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# Detection of unauthorized connections to storm drains based on passive radio frequency identification technology

***V.P. Dashevsky*[1], *V.I. Kondratieva*[2], *R.V. Rzhimsky*[1], *A.L. Ronzhin*[1] ✉**

[1] *St. Petersburg Federal Research Center of the Russian Academy of Sciences, St. Petersburg, Russian Federation*
[2] *State Research Institute of Industrial Ecology, Moscow, Russian Federation*

✉ *ronzhin@iias.spb.su*

**Keywords:** storm drains, wastewater, RFID, radio frequency identification, unauthorized connections, protection of water bodies, state environmental control, discharges from industrial enterprises.

**Abstract.** The paper presents the results of research on using radio frequency identification (RFID) technologies to prevent pollution by enabling early detection of industrial discharges. The goal of the study is to develop a method for detecting unauthorized connections to storm sewers using passive RFID technology. The authors justify the choice of passive RFID, based on the EPC Class 1 Gen2 standard (ISO/IEC 18000-63:2021(E)). The authors describe experiments to reliably detect RFID tags floating in protective casings on the water's surface by reader with the antenna positioned 0.5–1.5 m above the water. A key challenge is the difficulty in reading tags directly on the water's surface, as water shields and reflects the reader's electromagnetic waves. Additional tests were conducted to evaluate the impact of tag collisions on the accuracy and completeness of readings, as these collisions may cause missed tags when passing by the reader's antenna. The study confirms that passive RFID can address key challenges in detecting unauthorized storm sewer connections. RFID technology has the potential to improve the efficiency and accuracy of environmental monitoring, reduce control costs, and better protect water bodies from industrial pollution. The research is significant for advancing new methods and technologies in environmental protection and can be applied in state environmental control systems to identify and prevent unauthorized wastewater discharges from industrial facilities.

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## *1. Introduction*

Radio frequency identification (RFID) is widely used for detecting various objects and processes across different fields. One promising application is the use of this technology to identify unauthorized wastewater discharges to storm drains. This is especially important for environmental protection, as pollution of water bodies by industrial wastewater is one of the most serious ecological issues of our time [1, 2]. Pollution caused by industrial wastewater can lead to severe health consequences for the population, such as poisoning, illness, and even death, as well as the death of aquatic flora and fauna, disrupting ecosystems and reducing biodiversity. The ecological damage can affect the economy, particularly sectors like agriculture, fisheries, and tourism [3–5]. Many water bodies also have cultural and social significance for local communities, and their pollution can destroy traditional ways of life and harm cultural heritage.

Therefore, continuous monitoring of water resources and measures to protect water bodies from pollution are essential for adhering to national and international environmental standards and agreements. An important task is the effective detection of unauthorized connections of wastewater to storm sewers, which requires the development of new methods and technologies.

The primary distinction between stormwater drainage systems and industrial or domestic wastewater systems lies in their treatment infrastructure. Stormwater systems are typically not equipped with significant treatment facilities and discharge directly into water bodies. In contrast, domestic and industrial wastewater systems include treatment facilities that process the effluent before release, and the users are required to pay for the treatment of their discharges. As a result, the diversion of pollutants into storm water systems to reduce treatment costs constitutes a violation that must be identified and prevented, making methods to detect unauthorized connections to storm water drains essential.

The following are well-known methods for detecting unauthorized connections, along with their respective advantages and disadvantages [2, 6]:

- Visual inspection and diagnostics (tele-diagnosis method). This method allows for direct observation of the internal parts of the sewer system, helping to identify visible anomalies and unregistered connections. It provides real-time, accurate data about the condition of pipes and infrastructure. However, this method is labor-intensive and often requires the use of specialized equipment, such as remote-controlled cameras, which make it rather expensive.
- Smoke tests. This method is effective in detecting unauthorized connections through visible smoke outlets. It is relatively easy to implement and provides immediate results. However, it can lead to false alarms if there are natural venting points or if the smoke disperses unpredictably.
- Dye injection tests. Dye tests are highly effective in identifying illegal connections, especially when monitoring specific wastewater flows. They provide clear, easily traceable evidence of contamination and help identify the source of the illegal discharge. However, dyes can trigger complaints from the public, as their presence in the water is often perceived as pollution. Additionally, the complete washout of the dye may take a long period, delaying the process of locating the illegal connection. Furthermore, the method may lead to false positives if the dye interacts with other substances in the sewer system, and it can cause temporary environmental disruption while the dye remains in the water.
- Water and wastewater analysis. This method allows for the precise identification of industrial pollutants, heavy metals, chemicals, and biological markers that are indicative of unauthorized wastewater discharges. It is highly reliable for detecting contamination even in small quantities. However, it requires sophisticated equipment and laboratory analysis, which can be costly and time-consuming. Moreover, it may not immediately identify the source of contamination unless extensive sampling is performed.

The RFID-based method of identifying of unauthorized connections presents several advantages. RFID tags are cost-effective, compact, and do not contribute to wastewater contamination, making them an environmentally sustainable solution for detecting unauthorized connections. Furthermore, the electronic product code (EPC) stored in the memory of RFID tag can contain information about the time and location of its drop into the sewer system. This enables efficient, parallel detection of multiple illegal connections across different locations without the need for sequential examination of potential connections.

The main goal of this work was to explore the potential of using RFID technologies to develop sensors capable of promptly identifying unauthorized discharges of untreated wastewater from industrial facilities into storm sewers in urban areas, with the aim of supporting state environmental monitoring and control efforts.

RFID technology is widely employed for the automatic identification and tracking of objects using radio frequency (RF) tags. Its broad applicability is attributed to several key characteristics, such as the ability to read tags contactlessly at a distance, function in low-visibility conditions regardless of object orientation, and simultaneously read multiple tags. Additionally, RFID offers high data processing speeds, making it an efficient solution for various applications. Contemporary RFID systems not only allow for reading information from tags but also enable writing to them. Devices known as readers are capable of modifying or reprogramming the contents of tag memory, significantly enhancing the flexibility and functionality of this technology [7, 8].

RFID technology is classified into two main types: passive and active. Passive RFID tags operate without an internal power source, drawing energy from the electromagnetic field generated by the reader. They have a relatively short reading range (typically up to several meters) but offer advantages, such as durability, low cost, and an extended operational lifespan. Active RFID tags, in contrast, are equipped with an internal battery, enabling a significantly greater reading range (up to hundreds of meters) and additional functionalities. However, they are more expensive and have a finite lifespan due to battery depletion. They also have a risk of environmental contamination from hazardous chemical components. A review of RFID applications for animal tracking [9], based on data collected from 1970 to 2023, identified 70 patents for related devices. Of these, 40 patents were based on the use of passive RFID tags, while only 5 were based on active RFID tags. Thus, passive RFID tags emerge as the most suitable solution for the task of detecting unauthorized connections.

One of the significant challenges in RFID technology is the reduced efficiency of tag detection in dense environments, such as in water. Reading tags at long distances becomes significantly more difficult when the tags are submerged. The presence of water, especially in aquatic environments, introduces additional interference due to the absorption and scattering of radio waves, which diminishes the effective detection range. This is particularly true for ultra high frequency (UHF) RFID systems where the radio frequency waves are highly susceptible to attenuation by water. As a result, the range, at which tags can be read in aquatic environments, is substantially lower compared to air, limiting the ability to track or monitor objects over extended distances.

Despite the significantly reduced detection range of RFID tags in water, especially for UHF RFID [10], they can be used in aquatic environments for applications like fish tracking and underwater navigation. A study [11] demonstrated the use of two types of passive integrated transponder (PIT) tags, with implantation in different anatomical locations of fish. The study confirmed that RFID technology is functional in such conditions, although implantation can affect fish growth and survival. The use of a handheld reader and portable X-ray systems was employed to verify tag implantation and functionality. In [12], two types of antenna systems were described for the detection and abundance estimation of PIT-tagged fish in rivers: a raft-based antenna system and a shore-based floating antenna system. The raft-based system includes a 4.0 × 1.2 m horizontal antenna for shallow river areas and a 2.7 × 1.2 m vertical antenna for deep pools, while the shore-based system spans the entire width of the river, measuring 14.6 × 0.6 m, providing more comprehensive coverage. Both systems faced challenges, such as detection efficiency, which varied depending on tag size, orientation, and the proximity of multiple antennas. Additional challenges in the aquatic environment included interference from metal objects affecting the magnetic field, tag collisions, and the detection of “ghost” tags – those lost due to predation or natural mortality. These limitations required careful system design to maximize detection probability and minimize interference.

In [13], RFID technology was applied for marine sediment tracking using low-frequency tags, including ABS plastic disc tags (30 mm in diameter) and cylindrical glass tags (32 mm in length, 4 mm in diameter). Key challenges in underwater RFID application include the attenuation of electromagnetic waves, which limits signal penetration and reading distance, particularly in saltwater. To address these issues, a waterproof antenna was developed, enabling tag reading at distances of up to 50 cm and depths of up to 5 m, along with wireless data transmission to simplify tracking.

In [14], the application of passive UHF RFID tags for detecting blockages and unauthorized connections in sewer systems was explored. A total of 12 types of UHF RFID tags and three antennas with different gains (8, 9, and 12 dBic) were evaluated. Based on factors, such as cost, size, and maximum reading range, three types of tags were selected. The experiments revealed that tag sensitivity was influenced by their position relative to the reader antenna, the material of the casing, and the volume of air inside the casing. As a result, PLA plastic was chosen for the casing, with the internal area optimized for the selected tag types. Field tests were conducted using a 9 dBiC antenna due to its size and ease of installation. The optimal detection range was found to be between 0.6 and 3.5 m. The sensors demonstrated good resilience to flow conditions and solid waste in domestic wastewater. The study shows that UHF RFID sensors can provide a high-performance, reliable, and non-invasive method for real-time monitoring of sewer systems.

The primary objective of this study was to evaluate the feasibility of using EPC Class 1 Gen2 RFID technology with low-cost, commercially available RFID tags and to assess their performance in water-proximate environments, such as storm sewer systems. A key focus was the development of a method to encapsulate RFID tags in a lightweight, sealed, and radio-transparent casing, allowing them to function as sensors capable of transmitting data from a safe distance while protecting the reader equipment from water exposure. Additionally, the study aimed to investigate how the received signal power, measured by the reader’s Received Signal Strength Indicator (RSSI), varies with the distance between the antenna and the water surface on which the sensor is placed.

# 2. Methods

The general scheme of passive RFID technology application for storm sewer monitoring includes the following steps. The sensor undergoes initial initialization, during which:

- The EPC of the embedded RFID tag is programmed, including information about the location and time of its drop into the sewer system.
- If necessary, the tag information is additionally logged into the monitoring journal for further analysis of the percentage of lost tags.

After completing the initial initialization, the tag is dropped into the discharge manhole, after which it begins to move through the sewer system pipeline with the water flow. Since RFID technology incorporates an anti-collision algorithm for tags, readers can simultaneously detect multiple tags, enabling parallel monitoring of several industrial facilities for unauthorized connections as shown in Fig. 1.

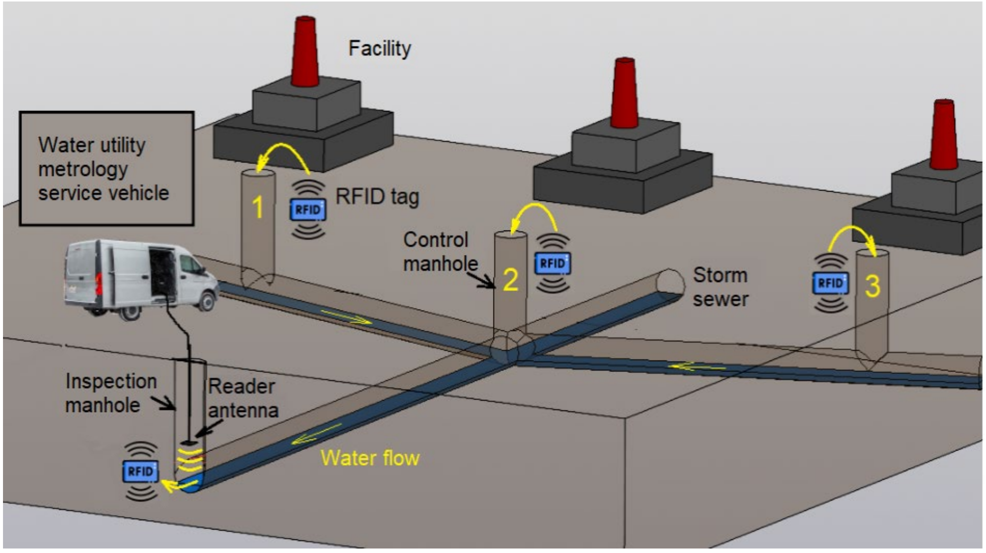



**Figure 1. General scheme of passive RFID technology application for inspecting the sewer pipeline.**

Multiple sensors can be dropped simultaneously into the control manholes of different facilities. After this, the reader antenna is lowered into the inspection manhole in such a way that the distance from the antenna to the water surface ranges from 0.5 to 1.5 m. Placing the antenna too close is undesirable for two reasons. First, the radiation pattern in close proximity to antenna body is still forming and may have areas with poor sensitivity, resulting in incomplete coverage of the water surface where a sensor might appear beneath it. Second, it has high risk of splashing, which could wet the antenna due to water flow and poor visibility inside the manhole. On the other hand, placing the antenna too far away will lead to significant signal attenuation, negatively affecting the detection quality of passing sensors.

The reader and its controlling computer (laptop) of the metrology service are located in the vehicle. The antenna is connected to the reader via a coax cable, the length of which allows the antenna to be lowered into the manhole at a distance of approximately 1±0.5 m from the water surface. This approach reduces the requirements for the reader's power and sensitivity and allows the use of less expensive tags for discharge into the manholes.

The experimental setup employed the ThingMagic M6-EU (UHF EPC GEN2) reader [15], capable of emitting a maximum power output of 1.4 W, which facilitates a reading range of up to 10–15 m in free space conditions. The reader was paired with the MT-242014/NRH/K antenna (865–870 MHz, 8.5 dBic RHCP), specifically optimized for extended reading distances. To mitigate potential signal attenuation due to cable losses, the antenna was connected to the reader using a 10-meter RG58 coaxial cable. This configuration accommodated the operational requirement of lowering the antenna into a manhole while maintaining an adequate distance from the measurement system.

The reader antenna is mounted beneath the ceiling of the room at an approximate height of 2.2 m above the floor. A support surface is positioned beneath the antenna at the maximum investigated distance of 150 cm. A plastic, radio-transparent container filled with water is then placed on this surface. The use of a radio-transparent container ensures that no interference is introduced to the reader's electromagnetic field. With the sensor floating on the water surface, measurements of the received signal are conducted. The experiment is subsequently repeated for the next distance. The distance between the antenna and the tag is adjusted using spacer boxes, each 25 cm thick, which are stacked beneath the water container as shown in Fig. 2.

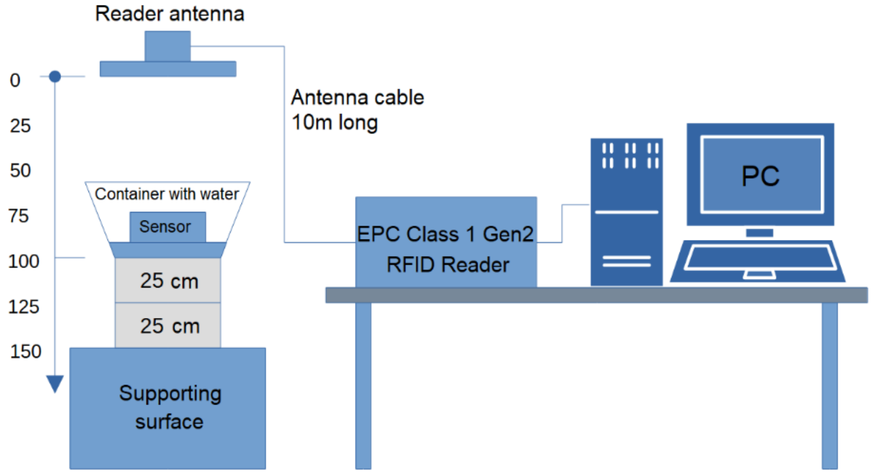
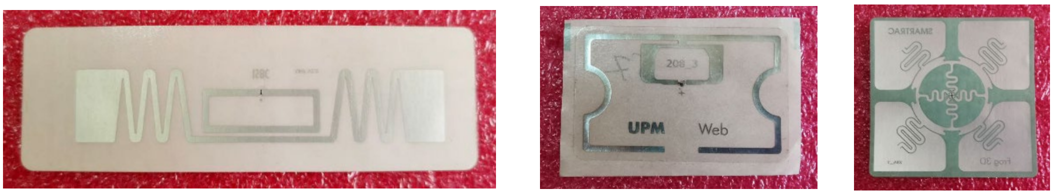



**Figure 2. Experiment for evaluating RFID tag read range in water.**

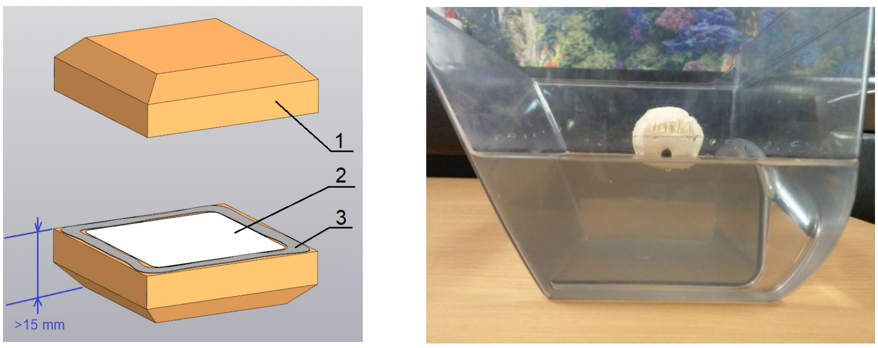
For the experiments, three types of RFID tags compliant with the EPC Class 1 Gen2 standard were applied (Fig. 3). These tags differ in antenna size and shape. The primary objective of employing multiple tag types was to investigate the relationship between the tag's reading range and orientation relative to the antenna's size and topology.




**a) NXP ISBC UCODE8, 87 × 27 mm** **b) Raftalac UPM Web, 54 × 34 mm** **c) Raflatac Frog 3D, 53 × 53 mm**

**Figure 3. RFID tags inlays of EPC Class 1 Gen2.**

The preliminary experiment with the provided RFID tags involved embedding them into a 3 mm thick plywood casing. The tags were successfully read in air; however, reading ceased after they were submerged in water. Two primary reasons account for this effect. Firstly, the distance between the tag and the main body of water was very small, around 1 mm. Secondly, plywood is highly susceptible to water absorption, as it readily wets and absorbs water into its porous wooden layers. Both factors lead to the blocking of the electromagnetic field, preventing the tag from receiving energy and interacting with the reader. Therefore, the casing had to be significantly improved for further work. Foamed polystyrene was chosen as the new casing material due to its substantially lower density compared to wood. Additionally, its low wettability prevents the formation of a continuous shielding water film on the casing surface. The thickness of the casing was increased to 40 mm to ensure the tag insert was sufficiently displaced from the water surface. An overall structure of the sensor, an encapsulated RFID tag, is shown in Fig. 4.




**a)** **b)**

**Figure 4. Sensor construction: a) exploded view, b) placement on water.**

The RFID tag inlays (2) were glued into the protective casing (1), made of polystyrene, by forming an adhesive seam (3) around the perimeter of the inlay. Foamed polystyrene is easy to cut and glue, which reduces the cost of manufacturing tags for use in sewer systems. The bright orange color makes them highly visible in natural conditions.

The dimensions of the sensors exceeded the size of the inlays by approximately 10 mm on each side. For example, a tag with an NXP ISBC UCODE8 inlay measuring 87 × 27 mm, when placed in the casing, had overall dimensions of 110 × 50 × 40 mm. Initial experiments with sensors encased in polystyrene demonstrated excellent results on water. Some tags were consistently read from distances of up to 2 m at the reader's maximum power. These sensors were subjected to a series of experiments to determine the conditions for stable tag reading at various reader power levels, as well as in scenarios involving potential collisions where multiple tags are simultaneously within the reader's field of view.

## *3. Results and Discussion*

Two series of measurements were conducted during the experimental work. In the first series, a single tag was placed in the reader's field at a time (single-tag setup). In the second series, all three tags were placed simultaneously (multi-tag setup), but measurements were taken for a specific type of tag that was positioned optimally relative to the antenna, providing the highest received signal level.

Each series of experiments involved varying two parameters:

1. **Reader transmission power** was varied from +30 dBm to +10 dBm in increments of 5 dBm. Here, 0 dBm corresponds to a power of 1 mW, thus +30 dBm = 1 W, +20 dBm = 0.1 W, etc.
2. **Distance from the antenna to the sensor** was varied from 50 to 150 cm in increments of 25 cm.

To assess the reliability of tag reading, two characteristics were measured in each series:

1. **RSSI.** Measured in dBm, the RSSI values typically fall below –35 dBm due to the weak reflected signal from the tag.
2. **Tag Read Rate.** This metric demonstrates the reliability of tag reading and the distance, at which signal degradation begins, leading to an increase in errors in the received signal.

**RSSI.** RSSI measures the power level of the signal received by the reader from the tag. It depends on the distance between the tag and reader, as well as environment like nearby metal, water, or other reflective surfaces. Since the reflected signal is typically weak, RSSI values are negative.

A high RSSI indicates a strong signal, high signal-to-noise ratio, and reliable communication, while a low RSSI suggests a weak signal and potential communication issues when the signal approaches noise levels.

RSSI analysis helps to diagnose and optimize RFID system performance. By identifying the signal level, at which tag reading becomes unstable or fails, and testing under various antenna and tag configurations, optimal reader and antenna placement can be determined. For fixed antenna setups, RSSI assists in defining optimal signal levels, guiding technical requirements for commercial readers in future measurement systems.

**Tag Read Rate.** The read rate parameter, measured in Hz, represents the number of tag detections per unit of time and is available through the reader's serial software. It is assumed that as the tag moves farther from the reader, signal errors increase, leading to a decrease in read rate and missed detections. By monitoring this parameter, one can determine the stable reception zone where tags are detected reliably, as well as the distance at which error rates reach 50 %.

In practice, readers typically accumulate tags over extended periods. The number of tag queries per inventory cycle in an EPC Class 1 Gen2 system depends on factors, such as channel access control and tag density. EPC Class Gen2 uses the ALOHA slotting algorithm to minimize collisions when multiple tags respond simultaneously. The reader initiates the inventory cycle by sending a Query command, which includes a Q parameter defining the number of time slots $2^Q$. Tags randomly choose a time slot, and if two tags select the same slot, a collision occurs, and the reader cannot receive valid responses. Tags not acknowledged in the current cycle are re-invited in the next cycle. This process repeats until all tags are identified. As cycles progress, tags choose different slots, reducing collision likelihood.

A single ALOHA slot [16, 17] takes about 400–600 µs. While one-slot inventory is possible, it guarantees collisions of several tags. Therefore, Q values of 3 or 4 (8 or 16 slots) reduce the collision probability. Consequently, an elementary inventory cycle lasts approximately 9.6 ms (600 µs * 16). Typically, readers perform long inventory cycles (0.5–1.5 s), comprising 50 to 150 elementary cycles, and a tag is considered detected if it is identified at least once. This makes the read rate less informative, as the likelihood of missing a tag after 50–150 attempts is almost zero, unless the tag moves out of range. As the tag moves further from the antenna, the RSSI decreases, but the read rate remains constant until it abruptly disappears. To improve the read rate's accuracy, inventory cycles should be shortened to single Query requests, though this is only available through the reader's API, not implemented in demonstration software we used. The results of reading tags in single-tag setup after processing are summarized in Table 1.

***Table 1. Measured RSSI from different tag types in a single-tag setup.***

| Reader power (dBm) | Distance (cm) | RSSI (dBm) | | | Read rate (Hz) | | |
|---|---|---|---|---|---|---|---|
| | | Tag 01 | Tag 02 | Tag 03 | Tag 01 | Tag 02 | Tag 03 |
| +30 | 50 | –54 | –58 | –45 | 19.70 | 19.97 | 19.91 |
| | 75 | –57 | –59 | –44 | 20.09 | 19.90 | 19.90 |
| | 100 | –59 | –65 | –47 | 20.10 | 19.95 | 19.90 |
| | 125 | –63 | –66 | –54 | 19.99 | 19.96 | 19.99 |
| | 150 | –67 | –71 | –57 | 19.96 | 19.92 | 19.87 |
| +25 | 50 | –54 | –58 | –45 | 20.15 | 20.06 | 19.90 |
| | 75 | –58 | –60 | –48 | 20.11 | 20.05 | 20.04 |
| | 100 | –60 | –64 | –52 | 20.11 | 20.05 | 19.99 |
| | 125 | –64 | –66 | –57 | 20.10 | 20.10 | 20.08 |
| | 150 | –69 | –[1] | –60 | 20.10 | – | 19.97 |
| +20 | 50 | –52 | –59 | –44 | 19.72 | 19.32 | 19.45 |
| | 75 | –60 | –62 | –51 | 19.44 | 19.55 | 19.36 |
| | 100 | –62 | – | –55 | 19.60 | – | 19.49 |
| | 125 | –66 | – | –60 | 19.54 | – | 19.34 |
| | 150 | –70 | – | –63 | 19.53 | – | 19.40 |
| +15 | 50 | –53 | – | –47 | 16.19 | – | 16.22 |
| | 75 | –62 | – | –54 | 16.22 | – | 16.23 |
| | 100 | –64 | – | –57 | 16.24 | – | 16.23 |
| | 125 | –70 | – | – | 16.24 | – | – |
| | 150 | – | – | – | – | – | – |
| +10 | 50 | –55 | – | –50 | 19.94 | – | 20.25 |
| | 75 | –62 | – | – | 20.27 | – | – |
| | 100 | – | – | – | – | – | – |
| | 125 | – | – | – | – | – | – |
| | 150 | – | – | – | – | – | – |

Notes: 1. A dash indicates that the tags could not be read under those conditions. 2. In the obtained data, for the reader power level of +15 dBm, a drop in the reading speed from about 20 to 16 times per second is observed. For the reader power level of +10 dBm, a speed recovery of about 20 times per second is observed. To assess the impact of tag collisions, all samples of three tags were simultaneously placed in a container with water.

In addition to testing the reading of a single tag, the system's performance with multiple tags is also of interest, as the tags can accumulate in the control zone of a sewer pipeline [18–21]. The reading process becomes more challenging due to the following two factors. First, tag collisions may occur during the inventory process, requiring the execution of an anti-collision algorithm. This introduces a delay, increasing the minimum required time a tag must remain in the field, thereby limiting the maximum read rate, particularly for a tag moving under an antenna with a narrow beamwidth. Second, tags draw energy from the reader's RF field, which imposes a load on the reader. As a result, in a multi-tag setup, there is a tendency for the read performance of individual tags to degrade. In addition, there are other negative factors associated with the aquatic environment, information security, dense and dynamic distribution of sensors in a wireless sensor network, which significantly complicates the operation of RF technologies [22-25]. To assess the impact of these effects, an experiment was conducted, in which all three tags were placed in a water container simultaneously.

The measurement results for multi-tag setup are presented in Table 2.

***Table 2. Measured RSSI from different tag types in a multi-tag setup (collision test).***

| Reader power (dBm) | Distance (cm) | RSSI (dBm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Tag 01 | | Tag 02 | | Tag 03 | |
| | | together | single[1] | together | single[1] | together | single[1] |
| +30 | 50 | –55 | –54 | –59 | –58 | –47 | –45 |
| | 75 | –58 | –57 | –66 | –59 | –50 | –44 |
| | 100 | –63 | –59 | –68 | –65 | –49 | –47 |
| | 125 | –65 | –63 | –64 | –66 | –57 | –54 |
| | 150 | –68 | –67 | –66 | –71 | –65 | –57 |
| +25 | 50 | –57 | –54 | –58 | –58 | –50 | –45 |
| | 75 | –63 | –58 | –64 | –60 | –56 | –48 |
| | 100 | –66 | –60 | –69 | –64 | –56 | –52 |
| | 125 | –66 | –64 | –67 | –66 | –61 | –57 |
| | 150 | –71 | –69 | –[2] | – | –64 | –60 |
| +20 | 50 | –58 | –52 | –60 | –59 | –52 | –44 |
| | 75 | –60 | –60 | – | –62 | –58 | –51 |
| | 100 | –63 | –62 | – | – | –57 | –55 |
| | 125 | –70 | –66 | – | – | –62 | –60 |
| | 150 | –74 | –70 | – | – | – | –63 |
| +15 | 50 | –60 | –53 | – | – | –55 | –47 |
| | 75 | –62 | –62 | – | – | –56 | –54 |
| | 100 | –70 | –64 | – | – | –61 | –57 |
| | 125 | – | –70 | – | – | – | – |
| | 150 | – | – | – | – | – | – |
| +10 | 50 | –63 | –55 | – | – | – | –50 |
| | 75 | – | –62 | – | – | – | – |
| | 100 | – | – | – | – | – | – |
| | 125 | – | – | – | – | – | – |
| | 150 | – | – | – | – | – | – |

Notes: 1. These columns are copied from table with single-tag setup for reference. 2. A dash means that there was no response from the RFID tags.

The results of the experiment (see Tables 1 and 2) show that with sufficient reader radiation power, all types of tags are successfully read at the specified distances with sufficient speed. The water surface at frequencies in the 868 MHz range works as a thin metal screen. Tags whose antenna is located in the water column or directly on the water surface are shielded by water and are not read. Tags located above the water surface are read. Tags in a lightweight case, which provides a distance from the plane of the tag insert to the water surface of 15 mm, are read reliably.

For reliable tag reading at distances of 50–150 cm, high reader power is not required. The experiments showed that tags with large antennas can be read from any distance within this range with a reading power of 20 dBm or higher, which corresponds to a power of 100 mW. Therefore, a reader power range of 150–250 mW is recommended, as this margin will allow for future simplifications in antenna design, reduced antenna size, and lower antenna cost.

The measured data indicates that a power of 15 dBm is insufficient for reading tags at distances greater than 1 m, and this effect is not related to tag shielding by water. A similar behavior is observed for tag inlays without any enclosure. This is likely due to the fact that when the energy density of the field drops below a certain threshold, the energy received by the tag's antenna becomes insufficient to power the embedded chip, preventing it from processing incoming queries from the reader.

As can be seen from the data in Table 1, the last recorded RSSI value differs for different tags and reader power as the tag is moved away from the reader antenna. Thus, for tag type 01, the RSSI value drops to –70 dBm, and for tag type 02, the maximum RSSI changes from –71 to –62 dBm. It can be concluded that the reason for tag loss is not related to the sensitivity of the reader when receiving a signal, since in this case the maximum range would correspond to approximately the same RSSI level of –70 dBm, but to a decrease in the energy received by the tag chip from the incident electromagnetic wave. Starting from a certain distance, the tag simply does not have enough energy, and it stops responding. From this point of view, the NXP UCODE8 tag is the most energy-efficient, it is capable of responding at the weakest signal. The Rafsec Frog 3D tag has a good antenna but a less energy-efficient chip compared to the NXP UCODE8. This is noticeable because its signal is about 10 dB higher, but the maximum range is shorter, apparently for the same reason, the lack of field energy to power up the tag embedded chip. However, a more powerful response signal is an advantage for less sensitive readers, and the Rafsec Frog 3D tag is more compact than the NXP UCODE8, 53 mm versus 87 mm.

During the experiments, it was found that the read rate of all tags approximately corresponds to the processing speed of the reader during its accumulative read process. Reading of a single tag occurs reliably 16–20 times per second and is practically independent of the distance. This can be explained by the characteristics of the reader's software implementation as described above.

Experimental data show that when several tags appear in the antenna field at the same time, the reader's radiation energy is distributed between several tags, causing the signal from them to weaken, which can be seen when comparing the data in Table 2. As can be seen from the data, the presence of three tags in the field of one antenna simultaneously reduces the reading range of each by about 25 cm. At the same time, two tags with the largest antennas retained readability at all distances at a power of 20 dBm and higher.

## *4. Conclusions*

Based on an analysis of existing RFID technologies, passive RFID technology, specifically the EPC Class 1 Gen2 standard (ISO/IEC 18000-63:2021(E)), was selected to address the problem of detecting unauthorized wastewater connections to storm sewers. Experimental studies demonstrated the stable detection of encased RFID tags on water surfaces from a distance of 0.5–1.5 m, using a directional antenna connected to a serial RFID reader with its demo software. As a result of the study, a list of key technical characteristics of RFID tags was compiled, along with specifications for the RFID reader equipment, to ensure optimal performance in storm sewer conditions:

1. Passive RFID EPC Class 1 Gen2 technology can be used to track water flow at speeds of up to 8 m/s from a distance of 50 to 150 cm. For the territory of Russia, it is necessary to select equipment that supports the European frequency range of 868 MHz. To implement this technology, readers with a power output of 150 mW and a sensitivity of –70 dBm can be applied.
2. For use as sensors, tags that support an EPC length of 128 bits are optimal. A shorter length complicates the encoding of information about the place and time of tag reset, longer EPC lengths will slow down reading and will negatively affect the detection of tags in a fast flow of water in the event of possible collisions.
3. For stable reading across the full range of distances, NXP UCODE8 (antenna size 87 × 27 mm) and Rafsec Frog 3D (antenna size 53 × 53 mm) tags are appropriate, as their antennas provide sufficient power to the embedded chip. These dimensions are compatible with the required specifications for storm sewer pipes with diameters of 200 mm and above.
4. The technology works with tags from different manufacturers, which simplifies supply tasks. The cost of EPC Class 1 Gen2 RFID tags suitable for making sensors is about 20–25 rubles per piece, plus the cost of encapsulation in a lightweight non-wetting case made of foamed polystyrene or other lightweight radio-transparent material.
5. The reader must have the following external interfaces for connection to the control computer: Ethernet, RS-485. These two interfaces allow the implementation of control software in any operating system. In contrast, the use of a USB interface may require specific device drivers and additional system software to facilitate communication with the reader, potentially limiting the choice of operating systems.
6. The antenna can be connected to the reader via a long cable, extending to a distance of 10 m or more, thereby enabling the antenna to be positioned closer to the water surface within the storm drain inspection hatch.

Thus, RFID methods for detecting unauthorized connections to storm sewers have advantages, such as mobility, autonomy, the ability to simultaneously monitor multiple drains, high speed and efficiency of data reading, protected by error correction codes. The use of RFID methods for the rapid detection of unauthorized connections is a promising and important direction to ensure effective environmental control (supervision) of this type of violation of environmental legislation and sustainable development of cities and towns.

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***Information about the authors:***

***Vladimir Dashevsky**, PhD in Technical Sciences*
*E-mail: vladimir.dashevsky@gmail.com*

***Victoria Kondratieva**,*
*E-mail: v.kondrateva@promeco-inst.ru*

***Vasily Rzhimsky**,*
*E-mail: vladimir.dashevsky@strategic-it.ru*

***Andrey Ronzhin**, Doctor of Technical Sciences*
*E-mail: ronzhin@iias.spb.su*

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