Bee colony remote monitoring based on IoT using ESP-NOW protocol

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Information and communication technologies, specifically the Internet of Things (IoT), have been widely used in many agricultural practices, including beekeeping, where the adoption of advanced technologies has an increasing trend. Implementation of precision apiculture methods into beekeeping practice depends on availability and cost-effectiveness of honey bee colony monitoring systems. This study presents a developed bee colony monitoring system based on the IoT concept and using ESP8266 and ESP32 microchips. The monitoring system uses the ESP-NOW protocol for data exchange within the apiary and a GSM (Global System for Mobile communication)/GPRS (General packet radio service) external interface for packet-based communication with a remote server on the Internet. The local sensor network was constructed in a star type logical topology with one central node. The use of ESP-NOW protocol as a communication technology added an advantage of longer communication distance between measurement nodes in comparison to previously used Wi-Fi based approach and faster data exchange. Within the study 5 monitoring devices were used for real-time bee colony monitoring in Latvia. The bee colony monitoring took place from 01.06.2022 till 31.08.2022. Within this study the distance between ESP-NOW enabled devices and power consumption of the monitoring and main nodes were evaluated as well. As a result, it was concluded that ESP-NOW protocol is well suited for the IoT solution development for honeybee colony monitoring. It reduces the time needed to transmit data between nodes (over a large enough distance), therefore ensuring that the measurement nodes operate in an even lower power consumption mode.

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9   **Abstract**

10   Information and communication technologies, specifically the Internet of Things (IoT), have been widely
11   used in many agricultural practices, including beekeeping, where the adoption of advanced technologies
12   has an increasing trend. Implementation of precision apiculture methods into beekeeping practice
13   depends on availability and cost-effectiveness of honey bee colony monitoring systems. This study
14   presents a developed bee colony monitoring system based on the IoT concept and using ESP8266 and
15   ESP32 microchips. The monitoring system uses the ESP-NOW protocol for data exchange within the
16   apiary and a GSM (Global System for Mobile communication)/GPRS (General packet radio service)
17   external interface for packet-based communication with a remote server on the Internet. The local
18   sensor network was constructed in a star type logical topology with one central node. The use of ESP-
19   NOW protocol as a communication technology added an advantage of longer communication distance
20   between measurement nodes in comparison to previously used Wi-Fi based approach and faster data
21   exchange. Within the study 5 monitoring devices were used for real-time bee colony monitoring in
22   Latvia. The bee colony monitoring took place from 01.06.2022 till 31.08.2022. Within this study the
23   distance between ESP-NOW enabled devices and power consumption of the monitoring and main nodes
24   were evaluated as well. As a result, it was concluded that ESP-NOW protocol is well suited for the IoT
25   solution development for honeybee colony monitoring. It reduces the time needed to transmit data
26   between nodes (over a large enough distance), therefore ensuring that the measurement nodes operate
27   in an even lower power consumption mode.

28   **Keywords**: Precision apiculture, wireless sensor networks, Internet of Things, Hiveopolis

29   **Introduction**

30   Monitoring, measuring and controlling systems are rapidly evolving in today's world in almost all aspects
31   of human life. Embedded systems, the Internet of Things (IoT), remote environmental monitoring, and
32   smart home automation are just a few of the applications that have been motivated by the creation of
33   wireless sensor networks (WSN) (Labib et al., 2019). The IoT has lots of potential and offers a wide range
34   of options to be applied in many research areas (Nguyen et al., 2020). The importance of IoT in research
35   has also been emphasized by (Doshi et al., 2019). Beekeeping, a traditional branch of agriculture, is one
36   of the areas where IoT can be successfully applied. The combination of beekeeping and information
37   technologies has led to the development of precision beekeeping (precision apiculture), a sub-branch of
38   precision agriculture, that focuses on an apiary management from the perspective of an individual bee
39   colony, where Information and Communication Technologies (ICT) and IoT plays a crucial role in

40 establishing and granting the possibility to collect bee colony related data in real-time (Zacepins et al.,
41 2015).

42 The aim of this paper is to describe a developed IoT based system for honey bee colony temperature
43 and weight monitoring, which includes five individual monitoring nodes based on ESP8266 microchips
44 and a main node (based around ESP32 microchip) with Wide-Area Network (WAN) interface. The
45 ESP8266 microchips are manufactured by Espressif
46 (https://www.espressif.com/en/products/socs/esp8266). Due to its technical specifications,
47 performance properties, functionality, and low price, the ESP8266 is a good choice for battery operated
48 WSNs and IoT-based systems, suggested also in a study by (Mesquita, 2018). The ESP32
49 (https://www.espressif.com/en/products/socs/esp32) is the successor of ESP8266 and provides more
50 features thus the application range is much wider than that of ESP8266.

51 Various data transmission protocols for IoT are expected to provide acceptable performance, which can
52 be seen from factors such as latency, power usage, transmission capacity, reliability, and security in
53 transmitting data (Glaroudis et al., 2020). Connectivity features and efficient energy usage are the main
54 factors for the future development of IoT technology and selection of the appropriate networking
55 protocol for the specific monitoring task.

56 Many networking protocols are currently available for the development of the IoT systems (Sen et al.,
57 2018). In general IoT communication protocols can be divided into two categories (Al-Sarawi et al.,
58 2017): low power wide area network (LPWAN) protocols (such as Sigfox, LoRa, Cellular network) and
59 short range network protocols like Wi-Fi, Bluetooth, ZigBee and ESP-NOW, to name a few.

60 All of the short range network protocols fall within the scope of local area communication protocols and
61 are suitable for IoT devices that require both point-to-point and point-to-multipoint transmission. From
62 the perspective of IoT devices, factors such as maximum range between two nodes, power usage, data
63 exchange speed, and signal resistance to obstructions are directly related to how good a protocol is
64 (Eridani et al., 2021).

65 Within this research ESP-NOW protocol was selected to enable communication between individual
66 nodes and the main node, forming a wireless sensor network in a star topology.

67 Since our previous work (Zacepins et al., 2020) included the monitoring of bee colonies by using
68 measurement nodes based on a Wi-Fi enabled microchip ESP8266, the main motivation was to reduce
69 the power consumption during data transmission without the need to change the node's hardware
70 configuration. Therefore one of the solutions was to switch to a different communication protocol, like
71 the ESP-NOW, that the same microchip already supports.

72 The ESP-NOW is a communication protocol developed by Espressif (ESP-NOW, 2022). In its essence, the
73 protocol does not require Wi-Fi connectivity to exchange data between devices, therefore does not
74 incorporate the handshake (a relatively time-consuming) process. But it requires device pairing to
75 enable a secure connection in a peer-to-peer manner (ESP-NOW, 2022). This protocol is very fast, but
76 limits the data packet size to be a maximum of 250 bytes (Espressif IOT Team, 2016).

77 Several studies have also investigated the maximum distance between devices connected via ESP-NOW.
78 As reported by (Labib et al., 2021), using the ESP-NOW protocol inside various indoor structures, the
79 maximum distance between sender and receiver is roughly 15 m, whereas the distance between ESP-

80   NOW enabled devices in an outside environment is approximately 90 m, however in a research by (Pasic
81   et al., 2021) the authors stated that it is possible to have a stable communication over a longer distance,
82   around 190 m. This was also supported by (ESP-NOW Two-Way Communication…, 2020) claiming the
83   distance to be around 220 m.

84   This protocol can be applied for different scenarios and in different research areas. For example,
85   (Isnanto et al., 2020) used ESP-NOW protocol to send agricultural soil data. The protocol was also used
86   in a developed data logging system by (Koushik et al., 2021) to record data about agricultural fields. In
87   (Yukhimets et al., 2020), the authors presented an approach based on ESP-NOW communication
88   protocol capable devices for the implementation of distributed automatic control systems. Other
89   applications include a voice communication system (Hoang et al., 2019), wireless synchronization tasks
90   (Zinkevich, 2021), aquaculture (Den Ouden et al., 2022) and a system for air quality monitoring, where
91   ESP-NOW was used in additional communication mode (Van Truong et al., 2021). The devices using ESP-
92   NOW are perfect candidates to form sensor networks, like the mesh network presented by (Labib et al.,
93   2021).

94   Within this study we present the application of ESP-NOW enabled devices to monitor temperature and
95   weight changes of the bee colonies. Bee colony weight monitoring provides one of the most important
96   kinds of data a beekeeper can have about the colonies (Fitzgerald et al., 2015). Temperature
97   measurements of bee colonies have the longest history and nowadays it seems to be the simplest and
98   cheapest way to monitor bee colonies (Zacepins and Karasha, 2013). Temperature is a critical factor in
99   colony health and is actively managed by bees applying heating or cooling to maintain a stable nest
100   temperature (Tautz et al., 2008; Stabentheiner et al. 2010).

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104   **Materials and Methods**

105   *1.   Location description*

106   This research and measurements were carried out at LBTU's (Latvia University of Life Sciences and
107   Technologies) apiary, located at Strazdu iela 1, Jelgava, Latvia (coordinates: 56.6630, 23.7538) starting
108   from 01 of June 2022 till 31 of August 2022.

109   *2.   Apiary description*

110   Five honey bee (*Apis mellifera*) colonies were selected (based on a beekeeper's suggestion) for remote
111   monitoring. Colonies were placed in different types of hives (Latvian design type and polyfoam hives).
112   All hives were put in the same location in an open environment.

113   *3.   Monitoring system*

114   3.1. Measurement nodes

115   All five colonies were equipped with a bee colony monitoring system based on the ESP8266 microchip
116   inspired by the monitoring system developed within the SAMS (Smart Apiculture Management Services)
117   project (Wakjira et al., 2021) and described in detail in (Zacepins et al., 2020). For weight monitoring, a

118 single-point load cell Bosche H30A was used. The accuracy of the load cell and the A/D converter was
119 empirically evaluated in (Kviesis et al., 2020 (a)).

120 Two DS18B20 1-Wire® sensors were used per colony to monitor temperature. One temperature sensor
121 (Dallas DS18B20) was installed inside the hive above the hive body (brood frames) as suggested by
122 (Stalidzans and Berzonis, 2013) and validated by (Cook et al., 2022). The second temperature sensor was
123 placed outside the hive, to monitor the ambient temperature. Each monitoring system was powered by
124 a Li-ion 18650 3.7 V 2000 mAh battery.

125 Data about the bee colony and battery discharge status were collected every 30 minutes and sent to the
126 main node using the ESP-NOW protocol. It should be mentioned that the ESP-NOW protocol is limited to
127 messages up to 250 bytes. The data packet containing all measured parameters, were serialized using
128 Protocol Buffers and was around 50 bytes in size therefore it fits well within the message size limit.

129 The number of individual nodes can be easily extended by simply adding new nodes. ESP-NOW protocol
130 allows connection of up to 20 devices (including 10 encrypted peers) (Espressif IOT Team, 2016), which
131 is still enough, because usually one apiary consists of 20 bee colonies. In case there are more colonies,
132 additional main nodes could be used.

133   3.2. Main node

134 Main node is based on the ESP32 microchip with an additional SIM800L module for the GSM (Global
135 System for Mobile communication) SIM (Subscriber Identity Module) card, which is used for the data
136 transfer to the remote data platform through an MQTT (a lightweight messaging protocol) broker.

137 The ESP32 board used in this study has a dual-core Xtensa® 32-bit LX6 microcontroller with adjustable
138 CPU frequency (80-240MHz) (Espressif Systems, 2022). In our case the operation of the main node
139 utilizes both ESP32 cores. The ESP32 uses a modified version of the original FreeRTOS - a real-time
140 operating system intended to be used in an embedded environment (on microcontrollers and system-
141 on-chip (SoCs) circuits) (https://www.freertos.org/index.html). As it is described in the ESP32
142 documentation (ESP-IDF FreeRTOS (SMP), 2022) the modified version of the FreeRTOS allows the ESP32
143 to use symmetric multiprocessing and therefore run multiple tasks in parallel on both cores. In our case
144 we used this feature to assign dedicated tasks to be run on both cores in parallel. Tasks that were
145 related to ESP-NOW message exchange with measurement nodes were assigned to Core0, where
146 incoming messages were added to a queue (a thread safe approach in FreeRTOS to pass messages
147 between tasks). After a predefined time, the contents of the queue were checked and read by a task
148 running on Core1 that also initialized the connection to a GSM network and sent the messages to the
149 remote server using MQTT protocol. In such a way, time consuming procedures, like establishing the
150 Internet connection and connecting to a MQTT broker, can be run in parallel without disrupting the
151 communication with measurement nodes.

152 To enable the connection to the Internet, we used a standard SIM card from our local mobile operator.
153 The main node was powered by a self-made mini solar power station containing a 12 V, 12 Ah lead-acid
154 battery and a 12 V, 10 W solar panel together with a pulse width modulation (PWM) type solar charge
155 controller.

156   3.3. Data transfer approach

157   Schematic overview of the data transfer procedure is demonstrated in Figure 1 below:

158   Figure 1. Architecture of the data transfer approach

159   The five monitoring nodes are communicating with the main node via the ESP-NOW protocol. After a
160   predefined time interval (if there is any data to send) the main node connects to the Internet and
161   transfers data using the MQTT protocol directly to the remote MQTT relay which then selects the
162   destination data endpoint. In our case two databases were used: InfluxDB
163   (https://www.influxdata.com/) and SAMS data warehouse (DW) (Komasilovs et al., 2019; Wakjira et al.,
164   2021). Grafana (https://grafana.com/), an open source web application, was used to visualize data
165   stored in InfluxDB, but SAMS user interface (UI) for data stored in SAMS DW. The screenshots below
166   (Figure 2 and Figure 3) demonstrate how the summary view and a detailed view of the colony
167   monitoring was shown to the user in real-time in both applications. In the SAMS UI's dashboard
168   information about last measurements (weight, inside and outside temperature and battery voltage
169   level) is shown to the user. Detailed reports are available under the "Reports" button.

170   Figure 2. Summarized view of five colonies in the SAMS UI

171   In the Grafana UI (Figure 3) all the information is presented as charts showing dynamics of the measured
172   parameters per hive.

173   Figure 3. Detailed view in Grafana UI

174   *4.   Setup of distance and node connection time tests between nodes*

175   Before the implementation in the field, we evaluated the distance between two devices using the ESP-
176   NOW protocol. We were mostly interested to test the distance in an open environment, since the bee
177   hives are placed in an (more or less) open field. For this purpose, we used the main node and one
178   monitoring node. The monitoring node sent a data packet in size of 50 bytes (similarly as it would be in
179   the bee colony monitoring case) every 5 seconds. The main node additionally was equipped with a
180   display to show the received data. After the data was transmitted to the main node, the onboard LED
181   (Light Emitting Diode) blinked and the received data were displayed on the screen, showing a successful
182   data transfer session. Afterwards, the approximate distance was measured using the Google Maps
183   distance measure tool.

184   To test the time that is required for the measurement node to establish a connection to be able to send
185   data we compared two scenarios - using Wi-Fi protocol (like in our previous work) and using the ESP-
186   NOW protocol. The time was measured within the software by calling the Arduino Cores built in time
187   function. In the Wi-Fi scenario we only were interested in measuring the time to establish a connection
188   with the wireless access point excluding the time to establish connection with the MQTT broker. In this
189   way the two scenarios could be comparable, because when using ESP-NOW, the MQTT broker is also not
190   directly involved (the connection is managed by the main node afterwards).

191

192   **Results and discussion**

193   *1.   Comparison of the short range network protocols*

194   Within this study we compared the short range network protocols using the available literature sources
195   (Gloria et al., 2017), manufacturer data sheets and already conducted experiments by other authors
196   (Eridani et al., 2021; ESP-NOW Two-Way Communication…, 2020). The general characteristics of each
197   protocol can be seen in Table 1 below:

198   Table 1. General characteristics of the short range network protocols

199   *2. Distance and node connection time tests between the ESP-NOW enabled devices*

200   Based on the performed tests it was concluded that data can be transferred reliably up to 250 m in an
201   open field (no obstacles) which is inline with the characteristics provided in Table 1. For the task of bee
202   colony monitoring such a distance is more than enough, as usually bee colonies are placed closely
203   together within one apiary.

204   At the experimental site, the hives with measurement nodes were placed at varying distances, where
205   the furthest distance did not exceed 20 m. Some problems were observed with one measurement node,
206   where the direct line of sight was being blocked by a wooden wintering building, therefore data
207   transmission from this node was inconsistent.

208   Besides the distance tests we also evaluated the time needed for the measurement nodes to establish a
209   connection with a main node in two scenarios: when using Wi-Fi (like in our previous work) where the
210   access point was considered as the main node and, when using ESP-NOW protocol, where the main
211   node was based on ESP32 (ref. to chapter Material and methods 3.2). On average it took approximately
212   5 seconds to wake the Wi-Fi module, set the wireless network credentials and establish a connection
213   with the access point. As mentioned in chapter Material and methods 4, here we did not include the
214   time needed to connect to the MQTT broker. In the case when using ESP-NOW protocol, the time
215   needed for the node to initialize the ESP-NOW, set configuration parameters and send data to the main
216   node, was approximately 5 milliseconds, which is significantly faster than in the first scenario.

217

218   *3. Power consumption*

219   3.1. Power consumption of the monitoring nodes

220   The operation of measurement nodes involves mainly deep sleep activity, when the node is consuming
221   significantly less current compared to active mode (sensor reading and data transmission). In our case,
222   the time it took for the node to take all sensor readings, initialize the ESP-NOW protocol and transmit
223   data was approximately 3 seconds (the majority of the time the node is taking multiple weight
224   measurements and selecting the median value), after which it was put to deep sleep (when the only
225   active part on the ESP8266 microchip is the real time clock (RTC) module) for 30 minutes. During the
226   active period, the node's current consumption was 40 mA on average, but during the deep sleep around
227   0.83 mA. The relatively high current consumption during deep sleep (as later found) was caused by
228   some inefficient electronic components and the SD (Secure Digital) card module for data backup
229   purposes. The current consumption measurements were made with the UT61D multimeter and its
230   logging feature.

231   Examples of the battery discharge curves of two measurement nodes are demonstrated below (Figure
232   4). The drop in both curves (on June 13 for Node 2 and on June 22 for Node 1) was due to battery

233 replacement. As Figure 4 shows, the monitoring nodes operated without interruptions for more than
234 two months.

235 Figure 4. Examples of battery discharge rates

236 Although it should be noted that during the experiments we observed different battery discharge rates
237 for some batteries and some measurement systems. This led to the assumptions that some of the
238 measurement system components and batteries might be defective or behave differently outside the
239 laboratory environment. An example of such an undesired behavior is presented in Figure 5, where two
240 different battery discharge rates (for the same system) are depicted. It can be seen that the system was
241 operating for 34 days without interruptions (battery discharge rate ~15 mV/day). After the battery
242 replacement (Figure 5 - circle 1), the system operated for about 15 days (battery discharge rate was
243 ~17 mV/day), then the voltage started to drop dramatically, leading to a battery discharge rate of
244 ~160 mV/day (Figure 5 - circle 2).

245 Figure 5. Different battery discharge rates for the same measurement node

246   3.2. Power consumption of the main node

247 Continuous power consumption measurements of the main node during the whole experiment were not
248 performed, but the current consumption was measured before installing the main module on field. The
249 measured current consumption was ~100 mA. The high current can be explained by the fact that the
250 main node is always on (the Radio Frequency (RF) module is not disabled) listening for incoming
251 messages. During the monitoring period it was observed that the main node was sufficiently powered by
252 the attached battery and solar charging system, since there were no significant interruptions (except for
253 some missing data points that could be due to connectivity issues) in the data, meaning it was operating
254 all the time.

255

256   *4.   Advantages and disadvantages of the ESP-NOW protocol*

257 Specific communication protocols are essentially required for connecting deployed IoT devices to the
258 network in a distributed manner. For the bee colony monitoring task ESP-NOW protocol is suitable and
259 can be used. The ESP-NOW protocol has great distance support in LoS (Line-of-Sight) conditions with low
260 latency. However, it consumes more power, compared to the ZigBee, and obstructions quickly weaken
261 the signal strength. But, if a responsive device, short-range communication, and a minimal amount of
262 data transmission is desired, ESP-NOW is suitable. For bee colony monitoring long-range is not a critical
263 point, as beehives are usually placed close one to another within the apiary location. With respect to the
264 Wi-Fi protocol, it is clear that establishing a connection is quite a time and power consuming task, but it
265 provides much higher data rates therefore is better suited for applications that require high data
266 transfer rates, such as video streaming or large file transfers.

267 The fast response speed of the ESP-NOW protocol provides a lot of general advantages, like direct
268 control of other paired devices and lower power consumption (Amponis et al., 2022) in a battery
269 operated scenario.

270 Some disadvantages of the ESP-NOW protocol can be mentioned as well. For instance from the security
271 aspect it is only possible to encrypt 10 nodes. The ESP-NOW is proprietary to Espressif Systems and it

272   could be difficult and require some effort to combine it with other vendor products (like Raspberry Pi,
273   although there have been some attempts to implement this in a Linux operating system). This can limit
274   its interoperability with other devices and systems. ESP-NOW is designed for small-scale applications,
275   and it may not be suitable for large-scale deployments that require a high number of devices. Another
276   disadvantage could be the payload size that is limited to 250 bytes per message and could be a
277   determining factor for some applications. These limitations are more general and not affecting the
278   applicability of this protocol for bee colony monitoring purposes.

279

280   *5.   Collected data*

281   One aspect of this research was also focused on the urban beekeeping approach, as it was important to
282   identify if the colony would have enough foraging resources within the city environment. This can be
283   determined by analyzing colony weight dynamics. The collected data showed that the active foraging
284   period started after June 22 and lasted till the first week of July, when the weight change was significant
285   for almost every hive (see Figure 6), except one (see Figure 6 - Hive 5), which swarmed and lost its
286   strength. During this period the weight for colonies 1 to 5 increased by approximately 19 kg, 23 kg, 37
287   kg, 27 kg and 8 kg, respectively.

288   Figure 6. Colony weight dynamics during active foraging in an urban environment

289   Additionally, the ambient temperature and temperature inside the hive was also monitored. The in-hive
290   temperature can provide valuable information about the bee colony state (Kviesis et al., 2020 (b)). It
291   should be emphasized that in order to get an insight of the colony status by temperature data (when
292   measured by a single temperature sensor), the position of the sensor within the hive is very important.
293   Honey bees regulate the brood temperature to be stable - from 35 to 36℃ (Seeley, 1985; Bujok et al.,
294   2002). Previous studies (Zacepins et al., 2011; Stalidzans and Berzonis, 2013; Kviesis et al., 2020) have
295   shown that it is sufficient to place a single sensor above the brood nest. An example of the in-hive
296   temperatures during the active foraging period in our experiment is illustrated in Figure 7. The recorded
297   temperatures of Hive 5 were not included due to sensor misplacement after the colony swarmed.
298   Another example of sensor misplacement can be seen in Hive 2 data, as it shows large fluctuations,
299   although the colony was healthy (according to the beekeeper).

300   Figure 7. Monitored in-hive temperatures

301   *6.   Costs estimation*

302   The economic aspect of the monitoring system is very important, so the costs should be kept as low as
303   possible to make it financially viable for beekeepers. The system hardware components used in this
304   experiment with approximate unit prices are summarized in Table 2. The provided costs are calculated
305   based on the market prices in our country Latvia and can differ in other regions.

306   Table 2. Cost estimation of the main and monitoring node

307   The calculated costs for the described experimental set (main node and five monitoring nodes) are
308   846.00 EUR. System installation, maintenance, data storage, GSM SIM card with appropriate data plan
309   and usage of the web system is not considered in these calculations. The total costs of the system can be
310   reduced by using only one weight system per apiary so that the beekeeper can roughly estimate the

311 start of the nectar flow at his apiary as well as the yield. With one weight system per apiary the cost
312 reduction would be by 400.00 EUR.

313 *7. System installation process*

314 System installation process should be as simple as possible, because usually beekeepers are not very
315 open to new technologies and mostly not very experienced information technology (IT) specialists
316 (Zacepins et al., 2017). In our case the user (beekeeper) only needs to put the scales under the hive,
317 insert a temperature sensor into the hive and switch on the nodes, no specific configuration and
318 assembling is required. All module configuration is done by the IT specialists before the initial
319 installation in the field.

320 **Conclusions**

321 IoT is trending in the field of ICT and builds the future of computing and communication.
322 Implementation of the IoT principles in precision beekeeping would provide a significant impact on the
323 beekeeping development process.

324 Developed honey bee colony monitoring system uses power efficient sensor nodes that consist of low
325 cost, accurate temperature sensors, load cell for weight measurements with fast communication
326 protocol. Such a system can be set up also in remote areas, since the main module is energy self-
327 sufficient and communicates with the remote server over a cell network. According to literature and
328 practical test results, the sensor nodes are able to communicate over large distances, even more than
329 200 m in an open field.

330 Developed monitoring systems can help to minimize manual bee colony inspections, which should also
331 reduce the stress of the bee colony and increase its welfare.

332 Application of ICT and IoT solutions and remote monitoring systems facilitates the beekeepers'
333 knowledge about behavior of individual bee colonies and can improve the efficiency of beekeeping
334 management.

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Figure 1

Architecture of the data transfer approach

Schematic view of the data transfer approach, including all components, like measurement and main nodes.

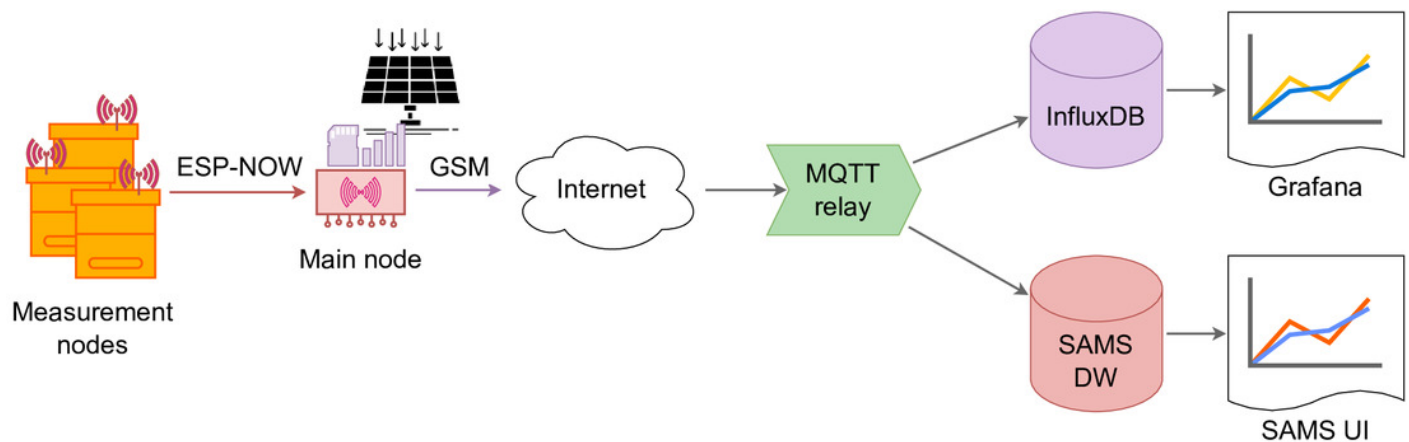



Figure 2

Summarized view of five colonies in the SAMS UI

Real time data about the measured bee colony parameters presented in the SAMS UI. Data is about weight, temperature in the colony, temperature outside and battery voltage level.

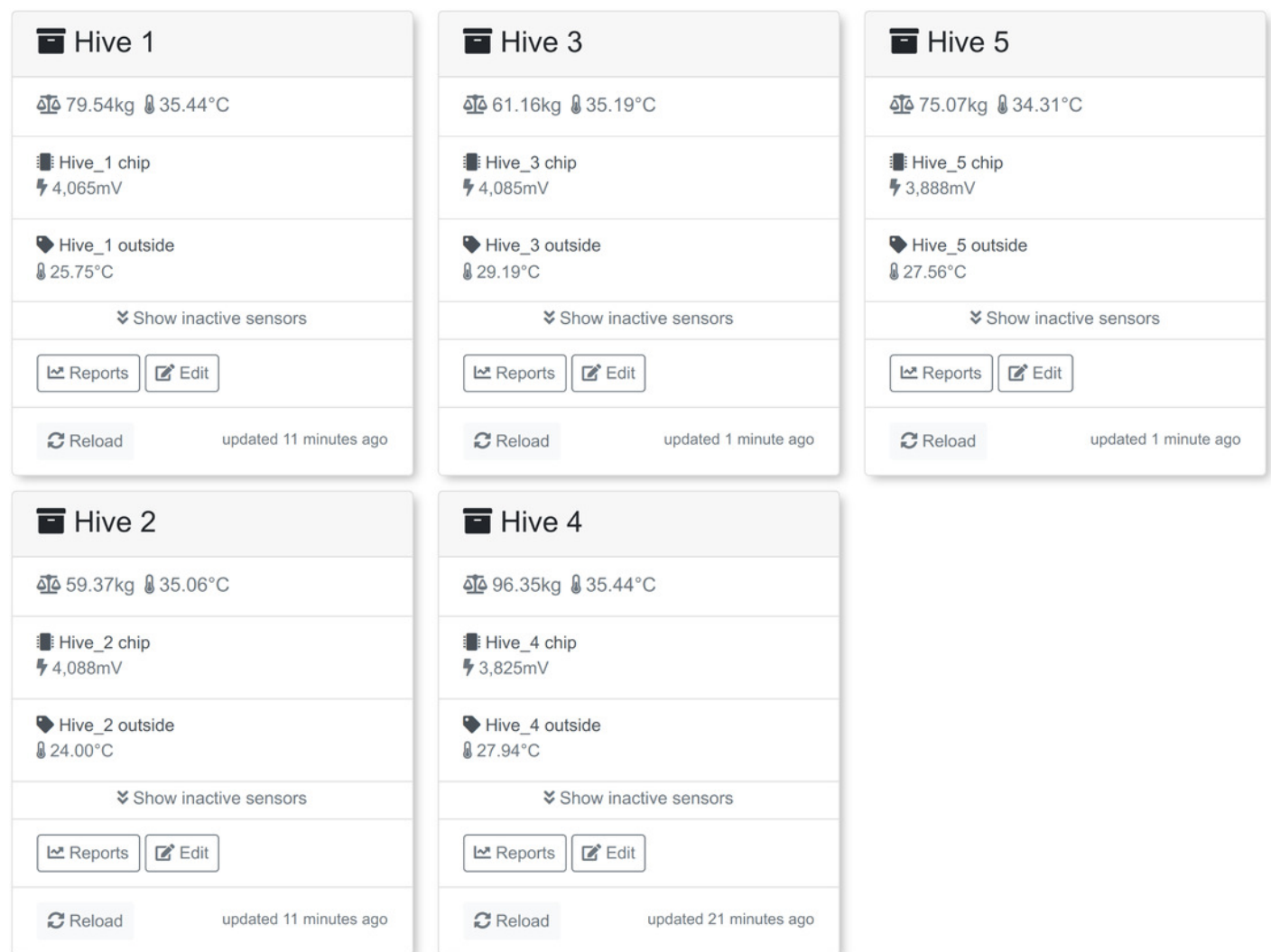



Figure 3

Detailed view in Grafana UI

Example of the bee colony data presented in Grafana UI. Charts are presented about bee colony temperature, weight and node baterry voltage level. Last measured values are also presented in a form of a table.

Figure 4

Examples of battery discharge rates

The lines represent battery discharge rates of two measurement nodes.

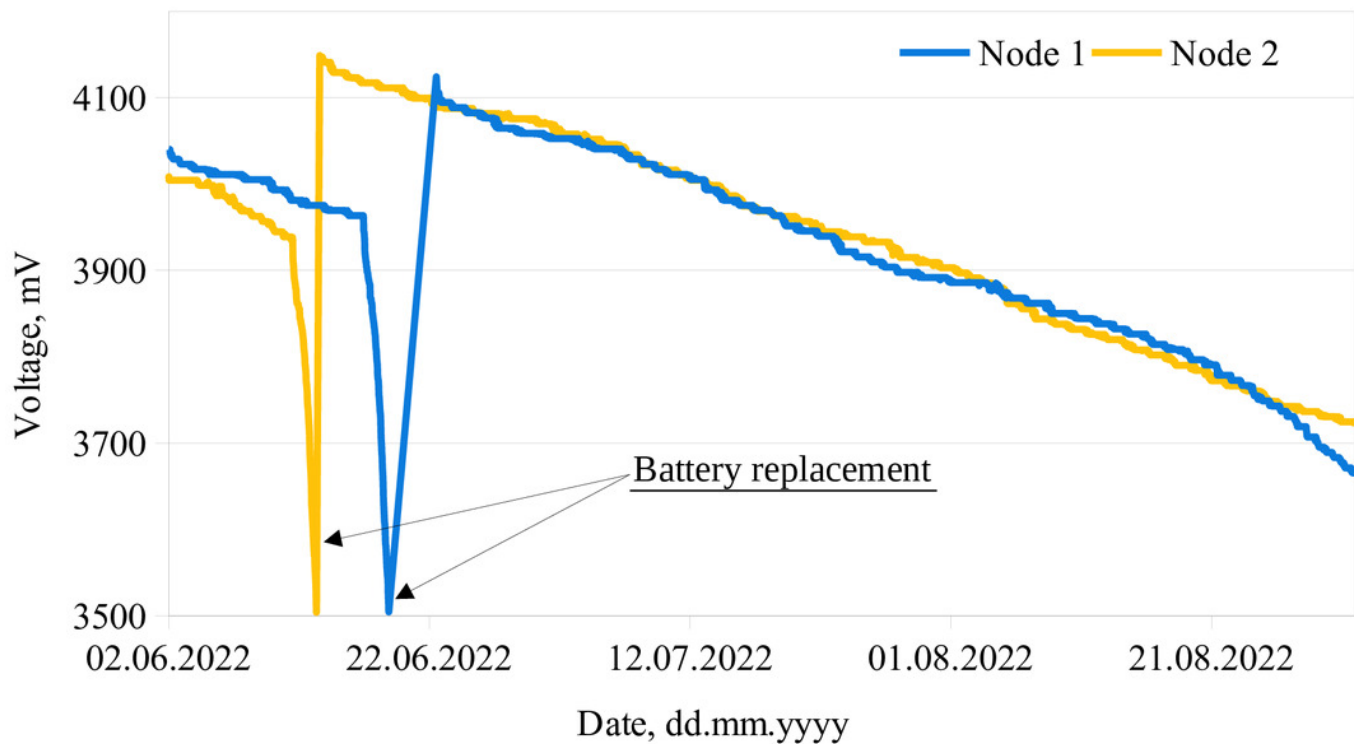



Figure 5

Different battery discharge rates for the same measurement node

The chart shows different discharge rates for one measurement node suggesting defective system components or batteries.

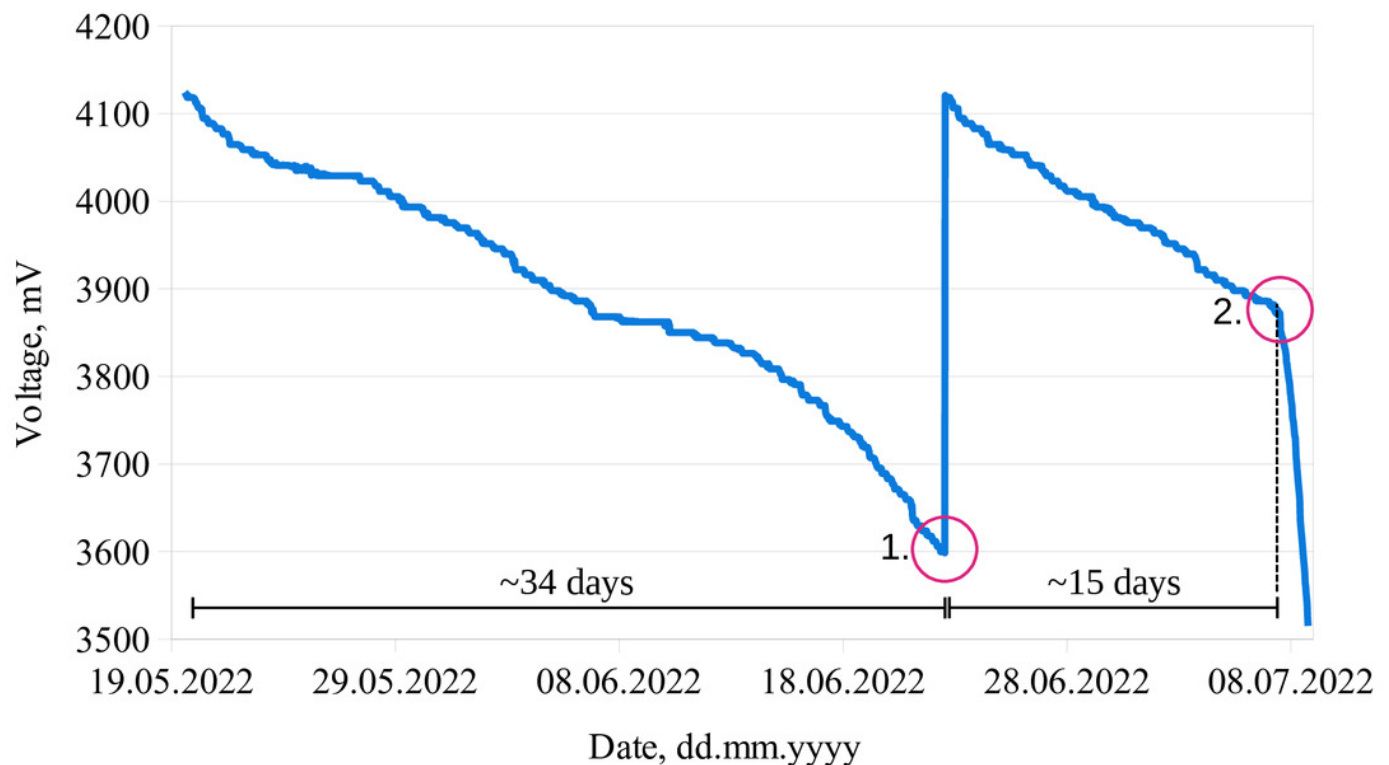



Figure 6

Colony weight dynamics during active foraging in an urban environment

Weight dynamics in bee colonies during active foraging period from 23.06.2022 till 08.07.2022 are presented.

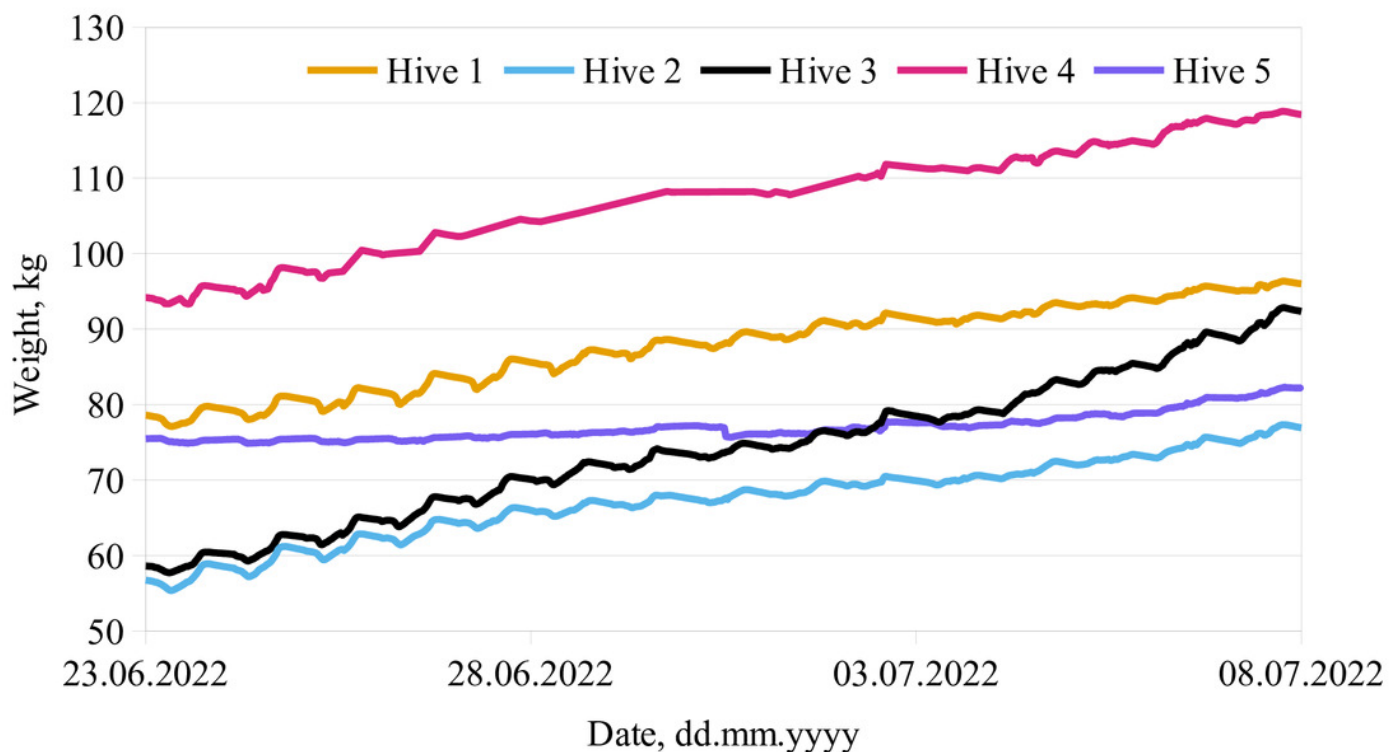



Figure 7

Monitored in-hive temperatures

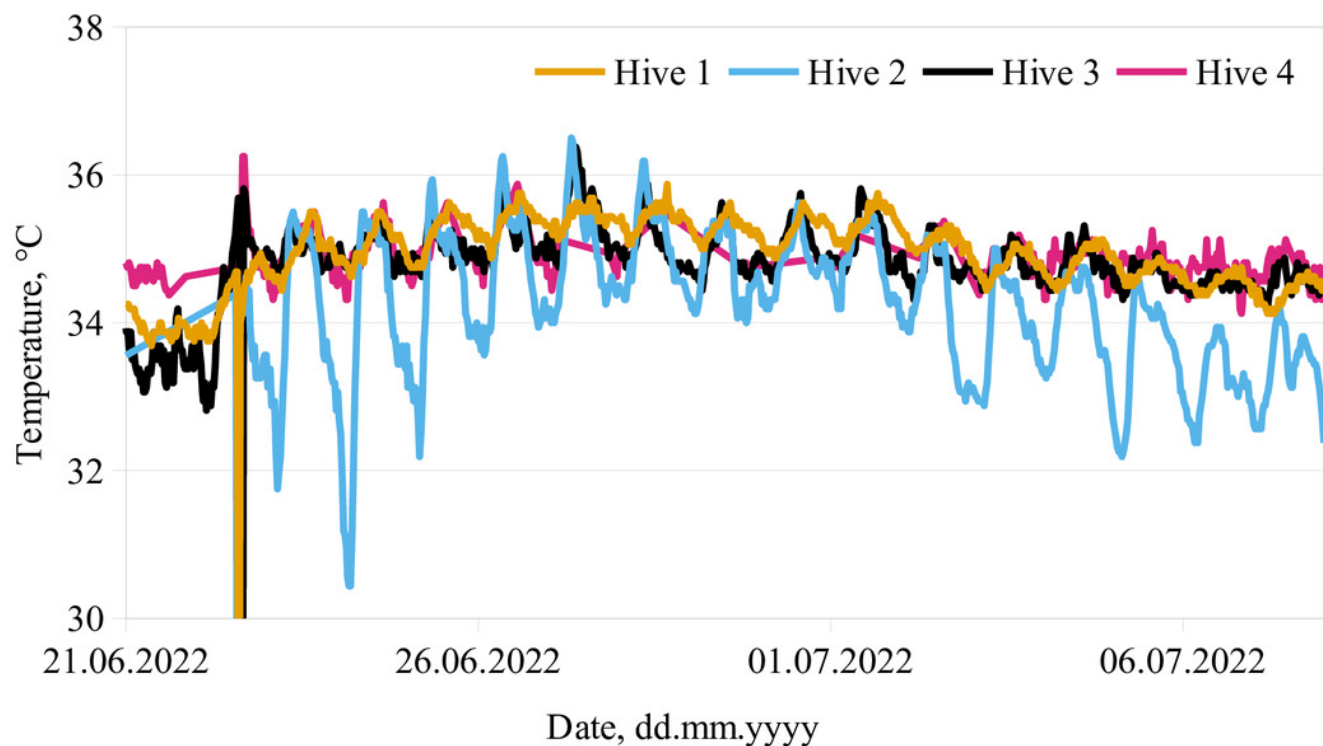
Temperature dynamics in bee colonies for the selected period from 21.06.2022 till 06.07.2022 are presented.

General characteristics of the short range network protocols

Table summarises main characteristics of four short range network protocols.

1 Table 1. General characteristics of the short range network protocols

Parameter	Bluetooth	ZigBee	Wi-Fi	ESP-NOW
IEEE specification	802.15.1	IEEE 802.15.4	802.11	802.11
Frequency	2.4 GHz	2.4 GHz	2.4 GHz and 5GHz	2.4 GHz
Data rate	approx. 784 Kbps	250 Kbps	54 Mbps	1 Mbps
Maximum range	100 m	100 m	100 m	220 m
Maximum payload	251 B	128 B	2312 B	250 B
Power consumption	1 – 35 mA	1 – 10 mA	100 -350 mA	60-100 mA

Cost estimation of the main and monitoring node

Summary of costs for the development of the main and monitoring nodes.

1   Table 2. Cost estimation of the main and monitoring node

Main node		
Nr.	**Name of the component**	**Cost (in EUR)**
1	ESP32 microchip based board	25.00
2	SIM800L module	5.00
3	Solar panel SOL10P (10 W, 12 V)	35.00
4	PWM solar charge controller	32.00
5	Battery GP12120 12 V, 12 Ah	34.00
6	Additional components	10.00
	Main node overall costs	**141.00**
Monitoring node		
Nr.	**Name of the component**	**Cost (in EUR)**
1	BOSCHE Wagetechnik Single point load cell H30A (200kg)	50.00
2	Platform for load cell	50.00
3	ESP8266 microchip (ESP-12F) including adapter plate	13.00
4	Temperature sensor DS18B20 (x2)	8.00
5	A/D converter HX711	5.00
6	Additional components (PCB, wires, resistors, capacitors, connectors, etc.)	10.00
7	Rechargeable battery Li-ion 18650 3.7 V 2000 mAh	5.00
	Monitoring node overall costs	**141.00**