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Wireless Platform for the Fatigue Measurement of Workers Employed in Underground Mines

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***Abstract*—human fatigue (tiredness) – identified as one of the major causes of injuries/accidents taking place in mines – can be easily determined and parameterized by examination of human pulse and haemoglobin oxidation level (SpO_2). Two sensors, enabling continuous registration of the factors mentioned above, combined with a ZigBee radio module, have been integrated into a biosensor in the present study. The novelty of the solution is based on a small, pill-sized (and shaped) biosensor form conveniently attachable to a miner's body for a constant reporting of his weariness level during regular work. Moreover, the biosensor is able to communicate with WLAN concentrators that, in turn, serve to convey each miner's health readings, via multiple hops, to the monitoring centre for analysing incoming results on-the-fly. Individual miner's fatigue control is expected to yield less accidents/injuries, which – beside the human aspect – will also considerably save costs of compensation paid to the injured miner/family and preserve the work continuity.**

***Index Terms*—Digital signal processors; ZigBee; wireless sensor networks; fatigue.**

I. INTRODUCTION

Every kind of work performed by a man, especially related to mining industry, is associated with symptoms of fatigue. It is obvious that the greater fatigue is, the less efficient of the work is noticed, and it may, eventually, lead to an accident. For this reason, it is extremely important to monitor the weariness level of a hard working persons. The current control systems allow for a flexibility in work management by transient moving of the person from the workplace of excessive tiredness. For this kind of control, a wireless measurement platform has been proposed for an on-the-fly fatigue monitoring and sending reports to a database handled by a skilled work manager. A person's weariness can be determined in terms of two basic health-related parameters; (1) the pulse and (2) the haemoglobin oxygen saturation (SpO_2). Respective sensors for measuring both parameters are therefore crucial elements of the platform. Any information gathered by the sensor is sent wirelessly using the ZigBee standard based on the IEEE 802.15.4 specification [1] directly to WLAN concentrators [2], [3]. An example of the wireless sensor network, designed for the health care is shown i.e. in [4].

These sensors together with ZigBee radio modules form a so called *biosensor*. The concept of a biosensor measuring a miner's fatigue-related parameters and sending them to the database via a teleinformation network has been presented in Fig. 1.

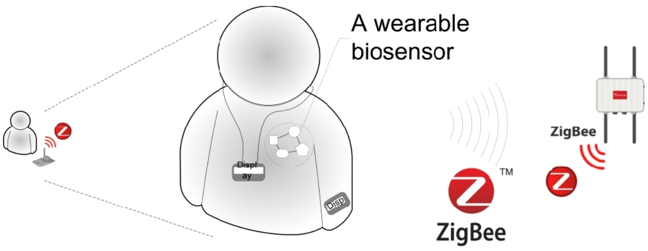

Fig. 1. A concept of the biosensor sending a miner's health-related parameters to the database via a wireless communication system.

II. NOVELTY ITEMS IN PRESENTED INVESTIGATIONS

As will be extended later, a product innovation in the present report is based on:

– Creating a complex system for tiredness monitoring, employing various energy-optimized radio techniques and associated frequency bands, efficient database and fatigue-processing 3-level emergency algorithms;

– Developing a novel integrated device combining features of surface measurement of the saturation and heart rate (HR) and communication facilities with a radio module based on ZigBee technology (Fig. 6(a)), which, as contrary to traditional devices (Fig. 6(b)), does not cause any inconvenience during miner's work, as it can be easily attached to the forearm or tibia.

III. HUMAN FATIGUE MEASUREMENT

Physiological fatigue, despite its multifactorial nature, appears to be relatively easily determined by registering of such well-measurable parameters as the pulse and the haemoglobin oxidation level (SpO_2). These quantities turn out to be the best factors corresponding to the subjective feeling of fatigue. In the course of present studies, it was found out that beside SpO_2 and HR, another variable is the age. Hence, intensive medical examinations were carried out to identify ranges of HR values with respect to the age and

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saturation (SpO_2). Individual organisms' response was then reported in terms of one of three possible tiredness stages, marked by emergency colours: green (rested), yellow (first sings of tiredness) and red (tired). Tables of HR values (vs. age and saturation) can then be used by the Early-Warning algorithm (denoted by EWA in Fig. 2).

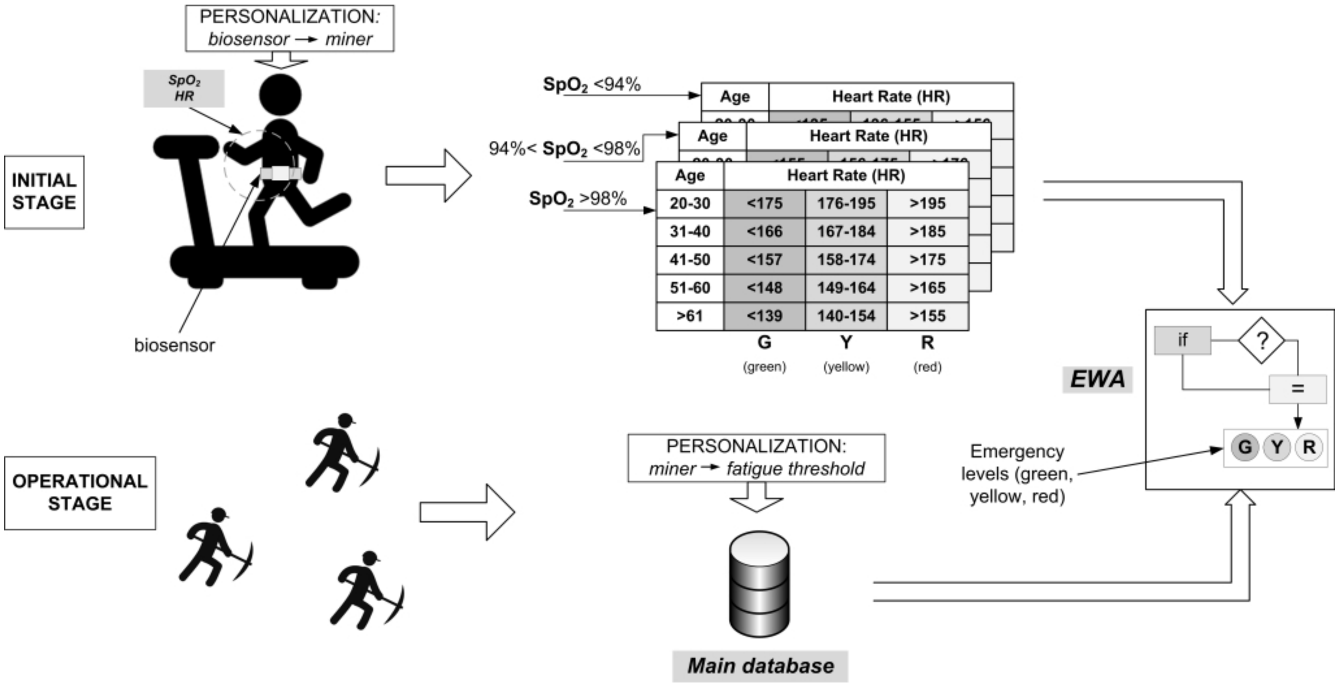


Fig. 2. Tiredness measurement procedure (Initial Stage) and the monitoring system at work (Operational Stage).

These complete tables, translating ranges of HR values, can be used as a reference for determining different fatigue levels of miners. These readings are going to be continuously processed by EWA and in case of a given miner's threshold HR (considering his age and reported saturation) being exceeded, his ID is displayed along with appropriate emergency colour, either yellow or red. Lastly, for the procedure to be successful, each miner has his biosensor linked in the database to his ID (name) which, in turn, is linked with his age and hence his personal HR range.

IV. A Wireless Data Transmission Platform

The wireless platform consists of three components: (1) the access/local, (2) the distribution and (3) the data acquisition/storage segment. Moreover, the system can be connected to the existing mine network infrastructure which facilitates an integration of the distribution segment (2) with an on-the-ground system for monitoring and management. Each segment will now be explained in detail.

A. *The Access Segment*

The main task of the access segment is to transmit information from the biosensors being at each miner's disposal to the local concentrator. The concentrator is fitted with a memory for writing and temporarily storing the biosensor information. Since the typical data volumes are small, even tens of biosensors sending information with the use of ZigBee to the concentrator is not a great deal of load to the WLAN technique which offers useful capacity of around 30 Mb/s (which is the user's effective throughput of the IEEE 802.11a variant [5]). The ZigBee technique used in the access segment enables data transmission in one of the unlicensed ISM bands: 868 MHz or 2.4 GHz. Devices operating the 2.4 GHz are able to transmit at higher data rates (up to 100 kb/s effective throughput) compared to their 868 GHz counterparts, however the former one is exposed to possible interference e.g. arriving from WLAN or Bluetooth appliances. For constructing the network described herein, ZigBee radio modules operating in both bands have been used. An example system topology depicting the two first segments together (i.e. the access and distribution) is shown in Fig. 3.

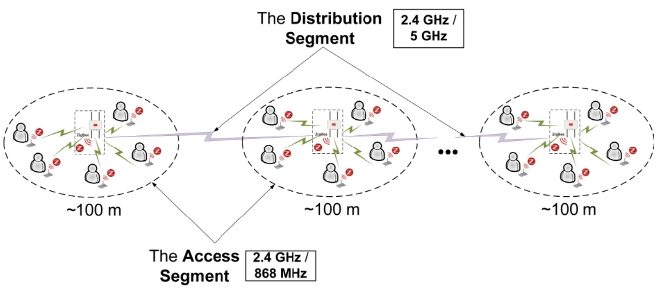


Fig. 3. The Access Segment (or Local) and the Distribution Segment of the teleinformation system for miners' fatigue management.

In order to construct the Access Segment, Libellium's waspmotes have been used – devices equipped with ZigBee radio modules. For these modules measurements have been carried out in a 10-storey building with one module located on the 8th floor while the other was being moved down in steps of one floor each time (a storey height was c.a. 3 m). The outcomes are presented in Fig. 4. As can be seen only the 5-storey difference between devices caused a noticeable decrease in observed data rate. Moreover, the retransmission option (up to 7 retries allowed in IEEE 802.15.4, or 3 our measurements – a default value) enabled during the measurements contributed the transmission quality, particularly under unfavourable bit error rate conditions. For the 6-storey difference communication – regardless the number of retries – was virtually impossible (in which case the signal strength indicator was c.a. -97 dBm).

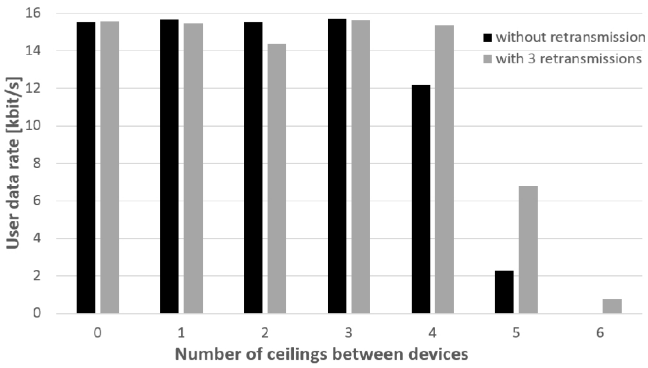


Fig. 4. The measured ZigBee data rates.

B. The Distribution Segment

The segment is composed of WLAN access points (ACs). The devices operate in the chain topology by transferring data in a series toward the edge AP playing a double role in the system, i.e. that of an ordinary concentrator for its own access segment and that of a transit node for passing these data (along with aggregated data collected from APs preceding it in the chain) towards the sink. In practice the number of such transit nodes should be limited up to 5-6 due to an exponential throughput loss with each consecutive hop [6] and a linear delay rise. Both these adverse effects are due to the multi-access CSMA/CA (*Carrier Sense Multiple Access/Collision Detection*) procedure. In order to meet this dual-system requirement, the devices have WLAN interfaces enabled for 2.4 GHz and 5 GHz bands (to work as transit nodes in chain topology). Apart from this functionality they also employ ZigBee modems for collecting data from sensors in their own access segments. The APs use the IEEE 802.11a standard and the OLSR protocol.

C. The Acquisition/Storage Segment

The segment basically consists of a large-capacity redundant database. The redundancy has been obtained by the physical multiplication of mass storage disks. In addition to that they have been located in different sites for data protection against, so called, SPOF effect (Single Point of Failure), or put simply – the risk of the system collapse if one and only storage component fails. To avoid this, data is saved at several physical locations simultaneously. The database contains a list of employees along with basic information enabling the sensor personalization (age, weight etc.). The data will be analysed e.g. during regular medical examination, since the measurement device is intended to be personalized i.e. permanently assigned to a person, that also allows uploading individually defined threshold levels for the physiological parameters obtained e.g. during periodic fatigue examinations. These levels constitute input information for the algorithms detecting when the save values have been exceeded and how to react to that.

V. THE BIOSENSOR – A MEASUREMENT PLATFORM

A. A Personal Transmission Platform

A test biosensor version has been released on the Waspomote platform from Libellium. The platform is equipped with ATmega1281 microcontroller operating at 14.7456 MHz, with 8 kB SRAM, 4 kB EEPROM and 128 kB FLASH. It has a built-in temperature sensor (for measuring the chipset temperature) and an accelerometer. Moreover, it has a series of expansions enhancing its functionalities. The manufacturer has exposed the microcontroller ports (the Sensor IO connection) to facilitate addition of new sensors, the use of an ADC transducer etc. It is noteworthy that the platform can easily scale to any wireless technology due to attachable radio modules. In addition, the producer appends the devices with its own API for controlling them in a basic manner. In the course of work however, the set of manufacturer’s instructions turned out to be insufficient and it became necessary to create some functions from scratch. One of such novelties included scripts enabling bi-directional communication between the biosensor and the concentrator. The script operation can be divided into a few stages:

– the platform initialization stage – begins with the start of the real time clock (RTC) and the radio module,

– a network attachment stage – the biosensor switches on encrypting (a 128-bit AES), performs the band scanning and synchronizes its internal RTC clock,

– a continuous operation stage – since the RTC clock setup, the biosensor reads parameters logged by attached sensors in pre-defined time intervals and sends them to the concentrator.

B. A Pulsoxymeter

A basic detector of the biosensor is the pulsoxymeter. It is a sensor for measuring the pulse and the haemoglobin saturation with oxygen. Pulsoxymeters are widely used in medicine with patients afflicted by respiratory disorders, in neonatology and intensive care wards. The use of this type of sensors with miners is aimed at determining – based on the measured parameters – the fatigue level as well as detecting sudden events related to the circulatory system, such as the heart attack.

Pulsoxymeters are non-invasive sensors usually coming in the form of a clip put on the finger or on the earlobe. Such a location is optimal due to sufficient blood supply which is an indispensable condition for a correct blood oxidation measurement. The operational principle consists in passing red and infrared light through the tissue and measuring the ratio of light absorption depending on the photodiode wavelength. The light emitting element and the receiving element are located opposite each other with the measured tissue in between. They may also be located next to each other on the same side of the tissue. The first case is referred to as a ‘transmission sensor’ for measuring the light passing thru the tissue, whereas in the other case the measured quantity is the amount of reflected light. The blood oxygenation level measurement is possible due to the fact that the oxygenated haemoglobin absorbs more infrared light and less so red light, whereas the deoxidized haemoglobin behaves in an opposite manner. The red and the infrared diodes are lit in turns with a precisely tuned supply current. It is no less important that the current flowing thru the diodes have the least possible noise within the measurement spectrum as it may affect the measurement accuracy and even make it impossible with persons having a very weak pulse. Both the measurement frequency (typically below 10 kHz) and the measuring impulse width, are usually small, which allows to limit the sensor current consumption. Between measurements, when no diode glows, the ambient light intensity is measured in order to compensate its value in the red/infrared light absorption measurements. The part of the light unabsorbed by the blood along with the ambient light, are received by the photodiode generating an electric current converted to voltage by the operational amplifier transimpedance circuit. At this stage it is necessary to remove the component derived from the ambient light, which magnitude is usually much greater than that of the components originated at the diodes. The voltage on the operational amplifier circuit is measured by means of an ADC transducer and transferred a microcontroller that computes the ratio of the oxidized to deoxidized blood, or put simply, the blood oxidation. The pulse is determined as the peak voltage detected on one (any) of the diodes. It is also possible to determine some finer features such as the blood pressure impulse width (indicative of the heart beat strength), which however requires some extra signal processing in the microcontroller. A general concept used in the biosensor is shown in Fig. 5.

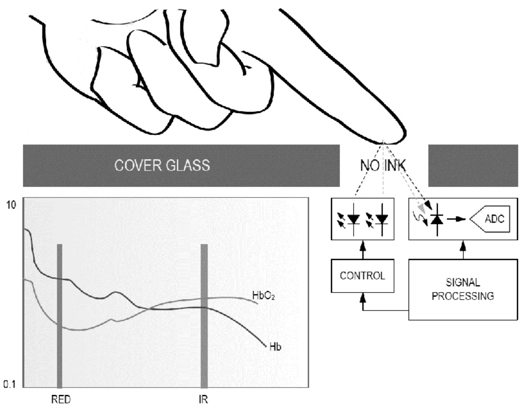
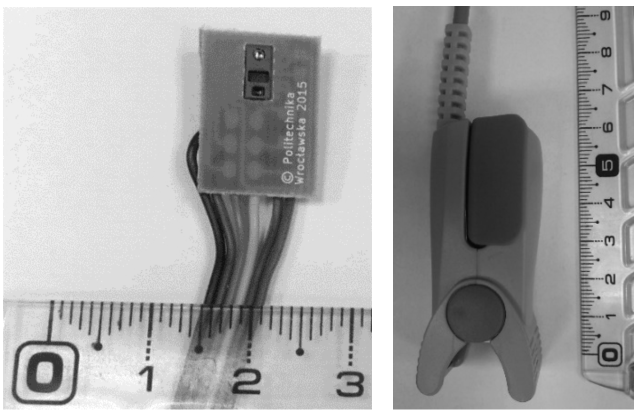


Fig. 5. A general concept of the pulsoxymeter operation (source: http://www.maximintegrated.com/).



a) b)

Fig. 6. A prototype of the pulse sensor based on the MAX3010x integrated circuit (a); a typical on—finger pulse sensor (b).

Pulsoxymeters are usually made in the form of a clip, which solution however turns out to be a major drawback as it cannot be applied in the target underground mine environments. For this reason, it was necessary to design an alternative construction of the measuring setup, making ergonomics and miniaturization to be top priorities. An alternative solution, however, requires a large current consumption, is shown in [7]. A solution meeting these requirements is the MAX3010x integrated circuit from Maxim Integrated, which comes in to available variants, namely the older MAX30100 and the newer MAX30101. The pulsoxymeter built based on this circuit is shown in Fig. 6 (a).

With the use of this circuit it is possible to design a circuit in the form of a flat board to be placed on the bottom finger side, which is a solution far less disturbing in performing normal tasks by a person whose health-related parameters are being measured. MAX3010x has all elements necessary to measure the saturation and pulse, i.e. the diodes, the photodetector and the analog processing circuitry, all integrated in a single unit 5.6 mm × 2.8 mm × 1.2 mm of size.

The pulsoxymeter block diagram is shown in Fig. 7. It was built on the basis of the Waspmote microprocessor platform fitted with the SpO_2 sensor. The sensor circuit communicates with the measurement platform via the I^2C bus which is used for the circuit configuration (the measurement frequency, the diode up-time, the diode current etc.) and data readout. Since the sensor circuit requires two supply voltages (3.3 V and 1.8 V), it was necessary to design an additional 1.8 V supply. Approximate amounts of energy consumed by particular components of the device are: 2.21 mAh for the SpO_2 sensor, 0.96 mAh for the Waspmote platform, 8.34 mAh for the radio module. Hence, the pulsoxymeter total energy consumption reaches c.a. 11.51 mAh which allows for 24 days of unceasing operation with an accumulator of 6600 mAh capacity, assuming the radio module always on and 87 days with the radio module off.

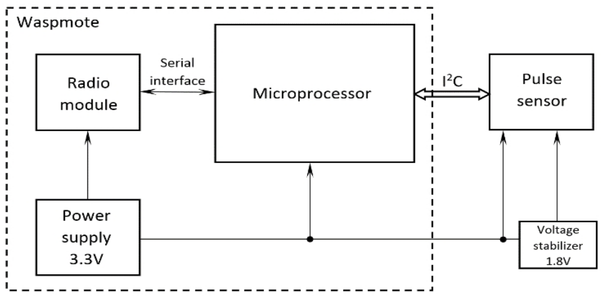


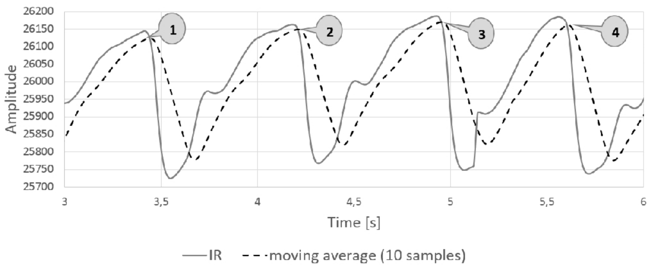
Fig. 7. The pulsoxymeter block diagram based on the Waspomote platform and the MAX3010x circuit.

In Fig. 8 the photodetector current flow is presented during the use of the infrared diode (IR). The measurement was performed with a 15-bit resolution, using the analog-to-digital converter built in the MAX30101 circuit. The sampling frequency was set at 800 Hz. Such a fine probing allows an expert in cardiology to determine some of the more advanced heart-related features. However, for the sole purpose of tiredness measurement it suffices to precisely discover the reported heart beats frequency (four of which have been demonstrated in Fig. 8).

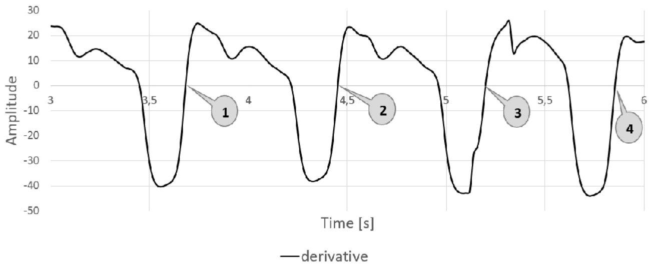
One of the peak detection methods consists in calculating a signal derivative and tracking the sign change. A necessary condition for a correct pulse measurement is to make sure that the monotonicity change in the registered signal is synchronized with heartbeats. To fulfil this requirement the registered voltage had to be averaged for removal of local monotonicity variations between heartbeats. For this purpose the sliding-window average was used with a 10-sample long window selected experimentally. Based on the averaged voltage (dashed line in Fig. 8(a)), its derivative was computed (Fig. 8(b)) which then was used by the microcontroller as grounds for an easy determination of the derivative zero-crossing moments which, in turn, correspond to the pulse.

The saturation (SpO_2) measurement is performed based on signals received by a photodetector, arriving from both diodes: the red (R) and the infrared (IR) one. For both signals it is necessary to find to minimum and maximum values in a certain period. Based on these readings, the R ratio is calculated according to the formula (1)

$$R = \frac{\left(I_{\max R} - I_{\min R}\right) / \left(I_{\max R} + I_{\min R}\right)}{\left(I_{\max IR} - I_{\min IR}\right) / \left(I_{\max IR} + I_{\min IR}\right)}. \quad (1)$$



a)



b)

Fig. 8. The photodetector voltage: normal and averaged (a); The averaged voltage derivative (b).

The R ratio is then used directly to find the blood oxidation level (the saturation). It has been determined that for R = 0.4, the saturation approaches 100 % whereas for R = 2 it linearly drops to 60 %. Based on this finding, the authors have accepted an empirical relationship between the saturation and the R ratio (approved by the medical society)

$$SpO_2[\%] = 110 - 25R. \quad (2)$$

VI. CONCLUSIONS

The physiological fatigue, despite its multifactorial nature, appears to be relatively easy determined by such well-measurable parameters as the pulse and the haemoglobin oxidation level (SpO_2). These factors turn out to be the most representative elements enabling monitoring of fatigue and might help in work management. On the other hand, this information may be useful in prevention of accidents, which result in many subsequent troubles in mining industry companies.

This observation was the main reason for undertaking this project venture expected to result in the creation of a telemetric system for fatigue management, consisting of three basic structural elements. The first, defined in the miner’s direct proximity, consists of a group of fatigue-related detectors integrated in a single measurement module, so called a biosensor. This module, connected with a personal transmitter using the ZigBee standard, forms the access component of the resultant telemetry network. The network consisting of multiple WLAN-based hops for conveying transit data from all access segments (or teams of miners associated with their WLAN concentrators) forms the distribution segment. The third element consists of the storage, prediction, management and reaction system for a quick response to even early symptoms of imminent weariness for each miner individually, in a short- (e.g. a sudden collapse) or a long-period manner.

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