of Machine Construction and Maintenance. The electronic version is published in DEStech Publications, Inc., Lancaster, PA, 2019, Proceedings of FUTURE ENGINEERING CONFERENCE.