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# DATA COLLECTION IN THE WILD: CHALLENGES AND SOLUTIONS

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***Abstract***

*Extensive monitoring plays a key role in environmental protection. This task, however, has many issues to solve, communication and data collection being a difficult one. This paper focuses on the challenges of observing hard-to-access areas, such as forests and wetlands. The performance of the possible solutions for this problem are compared, focusing to sensor networking and Low-Power Wide-Area Network (LPWAN) technologies, and a drone-based solution will be proposed. The presented method offers a robust, and reliable, yet simple data collection solution. The hardware and software architecture, the communication protocol will be described, and the estimated performance of the system is analysed.*

***Key words****: data collection, environment, LPWAN, UAV.*

## INTRODUCTION

### Sensor networks in environmental monitoring

Sensor networks consist of nodes with sensing, processing, and communication capabilities. Their main application area is data collection, especially on large areas or with large number of points. In most applications the power sources of the devices are batteries, since the mains current is not an option. Since the required lifespan of such a network is at least 2-3 years, the power budget must be highly optimized.

One of the most promising classic sensor networking applications was the monitoring of remote, non-accessible areas (Corke et al., 2010), such as rainforests (Wark et al., 2008; Cama et al., 2013), volcanos (Werner-Allen et al., 2006; Song et al., 2009) or glaciers (Martinez et al., 2004; Martinez et al., 2005).

Most conventional sensor network-based monitoring systems use a mesh routing protocol to send all measurement messages to a dedicated base station. In a typical setup the sensor nodes have a limited amount of power (most commonly batteries), while the power source of the base is practically unlimited (mains power or solar energy). These protocols often apply Time Division Multiple Access (TDMA), which relies on a tight time synchronization. In such a system each message is relayed through multiple subsequent nodes, which means extra energy consumption each time. Another less obvious disadvantage is, that nodes closer to the base relay more packets, thus they consume more energy.

Another possible approach is to use one of the modern Low-Power Wide-Area Network (LPWAN) protocols (e.g., Long Range (LoRa) (Ertürk et al., 2019; Migabo et al., 2017) or Narrowband Internet of things (NBIoT)). Firstly, these solutions obviously requite a working infrastructure. Secondly, they are typically not designed to transfer large amount of (measurement) data.

### Wetlands

Wetlands are usually considered as a specific biotope with high biodiversity potential located on the edge of the solid surface and the permanent or seasonal water covered areas. The presence of the water causes saturation into the soil due to the proximity of the water table. The periodic oxygen-free status of the ground results in anoxic hydric soils. Wetlands occur in different forms such as swamps, marches, estuaries, mangrove swamp, marsh, moorland, or peatland. Wetlands play vital role in biodiversity of vegetation and animal species all over the world and maintain stable ecosystems. There are many types of water in wetland soils such as freshwater, seawater or brackish water depending on the habitat's

location. The vegetation of the wetlands can be woods, trees, shrubbery, reeds, cattails, or sedges. Climate zones classified by Trewartha define the type of wetlands (Belda et al., 2014).
Beside the importance in habitat protection wetlands can be seen as natural water filters which collect sediment and pollutants and release almost pure water to the surrounding areas. Furthermore, wetlands regulate water floodings, climate change effects and can be considered also as recreational areas and cultural heritage (Mitsch et al., 2013).
Wetland are threatened by many effects, such as eutrophication, pollution, sewage and drainage problems, toxic contamination, acidification or salinisation. These effects are mainly caused by human factors and urban development.
Wetlands are protected by 'Ramsar convention on Wetlands of International Importance Especially as Waterfowl Habitat' since 1971 in which legal and institutional framework of the wetland areas' protection, conservation and sustainable use was established (Belda et al., 2014). The convention defined the list of wetlands of international importance, for instance Velence and Dinnyés Nature Conservation Area, which is located in the same geographical area as the Sóstó natural reserve (Figure 1), is also on the Ramsar list.

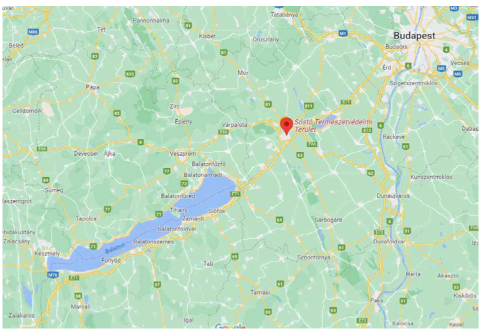


Figure 1. The location of Sóstó natural reserve in the Northen-West part of Hungary relative to Budapest and Lake Balaton (Source: Google Maps)

**The Sóstó natural reserve**

The Sóstó natural reserve (Figure 2) is located only two and a half kilometres in the southern direction from the downtown of Székesfehérvár and can be considered as an organic part of the city ("Sóstó Természetvédelmi Terület és Sóstó Látogatóközpont", n.d.). Székesfehérvár is located halfway between Budapest and lake Balaton. The wetland is located on 218 hectares of which 121 hectares are nationally and the rest is locally protected area. The visitor centre is in the vicinity of the local football arena.

Figure 2. The map of the Sóstó natural reserve (Source: https://sostoszekesfehervar.hu/turak)

In historic times Székesfehérvár was surrounded by deep swamps until the middle of the 19th century, since then the Sóstó area was partly drained and used as a recreational area. Two deep wells were used as water supply but after the Second World War 600 $m^3$ sewage sludge were deposited yearly which caused fast eutrophication and decay. The rehabilitation of the Sóstó area was started in the 1990's and in 2003 the area got a naturally protected status. New educational trail was formed for recreational and training purposes. The Sóstó biotope gives various possibilities to the flora and fauna, many protected species can be found there. The water supply of the wetland is provided by local purified wastewater source, 500 $m^3$ clear water feeds the lakes arrived by a 4 kilometres long pipeline.

## MATERIALS AND METHODS

### System architecture

The architecture of the monitoring system consists of several independent measuring nodes and a base station, which is attached to an Unmanned Aircraft System (UAS), flying over the measurement area at regular times, allowing to download the collected data (Figure 3). The sensor nodes do preprogramed measurements and store the collected data in flash memory.

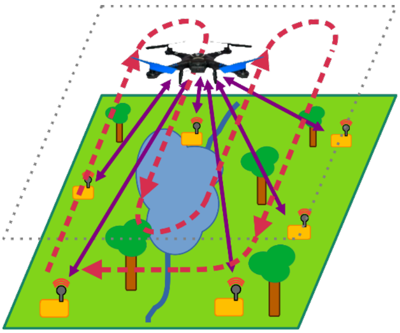

Figure 3. The architecture of the proposed system (own image)

### The proposed communication protocol

In the proposed monitoring system, the data collector nodes have limited energy (they are powered by batteries) similarly to regular sensor networking applications. Using a mesh protocol to collect the measured data, each message would be sent by possibly many sensor nodes. The proposed protocol uses a star topology instead, which requires to send each message only once, but on the other hand it assumes direct connection (i.e., line of sight). The speciality of the system is, that the base station is absent in the huge majority of the time and present only occasionally.

The goal of the proposed communication protocol is to detect the presence of the base station and transfer the collected data when the conditions are given. The sensor nodes don't necessarily hear each other; therefore, collision avoidance is the task of the base station.

The protocol utilizes the fast acknowledgements of the 802.15.4 MAC layer. Instead of listening for some kind of beacon messages transmitted by the base station, the sensor nodes emit hello messages regularly and wait for an ACK message. The time interval of the hello messages is a design parameter of the protocol.

The 802.15.4 ACK packet has 3 unused bits (Figure 4), which are used to sign, when the actual data transfer process is possible. Each of the 8 combinations can sign different waiting times. This way the base station can spread the time slots of the nodes. The nodes turn off their radio during waiting. Note that the nodes do not need to maintain tight time synchronization, for this task.

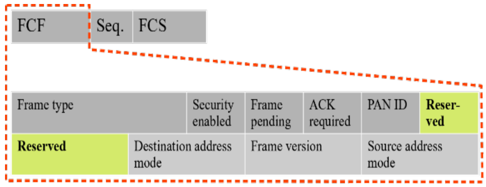


Figure 4. The format of the 802.15.4 ACK packet with the 3 reserved bits highlighted in the frame control field (FCF)

During the actual data transfer each node send the previously collected data divided into packets. Each packet is sent tightly next to each other, with acknowledgements by the base station.

### Sensor nodes

The hardware of the sensor node is based on an Unicomp UCMote Proton B mote (Figure 5). The base board has an 8-bit ATmega128RFA1 Soc as the main controller. The microcontroller core is running at 16 MHz, with an approx. 4 mA current consumption from 3.3 V. The microcontroller has different sleep modes, and can be stopped from program execution. When stopped, the current consumption is reduced to the approx. 0.1 mA range. Another important parameter is the wakeup time, which is in the range of microseconds. The SoC contains a 2.4 GHz radio unit, that supports the 802.15.4 range standard for low-power low-range communication. This communication channel is used only during testing for debug purposes only, for two reasons. First the 2.4 GHz band is not suitable for the proposed monitoring system because of the high absorption of. Second, the board has only a low gain chip antenna connected of the Soc.

The main board contains an additional AT86RF212 radio chip, which operates in the 868 MHz ISM band. This radio chip can be configured to use different communication speeds from 20 to 1000 kbps according to the link conditions. Depending on the communication bandwidth the receiver sensitivity can be as good as -110 dBm. With the +10dBm maximum power output the achievable link budget can reach 120 dB, which is well suits to the proposed system. This radio is connected to an MMCX RF connector, which allows to connect a high gain external antenna.

Since the UAS is located above the sensor nodes during the data download process the usual quarter wave vertical antennas are not a good choice for this purpose, given they have very low gain in axial direction. QFH antennas (Adams et al., 1974), however have good overhead gain, therefore they are much more suitable for the proposed system. The power source of the proposed sensor node consists of 4 D type non-rechargeable lithium batteries, providing 76000 mAh capacity at 3.6 V.

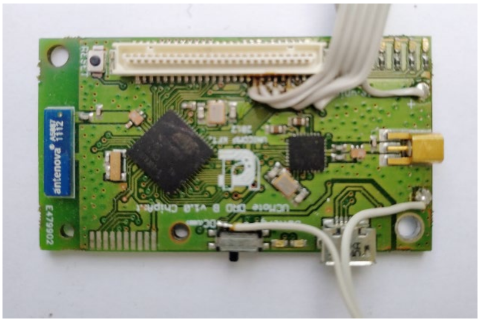

Figure 5. The UCMote Proton B mote

The software of the sensor nodes is built around the TinyOS. It is a component based real-time operating system, especially tailored for low-power applications. It has support for different types of microcontrollers, radios and sensors and the uniform interfaces make adding new device drivers and communication protocols possible.

TinyOS already supported the ATmega128RFA1 SoC with its microcontroller core and automatically put it in low-power mode, when it has no task to run and no event to process. The 2.4 GHz radio is also supported and 802.15.4 standard packets can be sent and received with a simple CSMA/CA MAC protocol. The other radio chip (AT86RF212, 868 MHz) is also supported with the standard CSMA/CA protocol, although the special low-power mode had to be implemented.

To achieve this, the header, which contains the source address, must be intercepted and the time-critical background lookup must be processed in parallel with the reception of the remaining part if the packet, before the full packet arrives (Figure 6) (Vakulya and Simon, 2013). Based on the result of the lookup one of the reserved bits of the acknowledgement packet is set of cleared, signalling the presence or the absence of a pending packet.

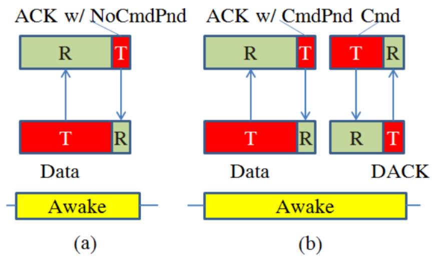


Figure 6. The timing diagram of the ACK piggybacking protocol (Vakulya et al., 2013)

## UAS technology

The Chinese DJI company can be considered as one of the leading UAV manufacturers in the world. The DJI Phantom 3 Advanced UAV is available since 2015 and beside its good features cannot be considered as the latest techniques (Udvardy et al., 2019).

The UAV weighs 1280 grams and has a 15.2V 4480mAh battery which allows maximum 23 minutes' flight time. The onboard Sony EXMOR 1/2.3" camera has 12 million pixels and has a FOV of 94° with 20 millimetres focal length. The ISO value changes between 100 and 3200 for video recording and 100 and 1600 for photographs. The shutter speed varies between 8 and 1/8000 seconds. The resolution of the video caption is 2.7K (30fps).

The camera is hanged on-board with the help of a 3-axis gimbal which helps to stabilize the camera during flight.

For navigation DJI Phantom 3 UAV uses GPS/GLONASS system outdoor and has a vision positioning system for indoor positioning. The hover's horizontal accuracy is between 0.3 and 1.5 meters and the vertical accuracy is between 0.1 and 0.5 meters depending on the positioning method.
This UAV can reach approximately 3 kilometres distance outdoor from the home point which is marked before the flight starts. The 'Go home' function helps to find the hover in case of being lost or invisible.

## RESULTS AND DISCUSSIONS

Using the proposed system, several different monitoring applications can be implemented. The following 3 demonstrative examples show measurement scenarios related to environment monitoring and calculations to communication settings and for the projected lifetime. Such a system has to be designed taking into account not only physical limitations but also legal requirements. The last two subchapters discuss these equally important aspects in terms of frequency usage and UAV regulations.

**Low density environmental data collection**
In this scenario, slowly changing environmental parameters are monitored. The sensor modalities are:
- Soil temperature with 16 bit resolution, one measurement every 5 minutes;
- Air temperature with 16 bit resolution, one measurement every 5 minutes;
- Ambient light intensity with 16 bit resolution, one measurement every 5 minutes;
- Relative humidity with 8 bit resolution, hourly;
- Soil moisture with 8 bit resolution, hourly.

A total of 15 sensor nodes are installed in the system. In each node a total number of 1776 bytes are generated each day. If the data is collected every two months, approx. 100 kBytes of data is fetched from each node. With a pessimistic 20 kbps bandwidth approx. 1 minute is necessary to download this data amount from each node. A 1-minute beacon interval for the sensor nodes would give a good balance between latency and power consumption. With these parameters the average flight time can be estimated to approx. 20 minutes.
The 802.15.4 packet has a 13 byte header (including the preamble, physical and MAC headers) and a 2 byte footer. The length of a hello message with a 5 byte payload is 20 bytes, which requires 8 ms to send with 20 kbps. The length of the ACK packet is 11 bytes, which requires 4.4 ms of time. Another approx. 1 ms is required to turn on and off the radio and approx. 2 ms of gap time is required between the two packets. This adds up to 15.4 ms. The actual data transfer requires approx. 60 seconds of time. The on time of the radio can be calculated as follows for a year.

$$T_{on,annual} = 60 \cdot 6 + 365 \cdot 24 \cdot 60 \cdot \frac{15.4}{1000} = 8454[s] \quad (1)$$

Now the annual power consumption of the radio can be calculated as follows:

$$C_{annual} = T_{on,annual} * I_{radio,on} = = \frac{8454[s]}{3600} \cdot 20[mA] = 47[mAh] \quad (2)$$

Considering only the radio communication, one D type cell would last for several years (practically the self-discharge limits the lifespan).

**Pollution related monitoring**
In this scenario, the focus is on pollution related monitoring, specifically air quality parameters. The sensor modalities and data collection parameters are as follows:
- Particulate Matter ($PM_{2.5}$) concentration with 16-bit resolution, one measurement every minute;
- Carbon Monoxide (CO) concentration with 16-bit resolution, one measurement every minute;
- Nitrogen Dioxide ($NO_2$) concentration with 16-bit resolution, one measurement every minute;
- Ozone ($O_3$) concentration with 16-bit resolution, one measurement every minute;
- Ambient Temperature with 16-bit resolution, one measurement every minute;
- Relative Humidity with 8-bit resolution, one measurement every minute.

In this scenario, a monthly data collection is scheduled. Each day, 15840 bytes of data is generated on each sensor, which means approx. 500 kBytes monthly. With 20 kbps bandwidth the net data transfer time is 190 s. Now let's choose a 30 s beacon time. The annual on time can be calculated as follows:

$$T_{on,annual} = 190 \cdot 12 + 365 \cdot 24 \cdot 60 \cdot 2 \cdot \frac{15.4}{1000} = 18468[s] \quad (3)$$

Now the annual power consumption of the radio can be calculated as follows:

$$C_{annual} = T_{on,annual} * I_{radio,on} = \frac{8454[s]}{3600} \cdot 20[mA] = 102[mAh] \quad (4)$$

In this case, the overall annual power consumption is twice as much as the previous case, but the same D type battery would also last for several years in this case. Note that only the radio communication was taken into account for the calculations. Powering the sensors take additional energy.

**Fine grain seismic monitoring**

In this scenario a demonstrational example for a fine grain environmental parameter (seismic activity) is presented. Here the sensor modality is a triaxial accelerometer with 16 bit resolution and 12.5 Hz sample rate. A total number of 6 nodes are required for this experiment.

This measurement setup generates much more data, than the previous example. Let's use a one-week interval for the data collection. The total data amount during a week is 2.1 MB in each node. In this case a higher data rate (250 kbps) is more suitable, which is only achievable when the distance between the nodes and the base station is smaller (the altitude of the UAS is lower) and when no significant obstacles (i.e. large trees) are present.

We can here choose similar beacon interval to the previous example (1 minute). Note that the nodes can use different data rates for the beaconing and for the data transfer. The calculated data transfer time is 472 seconds. Based on the calculations the annual on-time is:

$$T_{on,annual} = 52 \cdot 472 + 365 \cdot 24 \cdot 60 \cdot \frac{15.4}{1000} = 510198[s] \quad (5)$$

Now the annual power consumption of the radio can be calculated as follows:

$$C_{annual} = T_{on,annual} * I_{radio,on} = \frac{510198[s]}{3600} \cdot 20[mA] = 1822[mAh] \quad (6)$$

Considering a 19000 mAh battery capacity, the lifespan of the system would be approx. 10 years. Note that only the radio communication was taken into account.

**Frequency usage**

Although several frequency bands are referred as unlicensed, they are under legal control as well. The most well-known groups are the ISM (Industrial, Scientific and Medical) bands and the SRDs (Short Range Devices) (Loy, 2005). Our case is focused to the former one.

ISM bands are regulated by the International Telecommunication Union. Depending on the geographical region, different bands are allocated with different conditions. In several cases, more different services share the same band and, in general they either must tolerate each other or priorities are defined.

The compliance with the regulations is officially tested and validated as the part of the Certification Process. Only certified commercial off the shelf parts can be distributed. In case of custom-built devices, the certification is the task of the builder.

The 2.4 GHz band (from 2.4 to 2.5 GHz) is generally available worldwide as ISM band. The regulation of the UHF (specifically the 434 MHz, 868 MHz and 915 MHz) bands is different between the regions. In Europe, both the 433 and 868 MHz bands are allowed, with different conditions (e.g. bandwidth, power and duty cycle).

**UAV regulations**

In Hungary, the Unmanned Aerial Vehicle (UAV) and Unmanned Aircraft System (UAS) flight is regulated by strict law which is harmonised with the European legislations (Table 1), (EU Regulation 2019/947 on the rules and procedures for the operation of unmanned aircraft) (EUR-Lex – Access to European Union Law, n.d.).

Table 1. UAS requirements and limitations (https://www.easa.europa.eu/en/faq/116452)

<table>
<tr><th colspan="2">UAS</th><th colspan="2">Operation</th><th colspan="3">Drone Operator/pilot</th></tr>
<tr><th>Class</th><th>MTOM</th><th>Subcategory</th><th>Operational restrictions</th><th>Drone Operator registration</th><th>Remote pilot competence</th><th>Remote pilot minimum age</th></tr>
<tr><td>Privately built</td><td rowspan="3">< 250 g</td><td rowspan="4">A1<br>(can also fly in subcategory A3)</td><td rowspan="3">- may fly over uninvolved people (should be avoided when possible)<br>- no fly over assemblies of people</td><td rowspan="3">No, unless camera / sensor on board and a drone is not a toy</td><td>- no training needed</td><td>No minimum age</td></tr>
<tr><td>0</td><td rowspan="2">- read user's manual</td><td>16*,<br>no minimum age if drone is a toy</td></tr>
<tr><td>Legacy drones (art. 20)</td><td>16*</td></tr>
<tr><td>1</td><td>< 900 g</td><td>- No expected fly over uninvolved people (if happens, should be reduced)<br>- no fly over assemblies of people</td><td>Yes</td><td>- read user's manual<br>- complete online training<br>- pass online theoretical exam</td><td>16*</td></tr>
<tr><td>2</td><td>< 4 kg</td><td>A2<br><br>(can also fly in subcategory A3)</td><td>- no fly over uninvolved people<br>- keep horizontal distance of 30 m from uninvolved people<br>(it can be reduced to 5 m if low speed function is activated)</td><td>Yes</td><td>- read user's manual<br>- complete online training<br>- pass online theoretical exam<br>- conduct and declare a self-practical training<br>- pass a written exam at the CAA (or at recognized entity)</td><td>16*</td></tr>
<tr><td>3</td><td rowspan="4">< 25 kg</td><td rowspan="4">A3</td><td rowspan="4">- fly away from people<br>- fly outside of urban area (150 m distance)</td><td rowspan="4">Yes</td><td rowspan="4">- read user's manual<br>- complete online training<br>- pass online theoretical exam</td><td rowspan="4">16*</td></tr>
<tr><td>4</td></tr>
<tr><td>Privately built</td></tr>
<tr><td>Legacy drones (art. 20)</td></tr>
</table>

Each UAS of which the weight exceeds 120 grams or has onboard data recording equipment (i.e., camera) must be registered online first. In the following step, the UAS operators also must be registered together with their valid third-party liability insurance linked to their UAS at the Traffic Authority. The insurance must cover between 12-15 thousand EURO damage for a year (Légtér.hu Kft., n.d.) UAS operators must get the so-called flight licence and as a drone operator they get a unique registration number which is valid in all EASA (European Union Aviation Safety Agency) member state. This flight open category licence is available for those UAS's which are less than 25 kilograms of maximum take-off mass (MTOM), the maximum flight height is 120 meters from the above ground level (AGL), the UAS must remain in visual line of sight (VLOS) and the UAS cannot fly over assembly people and cannot transport dangerous materials and cannot spread any materials to the ground. This category contains A1-A3 and A2 subcategories with the difference in UAS weight, the minimum distance from and overfly time of uninvolved persons and the horizontal flight speed (Drónpilóták Országos Egyesülete, n.d.).

The competence exam is available and valid in every EU states. In Hungary, the Austrian A1-A3 exam is very popular as it is online and free.

After the fulfilment of the legislative background, the GoodID application for identification purposes and MyDroneSpace ny Hungarocontrol application right before flight must be used. UAS operators must ask for airspace usage permission for the exact time. The official administrative deadline for the permission is 30 days before flight but for special stakeholders there is a simplified procedure with 5 days lead time.

## CONCLUSIONS

Monitoring physical or natural parameters in harsh environments (e.g., forests and wetlands) has several challenges, getting the collected data being one of the hardest one. Both individual data loggers or classic wireless sensor networks have major flaws. The former requires frequent physical access to the devices, while in case of the latter, communication is the main issue. In this paper, a novel data collection approach was presented, using drone technology. The system design with the sensor nodes' hardware, software, the communication protocol and the UAS technology was presented.

The measuring devices are similar to the nodes of a wireless sensor network, but instead of a continuously maintained mesh topology communication they use a direct connection to an infrequently appearing base station. The line of sight is provided by UAV technology, which, at the same time results in low path loss, high possible bandwidth, quick data transfer and consequently a longer lifetime.

Three different demonstrative examples with different data density were chosen to show the applicability of the proposed system.

The first scenario is general, where most useful application of the collected data is climate research. Either long-term data analysis or comparing different points in the same period would be interesting. The title of the second example can be misleading. Although the word "seismic" is related to the motion of tectonic plates, the vibrations, which can be detected by accelerometers are most likely caused by animals or vehicles. Monitoring both animal and (forbidden) vehicle activity can be interesting in such a protected area. The third measurement scenario is related to the monitoring of air pollution, the importance of which cannot be overstated. Since this system enables the simultaneous and long-term data collection, it may facilitate locating the sources.

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