Low-Power WSN System for Honey Bee Monitoring

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***Abstract*—The paper presents a universal low-power system for biosensory data acquisition in scope of bees monitoring. We describe the architecture of the system, energy-saving components as well as we discuss the selection of used sensors. The work focuses on energy optimization in a scope of wireless communication. A custom protocol was implemented, which is the basis for presented energy-efficient devices. Data exchange process during network initialization and measurement collection was presented. The core principles are devices synchronization and parallel clocks. Devices wake up in their time slot in order to exchange data. For the energy consumption tests, Keysight N6705B power analyzer was used to draw accurate current intake characteristic. The most demanding operations in terms of power consumption were communication and microphone recordings. The performance of devices in case of non-optimized operation, i.e. when optimization techniques are switched off, was compared. It has been shown that devices equipped with 2200 mAh battery can operate continuously for 2 years and 7 months, which gives 3600% increase in operating days compared to the non-optimized case.**

***Index Terms*—bees monitoring, wireless sensors network, precision apiculture, smart IoT, wireless communication protocols**

I. Introduction

The network of connected devices has become a major part of modern living. Wireless sensor networks are widely used in industry [18], [27], smart cities [7], wearable devices. They make it possible to measure and analyze key signals for observed objects or phenomena. Basing on values one can take proper actions [11] and maximize profits. Agricultural economy can also benefit from the *Internet of Things* (IoT) infrastructure. Appropriate measurements and analysis of e.g. plant growth or animal behaviour can provide production gains or protection against the losses. One can observe a growing interest in beekeeping due to the advantageous contribution to agriculture. Also, an increasing number of threats that bees have to face with [4] enhances willingness of developing systems that help to identify and prevent against these threats. *Wireless Network Sensors* (WSN) are designed for completing such tasks, however, imposing some limitations.

In our research, we aim to develop energy-efficient system collecting data from beekeeping apiaries. The phenomenon called *Colony Collapse Disorder* (CCD) has been widely described and studied for years. There are many issues connected with the intensification of a sudden bees population drop which is a symptom of CCD. In order to investigate and prevent CCD, there is a need to develop a beehive monitoring system. It should be equipped with sensors whose measurements would be valuable for adverse phenomena detection. Apiaries are often located in places where it is impossible to supply external power sources. There is also a lack of access to WiFi network, which reinforces the problem. It is crucial to develop a solution that could monitor beekeeping apiaries in an uninterrupted, long period of time, therefore a need arises for using energy-saving solutions and protocols.

Our approach employs a star topology network system which implements custom wireless data exchange protocol. We study various quantities and present the motivation for their use. Suitable sensors have been selected in order to minimize the costs and maximize the ease of use. We present the structure of communication frames and the algorithm for their exchange. We obtained a year's long devices operation by implementing presented algorithm extended with device's sleep modes. Energy consumption characteristics have also been recorded and results were presented.

There are several commercial systems for bees monitoring. The most developed is BuzzBox from OsBeeHives company [19]. It is a battery-powered WiFi device that monitors, i. e. sound, humidity and temperature in the hive. Authors declare the ability to classify bee family for queen presence and diseases. OsBeeHives along with NU-Hive project have developed an open source sound dataset for bee colonies classification [8]. Next commercial system, Arnia is the system focused on remote beehive monitoring [1]. System includes a hive scale and sensors for hive humidity, brood temperature and colony acoustics. It does not require WiFi access and provides a client panel where one can browse the data. Authors declare protection against theft and vandalism.

II. Materials and method

The core principle of the presented system was to maximize the number of measured signals at the lowest possible energy costs. One of the main assumptions of the described system is its modularity in order to facilitate system adaptation to other domains where biosensory data acquisition is used. However, the objective for presented study is to collect the physical quantities important for the bee family so architecture should be adjusted for apiary-specific requirements. Measuring device dimensions cannot be too big due to the installation inconvenience. Such requirements enforces the use of a additional device for collecting and uploading the data. Based on discussions with beekeepers average medium-size apiary area is up to $1600\,\mathrm{m}^2$. Distance from collector to the measuring device should be at least $30\,\mathrm{m}$. Radio transmitter has to be insensitive for the nearby flora presence. The authors' interests is swarming phenoma [26] which is slow-changing processes so the frequency of data upload was set to one package per hour. Having such requirements in mind we extended our platform with energy-saving concepts which led to use of particular architecture. System should be able to upload measured signals on a remote server where more sophisticated analysis takes place. There are systems which are designed to work offline [15]. However, presented solution is designed to analyze data from hundreds of hives. It is not possible to visit each hive individually and retrieve the data.

A. Devices overview

Aiming to reduce energy consumption, a master slave architecture with a star topology was proposed with a block model.

In this approach only one device within the network is equipped with a GSM module connecting to the Internet. Master devices, also referred to as access points are based on STM32F4 chip, while slave devices (endpoints) use STM32L0 microcontroller. Access point uploads data from multiple endpoints during a single connection. Server communication was implemented with a single TCP socket. Choosing WebSocket connection over HTTP and REST endpoints is presented as preferable for IoT devices [21]. Such method eliminates additional layers and data overload, resulting in reduced communication time and energy consumption. Choosing master-slave architecture also reduces overall system costs where GSM module is the most expensive component. Due to limited optimization possibilities, subject of reducing energy costs for GSM data uploading will not be discussed.

Slave devices communicate with master via radio modules. Network's internal communication has a higher optimization potential due to the possibility of implementing proprietary communication protocols. Such methods will be described in section II-B1. Before entering a sleep mode, the processor switches off all sensors in order to eliminate power leakages and minimize power consumption. In order to successfully monitor the condition of bee colonies, it is necessary to specify the relevant quantities.

Temperature is one of the most important factors characterizing bees behaviour [2], [3]. Work presented in [13] refers to temperature as relevant for young bees development which in turn are crucial for prolonging the colony's life. Authors have shown that slight variations in temperature during pupal development have an effect on short-time learning and memory abilities. Furthermore, capped brood exposure to $20\,^{\circ}\mathrm{C}$ for a few hours results in higher mortality [25] which proves the relevance of temperature monitoring.*Humidity* is also a factor associated with the colony development. Colonies which are not well ventilated in high humidity environments are exposed to various diseases and threats [14], [16]. Presented system is equipped with TH02 sensor for temperature and humidity monitoring. Sensor's advantages include good accuracy, low price and small dimensions. Temperature measurement accuracy level is $0.5\,^{\circ}\mathrm{C}$ for the range from $-40\,^{\circ}\mathrm{C}$ to $85\,^{\circ}\mathrm{C}$ and relative humidity measurement accuracy is up to 4.5%.

Weight can be a source of information about honey growth, which indicates the strength of bee colony. The most commonly used sensors in weight measurement are strain gauges which change their resistance under pressure. Due to high prices of strain gauge beams it was decided to implement mini strain gauge beams used in bathroom scales. The difference is that mini strain consists of single components which have to be connected into a bridge circuit. Mini strain gauge beams and a dedicated HX711 electronic module were used for weight measurement. Such setup enables measurement of up to 120 kg with frequency up to 80 Hz.

Sound is the most valuable source of information for monitoring beehives. There are many kinds of sounds emitted by bees. Researchers try to analyze and link specific behaviours to particular sounds [17]. Work presented in [22] reveals the correlation between hive's sound combined with humidity, temperature and the queen bee presence. More newly discovered sound features are extracted from the sound and classified for the presence of different phenomena. Machine learning tools are used for this purpose [9]. The system is equipped with an electret microphone. In order to increase signal magnitude, a dedicated amplifier circuit has been used to amplify the signal with the possibility of amplification adjustment.

Additional sensors such as sunlight, rainfall detection or CO_2 concentration can be also used in the presented system. However, due to the system's energy-saving assumptions, they were excluded from this study. For example, CO_2 sensor could provide relevant information, but has long stabilization time, which excludes its use for long term monitoring.

B. Wireless Communication

Endpoint device is equipped with sensors described in section II-A. In order to transmit measured signals to the master it is necessary to use a wired or wireless communication. A wired solution is inconvenient and often impossible to implement. Beekeeping apiaries are placed in poorly accessible places and external cables can be damaged by wild animals. Described system uses wireless communication. The *WSNs* has the advantages of simple installation and modularity, but imposes increased energy use. This problem will be minimized with presented solution.

There are many options for wireless communication in today's top embedded systems. Very often prefabricated low-energy solutions like ZigBee based module - Core2530 allow for quick implementation, however, imposing certain limitations [6]. Various modules have a disadvantage of high power consumption. Such situation gives rise to a need for creating a custom solution. Implementation of a domain solution specialized for a problem will allow to achieve better energy-saving results [24]. Obsolete protocol specific bytes exclusion will allow to reduce the amount of transmitted data and provide minimum energy consumption.

Presented system was equipped with *nRF905* modules allowing custom communication protocol implementation and providing the acceptable energy savings. Price was also motivation for selecting presented module. Real time monitoring will require many devices, which excludes the use of expensive wireless solutions. Used module is based on the nRF905 chip which is a transceiver operating within 433, 868 or 915 MHz bands. Module is supplied with SPI interface and GPIO pins allowing for device configuration. The maximum transmitting power is 10 dBm. Device consumes up to $30\,\mathrm{mA}$ during transmission and up to $12.5\,\mathrm{mA}$ during reception. In a sleep mode current intake is about $2.5\,\mu\mathrm{A}$.

Access point aggregates data from endpoints with use of *nRF905* modules. In order to optimize energy consumption, the system utilizes an individual communication protocol. The network architecture implements star topology where all measuring devices have to be placed within the access point communication range. The protocol allows two-way communication between the access point and other measuring devices - endpoints.

1) Wireless communication algorithm: Presented protocol is based on 32-byte packets transmitted at 433 MHz with 10 dBm power. In order to achieve the lowest possible energy consumption, it is crucial to minimize device's connection time. Limited energy power and system energy requirements do not allow for continuous operation. Device's running time is related to the transmission and response-ready time. Moving forward, frame transmission time is closely related to the amount of transmitted data and bandwidth. Regarding above, following shall apply: to keep wireless modules running short, device must be able to determine when the other device intends to send a frame to it. Core principle will be a constant period of communication where all the devices transfer their data within device-specific time slots. Frames overlapping is avoided by different time slots for different endpoints which in turn are based on unique service number. Receiver knows when it should expect the data and is able to turn on and off the wireless module when needed. Two algorithms will be described below: network startup and standard operation mode.

2) Network startup: When power is turned on, all endpoints switch on receivers and wait for the synchronization frame. The synchronization frame contains information about current time and network startup. Access point starts constructing network by obtaining configuration from remote server. Such data includes unique endpoint's service numbers which should appear within access point's network. When the access point is ready, it starts to transmit the synchronization frame every second and waits for the responses to come. Endpoints which have received the synchronization frame respond with the confirmation frame within proper time slot and immediately switch off the receiver module. Having such, access point has the information about devices which are ready for corporation. A delay occurring while sending an acknowledgement by endpoint devices is calculated based on a formula

$$T_{ack} = 100 * (sn \mod 100) \tag{1}$$

where T_{ack} is the offset in milliseconds from synchronization frame reception time and sn is the unique service number of corresponding endpoint. The use of such delay prevents the different devices responses from overlapping. The access point keeps sending synchronization frames until a confirmation is received from all assigned devices or when the network start time is elapsed. Such offset, when network has to be started, is defined on a remote server by the user and downloaded by access point with configuration package.

3) Network operation: Within the network effective operation, data exchange between the access point and endpoints takes place over user defined period of time. Communication is divided into $N + 1$ time slots where N is the number of endpoints within the network. The first slot is a synchronization where access point transmits a frame in order to synchronize access point and endpoint internal clocks. Each of devices replies to acknowledge receipt of synchronization. Such procedure do not differ from the synchronization process described section II-B2 except different time magnitude offsets were used. The use of the same synchronization process in both communication and network startup makes possible to connect new devices during effective operation without a need of restarting the entire network. Devices might discriminate due to the external quartz vibration leakage. The accuracy of the vibrations can be affected by both the temperature and the unsuitable capacitors adjustment. A 0.5s time advance is used in order to avoid a situation where the access point sends a synchronizing frame before the endpoint wake-up and turning receiver on.

The endpoint switches on the receiver in its time slots and waits for the access point's frames. In this case receiver module switch-on advance is much smaller and set to 15 ms because of recently performed synchronization. Now, access point decides which frame should be send. If the device has not been configured yet, only the configuration frame is sent which contains information about the sensors to be operated and the periods with which they are to be read. If the device is already configured, the access point sends a command for reading the data. Such frame contains flags corresponding to the measurements which should be read, special counter and the corresponding endpoint's service number. Endpoint responds with a frame containing its service number, a counter and the part of the data. After sending all frames, communication finalizes. If the device needs to be reconfigured, a configuration frame will be transmitted at the end.

III. Results

In order to analyze the efficiency of presented system the Keysight N6705B power analyzer was used. Device allows to measure voltage and current consumed by the *WSN* devices with a minimum level of 8 nA for ammeter and $50\,\mu\mathrm{V}$ for voltmeter (with 0.025% accuracy). The power analyzer test

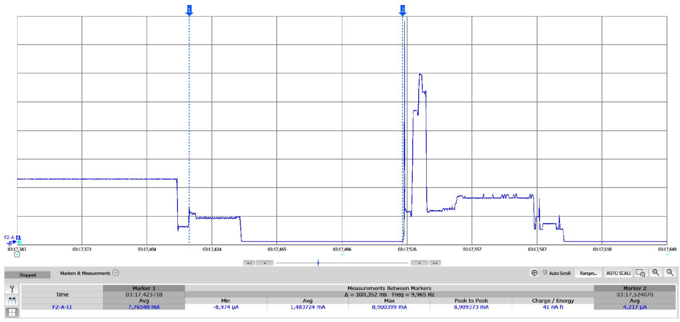

Fig. 1. Power consumption characteristic while receiving, processing and sending response to the synchronization frame.

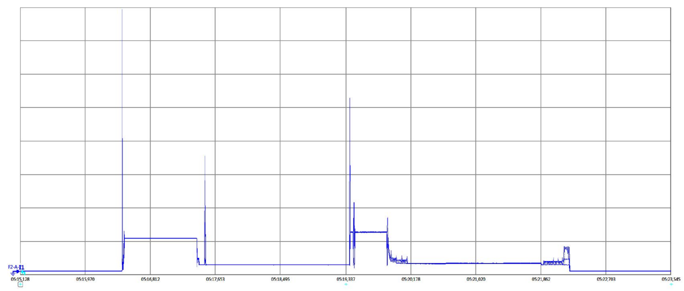

Fig. 2. Power consumption while receiving and processing the synchronization frame.

provides information about the execution path of communication algorithm and overall device's energy demands. In presented work we will focus not only on the quantity of consumed energy but also on its characteristic. The analyzer was equipped with an N67 module designed for low-power measurements and battery-powered devices. *Keysight* device was attached to one of the endpoints, set up with logging mode and sampling frequency set to 10 kHz. To assess the measuring device's energy demands, endpoint should work with at least one access point. Having such, network consisting of two measuring devices and one access point was configured. The endpoints were equipped with TH02 temperature/humidity sensor and microphone. Data collection period for TH02 sensor was set to 2 minutes and 10 minutes for the microphone. Network operation was configured as follows: the *WSN* internal communication period was set to 15 minutes while the communication interval for remote server and access point was 90 minutes.

During the tests, one hour of endpoint operation was logged and saved. Data has been divided into two separate sets which are: device initialization and regular work. Energy consumption levels and characteristic were measured and conclusions regarding the observed energy levels have been drawn.

A. Network start up

Device initialization is the most critical part for the energy consumption. In proposed system endpoint's radio receiver is turned on until the access point recognizes device by sending synchronization frame and receiving the confirmation. Figure 1 presents endpoint's power characteristic for that process.

At the beginning device is put into listening mode, waiting for the synchronizing frame to come. During that time communication module is turned on and average current consumption is set at $12.88\,\mathrm{mA}$. Drop around $3\,\mathrm{min}$ and $17.410\,\mathrm{s}$ indicates the end of frame reception. After that a communication module is turned off. First blue marker points to the moment where processor handles received data. Average current consumption level starts with $7.76\,\mathrm{mA}$ and remains around $5\,\mathrm{mA}$. When synchronization frame processing ends, device is put into a sleep mode where all peripherals are turned off. During this time device consumes only $5.2\,\mu\mathrm{A}$ which is only $0.55\,\mu\mathrm{A}$ higher than reference value for STM32L0 microprocessor presented in *Low power sleep mode*. Due to the device's additional components such as keying transistors and sensors the incremental growth has occurred.

The analyzed endpoint was assigned to the 4402001 service number and according to formula 1 after 100 ms the processor should be woken up to transmit a confirmation frame. Second marker points to the subsequent current consumption increase, where microprocessor wakes up, turns on communication module, builds a confirmation frame and transmits the data. Process starts with short peak at the level of $40\,\mathrm{mA}$ which is related to the processor awakening. Next consumption parabolic curve with the highest peak at $30\,\mathrm{mA}$ describes communication module powering on and initialization. Flat characteristic around the level of $8\,\mathrm{mA}$ indicates the frame transmission. At the end communication module is turned off and processor is put into sleep mode again.

Two minutes after receiving the synchronization frame the configuration exchange stage should take place. Figure 2 presents communication characteristic.

At around $5\,\mathrm{min}$ and $16.520\,\mathrm{s}$ endpoint turns on the communication module. Receives the synchronizing frame and within proper time slot sends back the confirmation for synchronization frame. After two seconds, communication module is switched on because of configuration data-exchange time slot occurrence. Few milliseconds later endpoint receives a configuration frame. Only in the next communication time slot if all devices within the network have been configured, network will switch to the 15-minute target period. At this point, the network will be configured as regular operation mode. Data transmission periods will be significantly longer due to the fact that endpoints have been able to collect first measurements and obtain some data. Results of data exchange process will be described in section III-B.

Regarding the study above, following conclusions can be drawn. The most power demanding process during network start up is the stage of first synchronizing frame listening. Device consumes $15.88\,\mu\mathrm{A}$ on average. This is much more in comparison with the second stage, where communication is already synchronized and reception/transmission can take place in short time intervals. In analyzed scenario network start up was successful so only 4.5 minutes after receiving the first frame network was configured and switched to normal operation mode. The average current of the second stage was $448.88\,\mu\mathrm{A}$. Whole network start-up process lasted 7.5 minutes and costed $899.38\,\mu\mathrm{Ah}$ in total. One should notice that there

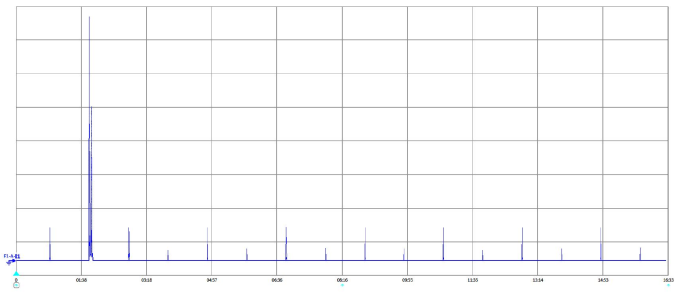

Fig. 3. Power consumption characteristic at regular endpoint operation.

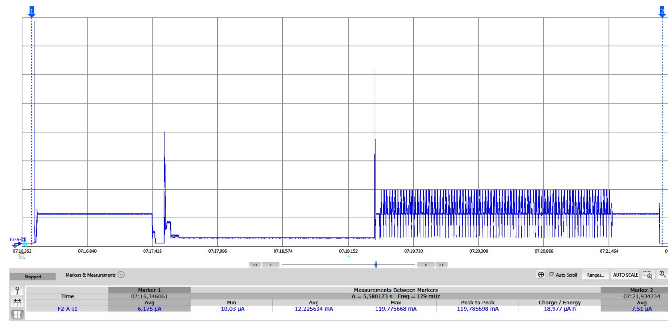

Fig. 4. Power consumption characteristic of a wireless data exchange communication between endpoint and access point.

is a hazard of an access point error occurrence in a case where synchronization frame is never transmitted. According to the algorithm all endpoint devices every half hour would turn on the receivers for 15 minutes and endpoint would discharge entire energy reserve very quickly.

B. Network operation

After successful network initialization devices are ready to operate and collect measurements. Figure 3 presents power intake characteristic of an endpoint at regular operation. Based on values contained in configuration frame described in section III-A intervals of two operations were set: atmospheric and sound measurements. Every minute one can see the periodic, varying peak current intake which indicates various types of operations. The lowest amplitudes are associated with cyclical CPU awakening only for updating firmware-specific runtime structures. Mid-amplitudes amplitudes are bound to the wake up and TH02 sensor operation. This process lasts almost $200\,\mathrm{ms}$ and can be divided into three stages: initialization, temperature measurement and humidity measurement. The overall energy cost of such process is $235\,\mathrm{nAh}$. The third type of excitation presented in Figure 3 is a TH02 measurement extended with acoustic signal recording. Such process lasts $857\,\mathrm{ms}$. In addition there is a stage of storing microphone's sampling data in external memory. The total energy cost is $1.07\,\mu\mathrm{Ah}$.

The most power demanding process is the wireless communication. Figure 4 presents detailed communication process between endpoint and access point. According to the algorithm, both synchronization and data exchange sub process should take place. Data exchange is the longest one which takes $5.59\,\mathrm{s}$ and depends on the amount of collected measurements. Characteristic presented on 4 illustrates both microphone recording and measurements transmission. Data frame containing this information was sent to the access point, which gave a total 2268 bytes of data for which 81 frames are needed. The whole process consumes $18.977\,\mu\mathrm{Ah}$.

IV. Discussion and conclusions

Using the collected data it is possible to calculate current intakes. Table I presents all types of device operation with energy cost and number of occurrences within one the hour. By collating type of measurements with assumed frequency of their occurrences one can calculate total demands for a single measure type. These calculations are true assuming that communication periods and sensor readings do not change over time and other sensors will not be connected to the working system. Temperature influence is ignored. According to the presented metering, device uses $94.68\,\mu\mathrm{Ah}$ during one hour of operation, which gives $2.272\,\mathrm{mAh}$ per day. Within one year of operation device consumes $829.397\,\mathrm{mAh}$. Using $2200\,\mathrm{mAh}$ batteries device can continuously workup to 2 years and 7 months.

TABLE I
Summary of measurements taken for the measuring instrument.

Stage	Avg. current intake	Count per hour	Cost
Network startup	$428.45\,\mu\mathrm{A}$	-	$428.45\,\mu\mathrm{Ah}$
Operation (NOP)	$5.2\,\mu\mathrm{A}$	-	$5.2\,\mu\mathrm{Ah}$
RTC Interrupt	2 nA	60	120 nAh
TH02 Measurement	235 nA	30	$7.05\,\mu\mathrm{Ah}$
Audio Measurement	$1.07\,\mu\mathrm{A}$	6	$6.40\,\mu\mathrm{Ah}$
Communication	$18.99\,\mu\mathrm{A}$	4	$75.91\,\mu\mathrm{Ah}$

In order to obtain a reference to the presented results, additional experiments were carried out. Endpoints with the energy optimization switched off were used where processor is never put into a sleep mode. All measurements and power characteristic were obtained while having same configuration and setup devices like in section III. The total energy consumption flow is very close to the characteristic for a device with energy optimization enabled. Difference is that low levels are shifted up by $3.28\,\mathrm{mA}$ because of processor continuous operation. Old wake-up events are now ordinary measurement events and have the same characteristic shifted upwards. Wake-ups associated with every minute RTC interruption do not exist and do not cause increased current consumption. Table II presents comparison between endpoint's optimized mode of operation versus non-optimized mode. Last column contains calculated energy savings.

Switching off the energy optimization discards presented endpoint as a battery powered device. The key to energy efficiency is to attain low power consumption during the idle periods, as shown in Table II. Moreover, operations that require a longer CPU time should be optimized and minimized. Acoustic recordings could be a prominent example. In the presented scenario, audio recording process lasts a few

TABLE II
ENERGY CONSUMPTION COMPARISON FOR DIFFERENT STAGES OF ENDPOINT'S OPERATION.

Stage	Optimized	Without optimization	Savings
Network startup	428.45 µAh	750.31 µAh	57.1%
Operation (NOP)	5.2 µAh	3.27 mAh	99.84%
RTC Interrupt	2 nAh	9 nAh	77%
TH02 Measurement	235 nAh	254 nAh	7.48%
Audio Measurement	1.07 µAh	2.91 µAh	63.33%
Communication	18.99 µAh	29.92 µAh	36.57%

seconds, but the processor is awakened only twice. First, at the beginning to power up the amplifiers and at the end to handle the obtained data. Inter process operations are done with a help of DMA (*Direct Memory Access*), which allows to sample microphone without the processor's concern. Such optimization techniques, including sleep modes, assure up to 36 times longer device work. Instead of 26 days device is able to run for 2 years and 7 months with self-contained power supply.

Our work presents versatile system for biosensory data accqusition in scope of bees monitoring. Presented WSN was implemented with a master-slave architecture in which one device communicates with the server. This method reduces overall costs and extends devices total operating time. Paper describes custom communication protocol focused on measuring devices energy efficiency. Low average current consumption is based on time shifts and accurate wake up of the devices. In this approach it is very important to synchronize the clocks of all devices, which is ensured by the presented communication protocol. At the end, the characteristics of current consumption level have been shown. We used the Keysight N6705B power analyzer to precisely measure the quantity. Wireless communication has been identified as the most power demanding process. Tests have been carried out in order to estimate the total measuring devices operating time, which for a battery of 2200 mAh was 2 years and 7 months. Future work will focus on expanding the system with airflow and vibration sensors. Methods of analyzing audio signals on the built-in device will be developed.

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