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INTELLIGENT ALGORITHMS FOR ROUTING SENSORY NETWORKS OPERATING IN EXPLOSION HAZARD ZONES

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Abstract: The article presents intelligent routing algorithms currently used in sensory networks, in terms of determining the possibility of their integration into systems working in potentially explosive atmospheres. Selected types of scribing algorithms were characterized. The analysis of simulation tests performed on selected types of scribing algorithms was carried out. The analysis of equipment solutions which can be used to build a network node operating in the conditions of methane and/or coal dust explosion hazard was carried out.

Keywords: *routing algorithms, Internet of Things, explosion-hazardous areas, sensors network, swarm intelligence*

1. INTRODUCTION

An implementation of the Internet of Things (IoT) concept typically results in communication networks with a complex structure. In such complex networks it is necessary to properly organize information transmission in order to ensure an operational reliability, a flexible configuration and operational safety. It is particularly important to ensure the reliability of sensory networks operating in hazardous conditions from methane and/or coal dust explosion (Jasiulek 2019), as these sensors related to safe work environments and machine diagnosis to which the equipment depend.

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The solution of this problem includes intelligent routing algorithms. Their characteristics and analysis are presented in this article. In addition to ensuring their operational stability in the communication of individual nodes of sensory networks, it is necessary to ensure appropriate hardware structure of each of the nodes. This article presents an analysis of hardware solutions that have the appropriate computing power, energy consumption from battery sources and have features that make it possible to work in conditions of explosive hazards.

The second chapter presents the characteristics of routing algorithms with the specification of mathematical formulas describing their operation. The third chapter of the article contains an analysis of simulation tests of selected scribing algorithms conducted by scientists from various universities. The analysis was conducted in several aspects:

- Changes in the operating parameters of a sensory network depending on the number of network nodes (in a working environment such as a hard coal mine we are currently dealing with a rapid growth of devices connected to wireless networks. There are also problems with managing the operation of such networks);
- Effectiveness of data delivery to the addressee (in hard coal mines, devices monitoring the state of work safety are often connected to the sensor network. Therefore, the key thing is the certainty of receiving data sent from such devices);
- change of the operating parameters of the active network depending on the speed of movement of network nodes (in hard coal mines the operating status of mobile devices is monitored by means of wireless active networks. Correct diagnostics of the operation of such devices is necessary for reasons of work safety).

The fourth chapter presents equipment devices that can be used to build network nodes in potentially explosive atmospheres. Devices operating in such zones must comply with the ATEX directive. This involves limiting the power propagated by such devices, resistance to environmental conditions and adequate protection of their power supply.

2. ROUTING ALGORITHMS

Sensory networks used in potentially explosive atmospheres, must ensure a reliable transmission of measurement data in order to detect fault conditions that pose a direct threat to the progress of the mining operation and often also to the health and safety of employees.

Working conditions in mines make it difficult to service machinery and equipment. The installation of a new measuring system, a replacement of a sensor, and maintenance actions should be simplified by the type of machine sensors used.

The following elements become important for operational reasons:

- An easy assembly and replacement of the sensor (no need to use wires makes it easier to install and adapt to the structure of the machine or the environment in which it works). The sensors should be powered by batteries or by energy recovery, with the sensory data transmitted via radio signal;
- Sensors should be replaced without the need to reconfigure the network in which they are located;
- Sensors should transmit information among themselves so that, due to interference from metal elements, it is not necessary to transmit information directly to the access point.

In order to meet these requirements, it is necessary to implement appropriate routing algorithms in sensory networks. Routing algorithms are divided into several types (Fig. 1).

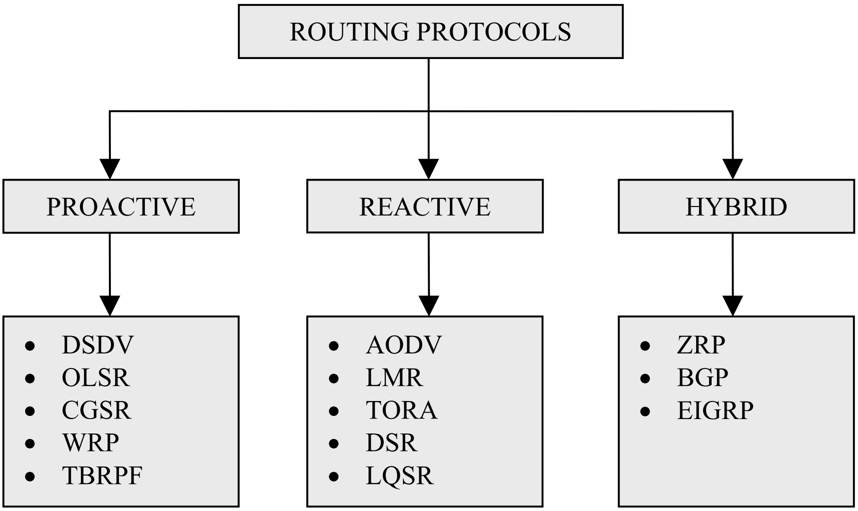


Fig. 1. Types of routing algorithms (Lalar 2017)

Proactive algorithms store routes between individual network nodes in the so-called routing tables. These routes are cyclically refreshed so that the stored data are consistent with the current state of the network (the so-called maintenance of paths takes place regardless of whether there is traffic to individual nodes of the network). There are several types of proactive algorithms: DSDV (Highly Dynamic Destination-Sequenced Distance Vector routing protocol), OLSR (Optimized Link State Routing Protocol), CGSR (Cluster Gateway Switch Routing Protocol), WRP (Wireless Routing Protocol), TBRPF (Topology Dissemination based on Reverse-Path Forwarding routing protocol), QDRP (Quality of Service-Directional Routing).

Reactive Algorithms - These Algorithms search for a route when necessary, at the time of sending a packet. There are several types of reactive algorithms: AODV (Ad hoc On-Demand Distance Vector routing protocol), LMR (Label-based Multipath Routing), TORA (Temporally-Ordered Routing Algorithm routing protocol), DSR (Dynamic Source Routing protocol), LQSR (Link Quality Source Routing).

Hybrid algorithms – In these algorithms, the network is divided into smaller parts. Only separated parts of the network are saved. There are several types of hybrid algorithms: ZRP (Zone Routing Protocol), BGP (Border Gateway Protocol), EIGRP (Enhanced Interior Gateway Routing Protocol).

There are also used routing algorithms based on Swarm Intelligence (SI). These algorithms are characterized by the fact that, regardless of the number of variables and space solutions, adapt to the limitations and help solve the optimization problem (Filipowicz 2010). The following algorithms have been distinguished:

- Ant Colony Optimization (ACO) – the algorithm was developed by Marco Dorigo (2004). It was developed on the basis of observations of ants' behaviour, specifically the way they reach food. A single ant (scout) moves randomly in order to reach food (solve the problem). While searching for a solution to the problem, each scout collects information about the characteristics of the problem and their own achievements. The ants pass the information among themselves thanks to the stigma mechanism (each of the ants leaves the information on the ground in the form of a pheromone). The remaining ants detect the pheromone and follow the path. The solution to the problem is the shortest path. The complexity of each ant is such that it can find a solution itself, but the solution will be of poor quality. Good quality solutions are the result of the cooperation of a whole colony of ants. The ants' algorithm calculates the shortest route in the graph by going through its successive vertices (Schiff 2008). The selection of the next vertex j adjacent to the vertex and through an artificial ant is done with probability shown in Eq. (1) (Schiff 2008).

$$p_{ij}^{k} = \frac{t_{ij}}{\sum_{j \in N_i} t_{ij}}, \tag{1}$$

  where: p – the probability of selecting the next vertex of the graph "j" adjacent to the previous vertex "i" by the ant "k", t – a quantity of pheromone deposited on element "j".

- Particle Swarm Optimization (PSO) was developed by Kennedy and Eberhart (Kennedy 1995). It is a stochastic algorithm that observes the behaviour of a swarm (bird flock, fish shoal, etc.). Each individual in swarm has a specific speed, position and direction. These variables are determined on the basis of their own best previous experience and the best experience of other individuals in the swarm (neighbours) (Chan 2007; Figielska 2015). The PSO algorithm works with a set (swarm) of potential solutions to the problem (particles). Each particle is described by:

- position $X_i = (x_{i1}, x_{i2}, ..., x_{im})$,
- speed $V_i = (v_{i1}, v_{i2}, ..., v_{im})$

in m dimensional space.

During each iteration, each swarm particle moves to a new position, taking into account its previous position and speed, as well as the best position found, $P_i = (p_{i1}, p_{i2}, ..., p_{im})$ and the best position found in the entire swarm, $G_i = (g_{i1}, g_{i2}, ..., g_{im})$ (Wiatrak 2015). For each particle, the new speed and location are calculated in Eqs. (2) (Chan 2007; Figielska 2015) and (3) (Chan 2007; Figielska 2015), respectively.

$$v_{ij}^{t} = wv_{ij}^{t-1} + c_1 r_1 (p_{ij} - x_{ij}^{t-1}) + c_2 r_2 (G_j - x_{ij}^{t-1}), \tag{2}$$

where: $j = 1, \ldots, m$, m – dimensional space, w – inertia weight, c_1 – cognitive acceleration coefficient, c_2 – social acceleration coefficient, r_1 – the random values between 0 and 1, r_2 – the random values between 0 and 1, p – the best position found, G – the best position found in the entire swarm, t – iteration step, v – speed vector of "i" particle, x – position vector of "i" particle,
and new position as New position:

$$x_{ij}^{t} = x_{ij}^{t-1} + v_{ij}^{t}, \tag{3}$$

where: $j = 1, ..., m$, m – dimensional space, t – iteration step, v – speed vector of "i" particle, x – position vector of "i" particle.

- Bee Algorithms (BA) are based on observing the behaviour of a bee swarm when it reaches the food. First, bees are sent from the hive to search the area randomly. When they return, they inform the colonies about the food they have found in the form of a bee dance. The following information is provided: direction, distance and quality of the food source. On the basis of the information received, the colony decides on the quantity of workers sent from the hive (decides on the quality of food and the amount of energy required to obtain food). While collecting the food, the workers refresh the information about the state of the source of food and pass it on when they return to the hive. This information is used by colonies to make further decisions (Chmiel 2011).

3. ROUTING ALGORITHMS – SIMULATION TESTS

Specialists from the Silesian University of Technology (Krupanek 2018) analysed the proactive OLSR protocol and two reactive AODV and DSR protocols. Simulations were carried out for the number of network nodes ranging from 10 to 50. The area occupied by the network was 0–1000 m.

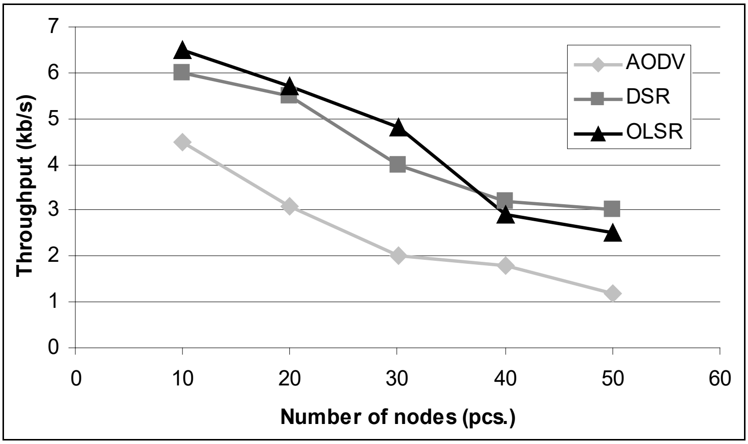


Fig. 2. OLSR, DSR and AODV protocols comparison
– number of nodes/throughputs (Krupanek 2018)

The simulation data presented in Figure 2 show that with the increase of number of nodes, the data transmission throughput decreases. The best parameters in this simulation were obtained by the DSR protocol.

Another parameter, tested in the simulation, was PDR (Packet Delivery Ratio – which describes the effectiveness of data delivery to the receiver).

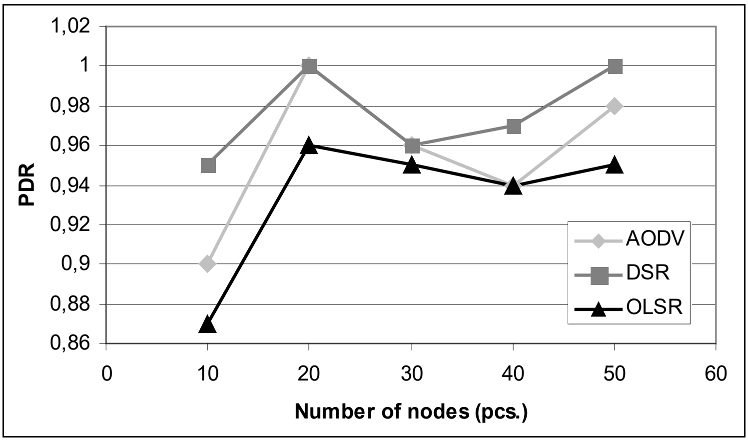


Fig. 3. OLSR OLSR, DSR and AODV protocols
– number of nodes/PDR (Krupanek 2018)

The data in Fig. 3 shows that PDR was unstable for all routing algorithms.

Conclusions from the analysis, carried out by experts from the Silesian University of Technology, indicate that OLSR protocol in terms of surcharge, delay and throughput is better than other AODV and DSR protocols. However, if the number of network nodes is increased (a large number of network nodes is characteristic for sensory networks), the performance of all algorithms presented deteriorate.

The analyses carried out by Wasko S.A. together with the Warsaw School of Information Technology (Smolarek 2012) show that proactive and reactive algorithms (in this case DSDV and AODV), perform better in networks with lower node counts and a static topology (Fig. 4).

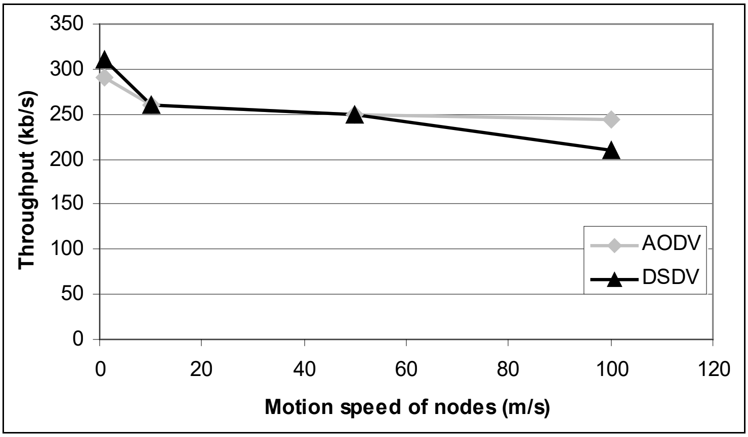


Fig. 4. Parameters of routing algorithms
depending on the speed of network nodes traffic (Smolarek 2012)

Simulations carried out for 50 network nodes indicate that with increasing speed the movement of nodes decreases the transmission throughput (Figure 4).The results of the presented tests show that the performance parameters of reactive and proactive algorithms deteriorate with the increase in the number of network nodes and the speed of individual nodes.

Significantly better parameters in this range are characterized by routing algorithms based on the swarm intelligence. Specialists from the IDSIA Institute in Switzerland conducted simulation tests comparing the AODV algorithm with the AntHocNet algorithm (Gianni 2005). The AntHocNet algorithm was designed by IDSIA specialists on the basis of the ACO form protocol.

The results of the analysis showed that the ACO algorithm has a shorter time of data packet delivery to the access point compared to AODV (Fig. 5a). The AntHocNet algorithm also exceeds the AODV protocol in terms of the efficiency of data delivery (PDR coefficient), as the number of nodes in the network increases (Fig. 5b).

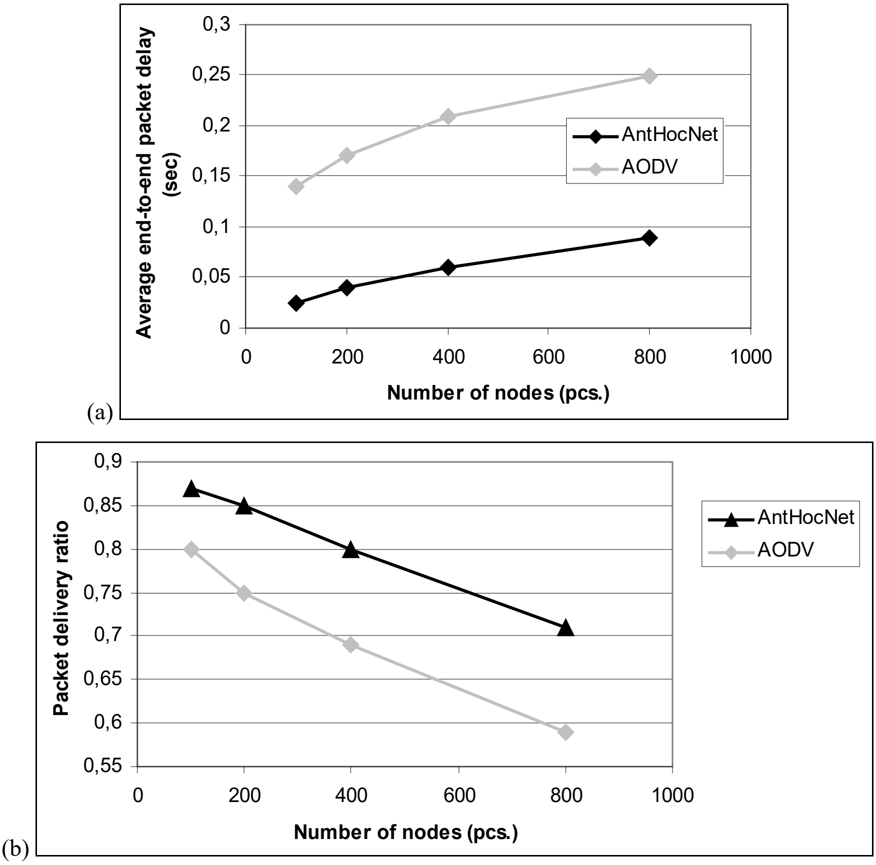


Fig. 5. Average packet delay (a) and delivery ratio (b) of AODV and AntHocNet algorithms (Gianni 2005)

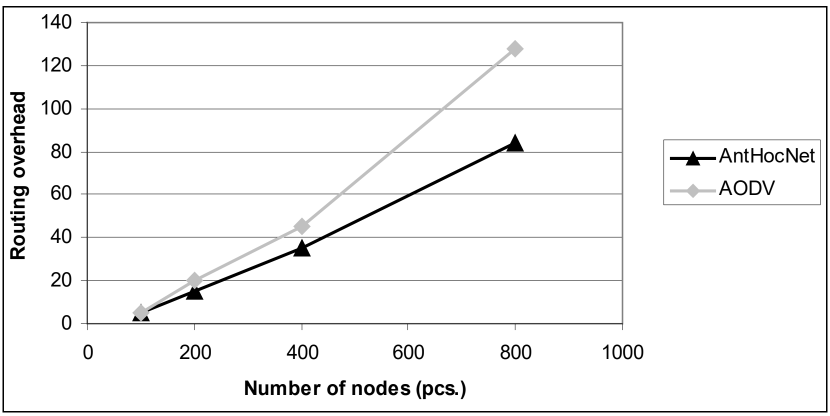
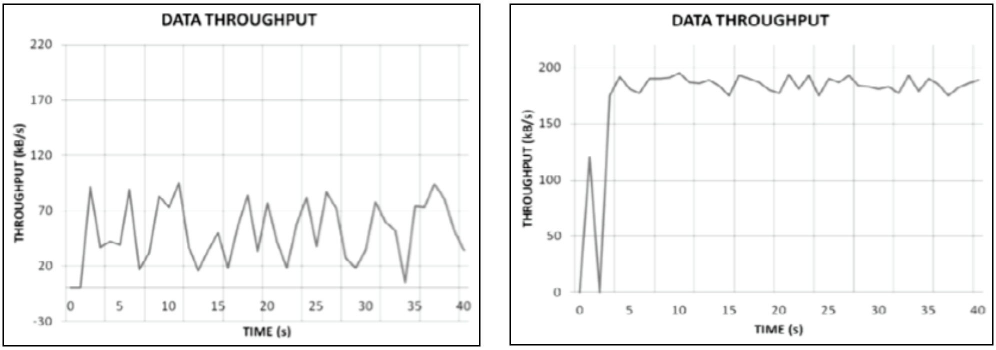


Fig. 6. Routing overhead of AODV and AntHocNet algorithms (Gianni 2005)

The number of packets required for routing process is much higher for AODV algorithm when there are more network nodes (Fig. 6). The AntHocNet algorithm is therefore a protocol with a higher scalability in relation to the number of nodes in the network than the AODV algorithm.



(a) (b)

Fig. 7. AODV and SSKIR algorithms (Stankiewicz 2019)

The graphs (Fig. 7) present a comparison of reactive AODV algorithms and algorithm based on the PSO (SSKIR) optimization algorithm. The graphs show that the transmission capacity in a network with 500 nodes for the SSKIR algorithm is maintained at the level of 200 kB/s, while in the same network using the AODV algorithm, the transmission capacity is unstable and reaches only about 95 kB/s.

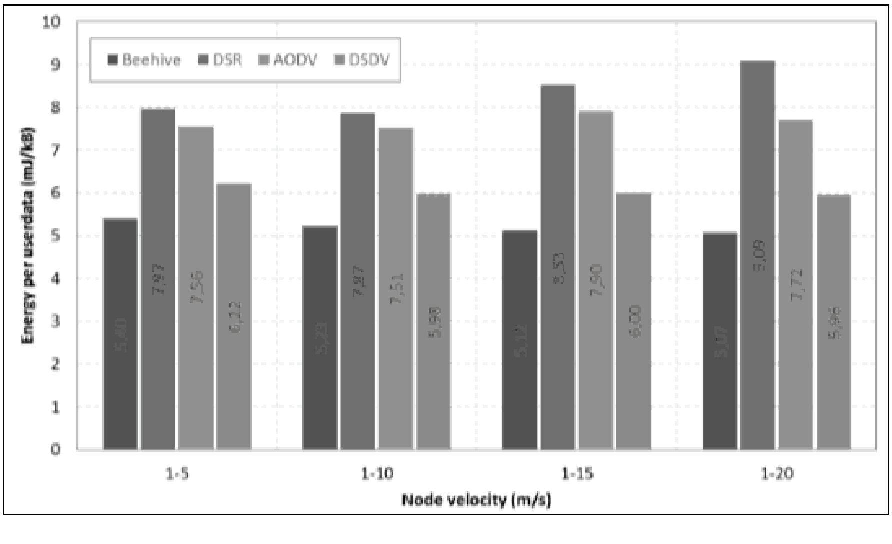


Fig. 8. Energy consumption – Beehive, DSR, AODV, DSDV algorithms (Wedde 2005)

The Dortmund experts differentiated the selected protocols in terms of energy consumption in relation to the data sent, as shown in Fig. 8. The Beehive algorithms has the lowest energy consumption compared to other routing algorithms. All the simulations were performed on a network with 50 nodes, which moved at a certain speed in a 2400 × 800 m area.

The use of SI based protocols positively influences the stabilization and increases the bandwidth in sensory networks in comparison with typical reactive or proactive routing algorithms. The presented test results come from a simulation environment, and therefore it is necessary to implement selected types of protocols in hardware solutions. Algorithms implemented in real network nodes must be subjected to a series of tests that will verify the results of simulations. Hardware solutions for this testing are discussed in Section 4.

4. POSSIBILITIES OF HARDWARE IMPLEMENTATION AND VERIFICATION OF PROPOSED SOLUTIONS

System on a Chip (SoC) solutions is designed for IoT hardware implementations. These systems include microprocessor, memory, radio and analogue circuits. Ministerstwo Cyfryzacji (2019) outlined the characteristics such as solution as:

- Containing sufficient computing power to perform the necessary calculations required by the algorithm and to ensure an adequate speed of execution of the algorithm;
- electronic elements used for the construction of the systems should be characterized by low energy consumption. SOC systems used in IoT systems are powered by a battery or using energy harvesting technology, which captures other forms of energy, such as mechanical or thermal, and converting to electrical energy;
- small in size, for easy adaptation to the working environment;
- be resistant to environmental conditions.

Several hardware solutions that can be used in the proposed solution have been listed:

- CC2x module from Texas Instruments;
- nRF52 module from Nordic Semiconductor;
- MGM12P module from Silicon Labs;
- ESP32 module from Espressif Systems.

The CC2x module from Texas Instruments is equipped with 8-bit 8051 microcontroller. The module consumes about 30mA of current at the moment of transmitting at a supply voltage of 3.3 V. The device can communicate with an external processor by means of a UART serial bus. Depending on the radio module used, it is possible to configure the module.

In all the selected modules it is possible to implement a custom solution starting from the low-level layer. It is possible to modify the firmware of selected hardware modules in terms of routing algorithms.

The Nordic Semiconductor nRF52 radio unit is equipped with a 32-bit ARM processor in Cortex-M4 core (higher computing power than CC2x module). The module consumes about 8mA when sending data at 3.3 V power supply (the value is three times lower than Texas Instruments' solution). Communication with an external microcontroller is possible via SPI, 2-wire and UART buses.

The Silicon Labs MGM12P contains all the features of the nRF52 module.

Finally, The Espressif Systems ESP32 module also has a 32-bit microprocessor. The only aspect that makes it different from the presented solutions, apart from the price, is the current consumption at the moment of transmitting. It is about 200 mA at 3.3 V power supply.

Table 1 shows the parameters of different hardware solutions.

Table 1. Parameters list of radio modules

No.	Radio module	Manufacturer	Supported protocols	Power consumption	Radio frequency	Interfaces
1	nRF52	Nordic Semiconductor	Multi-protocol support	7.5 mA TX / 5.4 mA RX at 3.3 V	2.4 GHz	SPI, 2-wire, I^2S, UART, PDM, QDEC
2	MGM12P	Silicon Labs	Zigbee, Thread, BLE, Multi-protocol support	10 mA RX / TX at 3.3V	2.4 GHz	UART, SPI, SmartCard (ISO 7816), IrDA, I2S, I^2C
3	CC2x	Texas Instruments	ZigBee, RF4CE, IEEE 802.15.4, SimpliciTI, Multi-protocol support	29 mA TX / 24 mA RX at 3.3 V	2.4 GHz, Sub 1 GHz	UART
4	ESP32	Espressif Systems	Bluetooth, WiFi,	190 mA at 3.3 V	2.4GHz	SPI, UART, I2S, I^2C, CAN, ETH

Each of the above equipment solutions must meet the environmental requirements for areas that present an explosive risk from methane or coal dust. It must be designed for operation in Zone I, Group M1 with protection level "*ia*"(accordance with ATEX directive). Therefore, it is necessary to design power supply systems meeting the requirements of the ATEX Directive, as well as to design the enclosure of devices meeting these criteria.

Such an approach will increase the production cost of a single unit, so it is necessary to take into account economic aspects by choosing a specific hardware solution for building a sensory network node. Below is a summary of different costs associated with the specified hardware solutions:

- MGM12P – 180 PLN;
- ESP32 – 50 PLN;
- nRF52 – 50 PLN;
- CC2x – 30 PLN.

While the cheapest solution is the CC2x, it is limited by an 8-bit 8051 microcontroller (low computing power). Therefore, a trade-off is required to ensure that there are adequate computing power verses the cost. The nRF52 is a mid-cost solution but has the advantage of lower energy consumption and therefore is the best solution in terms of price, energy consumption, computing power and size.

4. SUMMARY

The results of the analysis of individual routing protocols indicate that the highest probability of successful implementation of the algorithm in sensory networks, working in a potentially explosive environment, have protocols based on swarm intelligence. The use of these algorithms allows to maintain, at an appropriate level, the parameters of data transmission carried out in sensory networks (bandwidth, low latency, high reliability of data transmission). In addition, sensory networks working on the basis of swarm intelligence algorithms have features of self-organization and multi-redundancy. However, it is necessary to implement algorithms to selected hardware modules in order to verify their effectiveness in real conditions (comparison with computer simulations).

In order to apply selected hardware solutions in explosion hazard conditions, it is necessary to design power supply systems and equipment housings that will ensure compliance with the requirements of the ATEX Directive.

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