An Approach to Environmental Study from Observations and Sensing Towards a Digital Twin

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Abstract. Long-term well-living is highly correlated to the level of environmental studies. Arctic ice melting, global warming, storms, and forest fires occur more and more often. In the process of digitalization of life, a new technology of digital twins is becoming appropriate for better studies and prediction of disasters. Many papers and projects have been focused on wildfires last decade and some of them present the idea of forest fire simulation. In this work, we present an IoT-cloud-digital twin solution where a new sensor for environment sensing is developed, integrated with the drone observations of the area, and feeding the database on the server locally and in the cloud with fresh data from the observation. All data collected in real-time, near-real-time, and non-real-time feed a digital twin model where the fires are simulated. The unique combination of real data and simulated data in the virtual environment allows better prediction of disasters, coordination in prevention procedures, and clear analyses of the risk for the environment and citizens.

Keywords: Sensors · Digital Twins · Data Sharing · Edge · Dew · Fog · Cloud Computing Technologies · Risk Analyses · Disaster Prediction

1 Introduction

Last decade digital twin technology is becoming more and more important for different industrial sectors. It was proven to be helpful in production management and failures [1], autonomous robots [2] where intensive standardization is taking place [3]. International

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Standard Organization (ISO) [4] and IBM [5] are among the leaders in this process. While applying digital twin technology the systems need to be sustainable, scalable, and interoperable, open to be fed with fresh and historical data, and be expanded with new features and functionalities [6]. The accuracy of the models, real data, and simulated data implemented in digital twins is a matter of intensive analysis because of the reflection to risk evaluation and preventive measures of nature and citizens [7].

Digital twins are successfully implemented in intelligent transportation systems [8]. Smart home and smart office solutions [9] are very promising implementation places for the technology as well as the energy sector [10]. The domain-driven approach is demonstrated in [11].

Forests and other wooded land cover over 43.52% of the EU's land space, with about 16 million private forest owners. Also, 40% of forests are publicly owned. In recent years large pieces of forests have been destroyed by fires, due to climate changes. Fire-fighting teams must be aware of the possibility of fire occurrence and spread, to act immediately in case of real crises. The best solutions used so far with thermal cameras on towers can only detect forest fires and cannot be used in rugged and uneven terrains, such as most forests.

According to data on wildfires by EFFIS [40] over 400000 ha of natural areas have burnt in the EU for the first 10 months of 2020, despite the use of the available technological means like fire monitoring towers. EFFIS graphics show a constant increase in the number of fires and burned areas during the last years. But "healthy and resilient forests are a key part of efforts to combat the negative impacts of climate change. Studies have shown trees can reduce temperatures by 9 degrees and energy costs by $7.8 billion a year".

The social impact of the solution includes:

– more saved human lives and health of firefighters and affected people, also saving of flora and fauna in wild areas
– reduction of materials and finance needed for the fire fighting and further recovery
– reduced carbon emissions.

The work objective is to develop a new solution for forest fire monitoring, based on a drone-sensor system, that can be applied to all types of surfaces including rugged and uneven ones.

In our work, we present the architecture and idea of digital twin implementation in forest fires. The work is inspired by the environmental problem raised recently thanks to the wildfires and the necessity to look for solutions for risk management and preventive measures of authorities.

The paper is organized as follows. We define the architecture of the platform at the beginning and continue with the presentation of its parts. Sensors, drones, traveling schedules, and the communication protocol are defined next. In the end, we present services and numerical results.

2 Literature Review and Problem Definition

The creation of a digital twin of the area where wildfire is expected faces multiple challenges. The first question is which areas are more vulnerable to the fires. The authorities in every country in the world create a so-called risk map for the fires and this information is shared with the Emergency Response Coordination Centre [12] and World Health Organization [13]. This study is based on observed fires and historical data from satellites.

Our work proposes a way to build and define the main functions of a digital twin of the areas that are at risk for wildfires. The solution could be used in the short term and be developed in the medium and long term. The idea is to warn citizens and authorities about the risk well in advance and try to localize the source as early as possible. This might be the way to save resources and prevent the environment. Areas protected by Natura 2000, national parks, agriculture crops, and areas with historical significance are also a matter of special interest.

Many papers last years have been published in digital twin development. Basic guidelines on how to correlate real-time data and other data models in the digital copy are presented in [14]. Problems in digital twin development and continuous exploitation are highlighted in [15]. Detailed surveys on technologies and future trends are published by Mihai et al. in [16]. Technology such as FIWARE has a feature to coordinate open data with digital twins [17]. Correlation between Industry 5.0, Society 5.0, and 5G/ 6G networks could be seen in [18]. A serious survey on digital twin implementation for edge solutions is presented in [19]. Implementation with drones could be seen in [20]. Implementation in the metro transport management using a digital twin is shown in [21]. The smart city digital twin idea is presented in [22]. Special attention to security issues is published in [23]. A digital twin of ocean observations and specific implementation in the Baltic Sea is shown in [24]. Many challenges in preparing and exploiting a digital twin in the long term are published in [25].

Most of the wildfire solutions and especially predictions are based on the implementation of Machine Learning and Neural Networks algorithms [26–28]. Correlation with vegetation process similar to the proposed here solution is done in [29]. Special attention is paid to the wildfires spreading [30]. Wildfire path prediction is important for forest fire authorities while planning their activities and evacuating citizens [31].

There are two solutions for wildfire digital twins in [32] and [33]. The first one implements machine-to-machine technologies for interaction between field devices and the digital twin. The work of Sanchez-Guzman in [33] models burning times estimates.

Sensor network implementation for wildfire detection is shown in [34]. Image processing techniques implemented on astronomical images are shown in [35]. Software asset reuse that is important in digital twin technology is seen in [36, 37].

In our work, we present a new forest fire sensor that could be fixed on the trees or flown on a drone. The drone carries the controller that collects near-real-time data from sensors. All data are transferred to the local server and the cloud where the service and the digital twin are fed. Further on by implementing Chandler Burning Index, using real data and historical data, data from other sources such as the predicted risk level of wildfire is analyzed precisely and appropriate alarms are raised to the authorities. The work is supported by projects UFO (emerging indUstries new value chains boosted by small Flying Objects) and 4F (Flying Forest Fires Fighting) [38, 39] where multiple flying object solutions could be seen.

3 Flying Forest Fires Fighting Architecture

The architecture of the 4F platform including the digital twin is presented in Fig. 1. It includes a typical Internet of Things (IoT) solution developed and implemented in the forest. Services for real data monitoring that could be run locally on a server and in the cloud are created. The right part of the picture demonstrates the digital twin structure that is fed by real data from the deployed infrastructure and simulates the rest of the parameters necessary for the simulation of the real environment and the implementation of additional algorithms for risk analyses and disaster prediction.

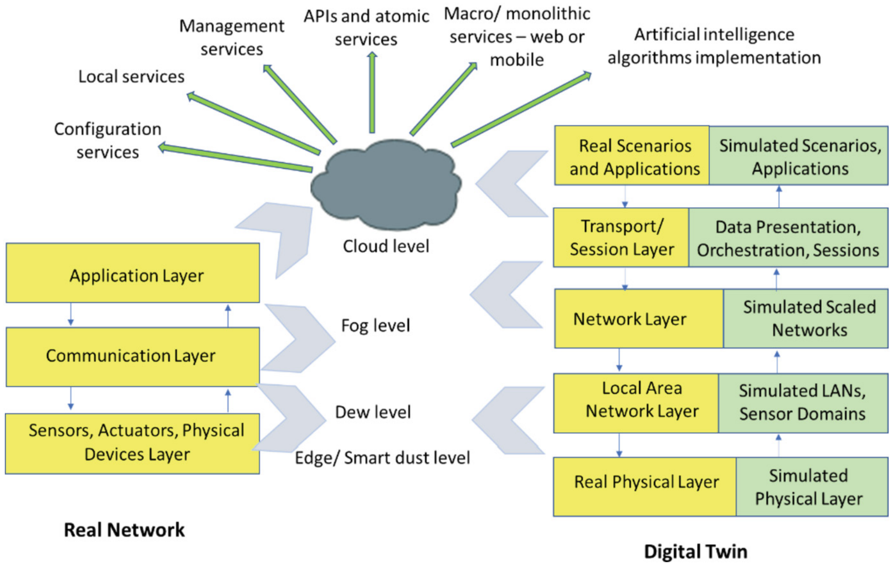

Fig. 1. Flying Forest Fires Fighting Architecture.

The left part of the model has only three layers that are typical for IoT solutions. The right part has 5 layers and every layer is divided into two different sections, one for the real network mirror copy and one for the simulated copy of the network. There are no rules on how to coordinate the real and simulated networks together yet and in our solution we implemented well-known technologies for network simulations from phone and computer networks where the event-driven model is run in different time scales and estimation of the parameters is based on the independent samples of events and the law of large numbers.

The simulated part is developed after a careful study of the nature of the model parameters. It implements different distributions for different types of events. Transitional and steady-state states of the digital twin model are analyzed to allow estimation of events such as the probability of the biomass to fire, estimated time for the biomass to burn, the way and the rate at which the fire might be spread, the correlation between the rate of the wind and the fire spreading pattern in specific forest area, the correlation between the temperature and humidity predictions and fire spreading in short-term, etc.

Where the physical platform is distributed the digital twins of different regions could be centralized or distributed by implementing known cloud/ fog/ dew/ edge computing technologies. This will help the process of enhancements with Machine Learning algorithms, atomic and monolithic services, different APIs, managed services, and many other additional functions.

When developed the model of the forest could be enhanced further with more precise instruments to reach better accuracy in preventing measures. Furthermore, the model could be easily reused in different regions implementing similar sensors or being part of another digital twin for estimation of another disaster such as floods for example.

Digital Twin could become an interesting place for the training of firemen and citizens, especially children and senior adults. The prevention services developed on top of the model may have a high social impact.

4 Drone-Based Sensors

The objective to create a new sensor and to integrate the existing ones into the solution is to perform Earth observation for detection and measurement purposes, before, during, and after a forest fire. Consequently measurements:

- before the fire are useful for risk analyses and prevention
- during the fire are implemented for fire spread analyses, resource damages analyses, and fighting activities planning
- after the fire are important for restoration activities and monitoring as well as for better prevention planning.

Measured parameters are related to climate changes and their level of correlation to the forest fire management parameters and procedures. The solution consists of:

- sensors for measuring soil (or biomass) moisture and temperature, installed in forests (Fig. 2 and Fig. 3)
- sensors for measuring air temperature, humidity, and particle matter mounted on a drone (Fig. 4)
- communication gateway mounted on a drone

Technical challenges solved during the development of the solution are:

A. Selection of microcontroller of the latest generation LoRa (Low Range) radio modules with minimal energy consumption. A study has been conducted on the latest developments of radio modules that implement the latest generation of SX1262 LoRa transmitter, created by the patent holder Semtech Corporation.
B. Minimal energy consumption for measurement and communication. Three models of LoRa radio modules are studied and tested in different operating modes.
C. Optimal use of the capacity of the power supply battery. A battery with optimal characteristics is selected, as well as a low-dropout voltage regulator.

Fig. 2. Soil moisture and humidity sensor

Fig. 3. Air moisture, humidity, and temperature sensor.

Fig. 4. The drone carries sensors and a gateway.

D. Ensured communication exchange between a sensor and a gateway at a certain drone flight speed. A basic algorithm has been developed, that guarantees data communication exchange between the sensor and the gateway in a minimal time slot window.

E. Integrating an antenna with an optimal radiation pattern. Seven types of LoRa antennas have been tested. The selected antenna, that is implemented in the sensor, provides the best communication connection with the gateway on the drone, regardless of the direction of the drone's flight.
F. Measurement of moisture and temperature of soil and biomass at optimal accuracy/energy consumption ratio.

The sensor for Moisture&Temperature (M&T) measuring supports communication according to a Low Power Wide Area Network (LPWAN) protocol and has a probe for soil moisture and T(temperature) measuring.

Contemporary sensors are implemented in the forest that do not require a change of batteries for the lifetime of the sensor.

Because the M&T sensors are spread in a broad range in the forest, the gateways for data collection could not be stationary. This is the reason to propose a gateway that could fly on a drone and collect data from sensors under the flying schedule and routes.

Climate parameters are not changing in real-time and this allows monitoring of the sensor data in non-real-time, i.e. in intervals from hours to days. Drones also could not fly in all conditions.

To avoid missing data, the M&T sensors take measurements periodically and record the average, maximal, and minimal values in buffers for the last 10 days and the last 10 weeks. When a drone appears, the sensors send the buffered data.

The 4F drone-based sensor system is applicable for all types of terrains, incl. rugged and uneven ones, and at the prevention, detection, and restoration phases of wildfires. Our approach is to collect, process, and analyze information from sensors located in forests and on the drone to predict and detect forest fires, as well as to monitor the recovery after fires (Fig. 5).

The main technological challenges are:

– Moisture measurements
– Network planning including drone flight plan and schedule
– Data analyses and risk management using Machine Learning to avoid false alarms.

The focus of the innovation is to use a wireless LPWAN sensor network, where the central communication device called "gateway" is installed on a drone.

If the gateway is located on the Earth's surface, then communication between it and the sensors might be impossible due to the presence of rocks, uneven terrain, and dense foliage, which prevent the propagation of radio waves in the horizontal direction. But if the gateway rises in height, then it can collect data from all sensors within a radius of several kilometers.

The second problem solved is the communication between the gateway and the software IoT platform that collects data from the sensors. Most often, the land surface in forests lacks coverage with 3G/4G/5G communication networks. But when the drone rises above the ground and flies over a wide area, it can get good coverage of the 3G/4G/5G network and transmit the collected data to the IoT platform (Fig. 6).

The innovation is aimed at applying existing technology in a new area, i.e. application of a wireless LPWAN sensor network for the phases of prevention, detection, and restoration of forest fires.

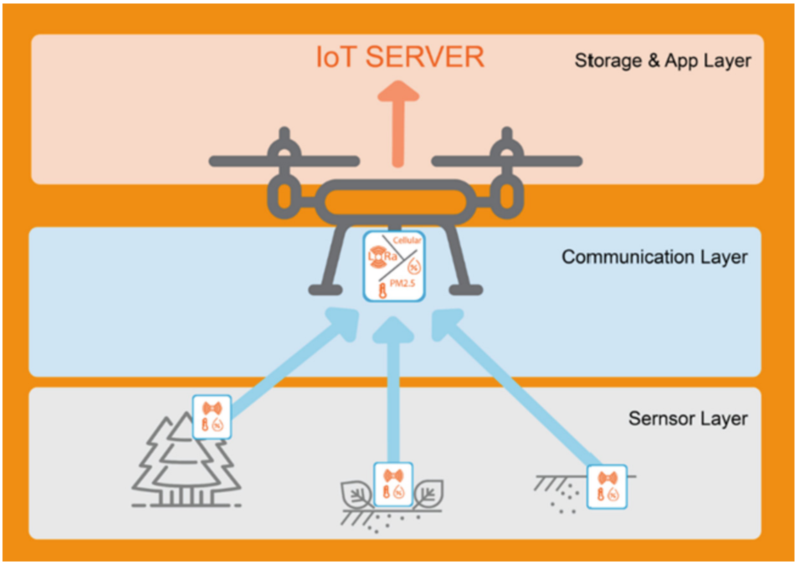

Fig. 5. Collection of data.

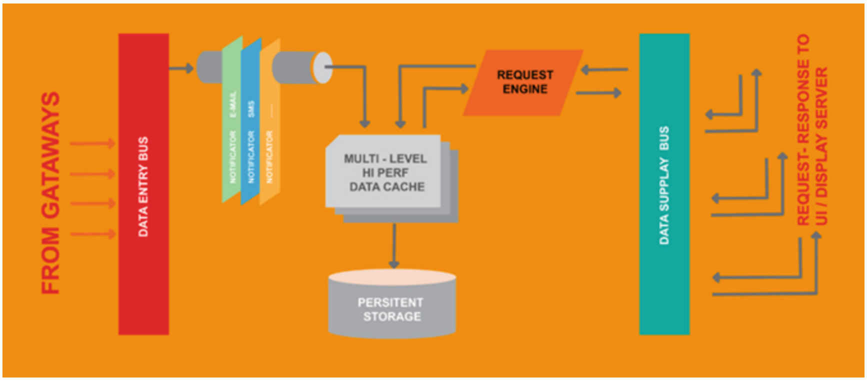

Fig. 6. Gateway structure.

The experiments are organized by:

- semi-professional drone, providing the necessary flight time and power supply for the installed gateway and sensors
- one communication gateway mounted on the drone with the capacity to collect and keep sensors' data from many measuring flights
- set of sensors for measuring temperature, humidity, and particle matters mounted on the drone
- several sensors for measuring soil (or biomass) moisture and temperature, installed in a forest

The monitored forest is flown around periodically. The collected data is processed, visualized, and analyzed. Selection of the most suitable LPWAN technology, radio frequency, modules, sensors, communication devices, and a drone for the experiments is done.

After-fire monitoring is useful for the correct recovery of damaged areas and for further prevention. The data gathered by the drone is collected to the special data matrix and is a matter of further analysis (Fig. 7). The data is also visualized on the map of the area that is under observation (Fig. 8).

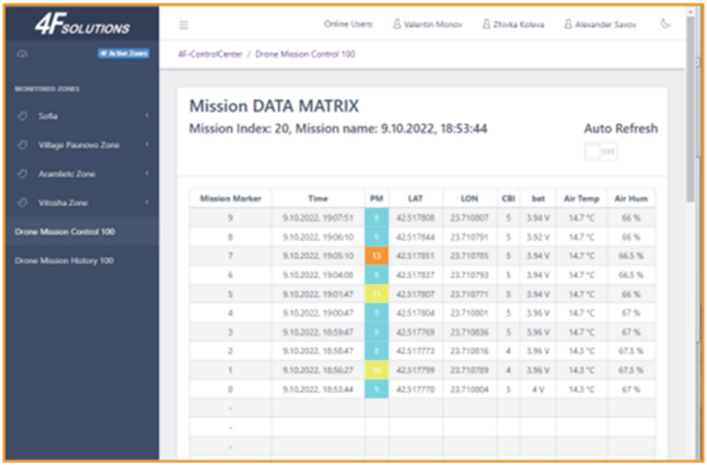

Fig. 7. Mission Data Matrix.

5 Communication Protocol

Successful experiments have been carried through multiple configurations and preliminary results have been obtained to prove the vitality of the solution. The first thing to define was the structure of the payload of the LoRa messages exchanged. Three types of messages are implemented (Figs. 9 and 10):

- DATA
- POLL
- ACK

For every sensor, the DATA message carries message type, sensor number, timestamp, soil moisture, soil temperature, air temperature, air relative humidity, and battery voltage including the data from sensors from the last 15 days. The total payload length is 72 bytes.

POOL message has only 7 or 3 bytes depending on the presence of the timestamp in the payload including also sensor identifier and message type. It is intended to ask for data from the sensor.

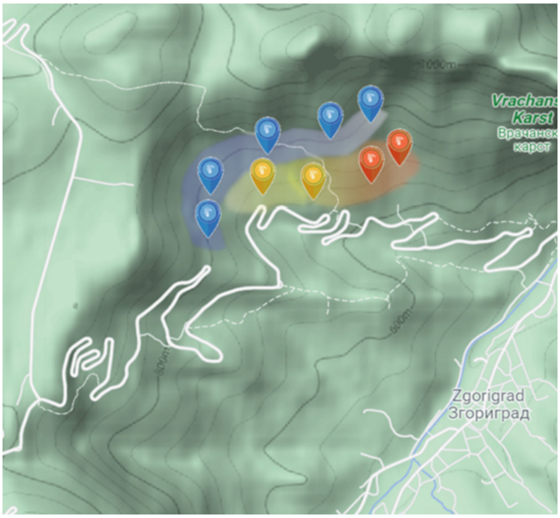

Fig. 8. Map of the area under observation.

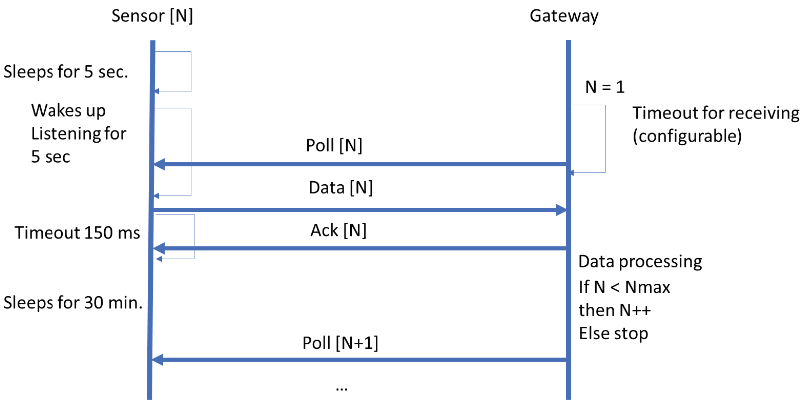

Fig. 9. Standard data poll.

The standard implementation of the LoRa protocol is shown in Fig. 9. The version with data repetition is drawn in Fig. 10. The timeout for receiving data at the gateway could be changed. Every gateway knows all assigned own sensor identifiers and is pooling them one by one. The schedule for pooling could be changed in specific implementations.

6 4F Services

The collected data needs to be not only stored but also analyzed to enable the creation of services and appropriate alarms to the authorities related to the levels of risk of forest fires, detected fires, and the way Nature is restored from fire. This data needs to be also visualized and correlated to the previously defined reference levels and values of wildfire

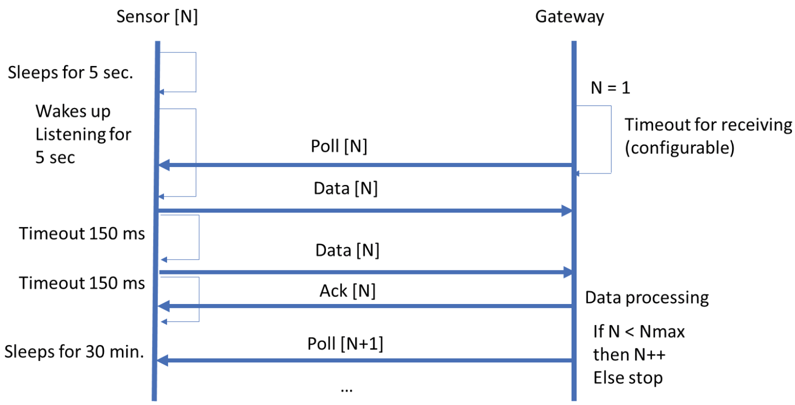

Fig. 10. Data poll with repetition.

management. Data correlation, and data visualization in different scales are supported by the IoT software (Fig. 11). The 4F solution allows the development of new services for fire brigades, citizens, and other stakeholders. Alarms and reports are generated.

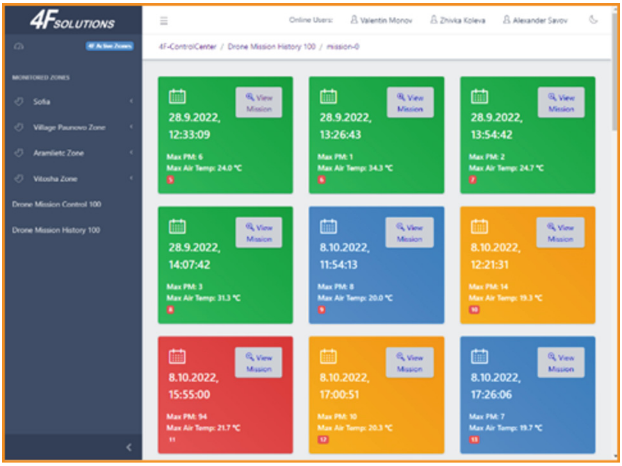

Fig. 11. 4F Services.

The presented service is made out of the near-real-time data collected from the sensors. However, additional data could be implemented and additional simulation modules could be developed in the scope of the local services and digital twin of the area under observation. Configuration and managed services are developed and not included in this paper.

The IoT software platform has functionality for data gathering into the database, map visualization, measurements report, alarms, and reference values for the alarms from sensors. The work is intended for forest fire risk analyses and management at the prevention, detection, and restoration phases. There are many various ways to estimate the fire danger. One of the fastest and easiest is the Chandler Burning Index (CBI). It uses air temperature and relative humidity. That number received is correlated to the Fire Danger severity measured in percentages.

The calculation is based on the following formula

$$CBI = (((110 - 1.373 * RH) - 0.54 * (10.20 - T)) * \left(124 * 10^{-0.0142 * RH}\right)))/60,$$

where RH is humidity in %, and T is temperature in degrees Celsius.

7 Numerical Results

The presented numerical results show only the information necessary for protocol configuration between the gateway and the sensors (Table 1). There is a high correlation between the bandwidth, Spread Factor (SF), number of bytes to transmit, and Time on the Air (ToA). The values for the timeouts in the protocol are selected to succeed the transmission without any problems.

Table 1. Time on air of messages

No	SF	Bandwidth [kHz]	ToA 3 bytes [ms]	ToA 7 bytes [ms]	ToA 72 bytes [ms]
1	SF7	500	7,744	9,024	33,344
2	SF7	250	15,488	18,048	66,688
3	SF7	125	30,976	36,096	133,376
4	SF8	500	15,488	18,048	59,008
5	SF8	250	30,976	36,096	118,016
6	SF8	125	61,952	72,192	236,032
7	SF9	500	25,856	30,976	107,776
8	SF9	250	51,712	61,952	215,552
9	SF9	125	103,424	123,904	431,104

The transmission time of big data messages will limit the number of sensors assigned to the given gateway. There are different scenarios implementing different gateway flying schedules with different sets of sensors. The mapping between the flying plans and sensor network scaling and scenarios implemented are under intensive analysis.

8 Conclusions and Future Work Plans

This work presents an idea of how to build a digital twin of the areas at risk of wildfires. The intention is to define with more precision how Nature could be prevented, how the citizens and local resources could be prevented, and how the local authorities could react in the prevention, detection, and restoration phases of the fires. The platform proposed is open for data and function enhancements. The experiments conducted show the way the data starts from the sensors and goes to the cloud and digital twin.

Potential customers of the 4F solution could be addressed such as:

– Public authorities to assure better protection and reaction to forest fires
– Private forest owners
– Commercial companies who want to install the proposed solution.
– European and national programs for environmental protection

We also work on expanding the 4F solution for alternative applications like agriculture, flood management, draughts management, pipeline inspection, border security, and many others.

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- 2022 - 2023 Prototype Design of the LoRa® Repeater for Unified Signals and Channel Selection Management (LIOREPLICON), National Innovation Fund, Bulgaria.

- 2020–2021 Research and Development of Prototype of Multifunctional IIo LPWAN Communication Model for Wireless Data Transmission of Ecological Parameters Using Sensors – TeleEco, National Innovation Fund, Bulgaria.

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