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RADIO FREQUENCY IDENTIFICATION IN TRANSPORT APPLICATIONS

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Abstract. RFID (Radio Frequency Identification) has been widely used in many areas of science and technology as well as everyday life. An intensively developing line of RFID applications is the identification of fast-moving transport objects. Despite numerous scientific articles, the latest results on the subject are poorly reflected in the existing surveys. This paper fills the gap by overviewing key publications on RFID technologies and standards and the features of signal propagation in a wireless communication channel between RFID tags and a reader. We describe related theoretical and experimental results as well as the architecture and hardware and software tools for the practical implementation of ground vehicle identification systems. In addition, this survey covers publications on utilizing RFID on the base of unmanned aerial vehicles.

Keywords: radio frequency identification, transport, unmanned aerial vehicle, reader, tag.

INTRODUCTION

Radio Frequency Identification (RFID) has been widely used in many areas of science and technology as well as everyday life (libraries, stores, subway and bus check-in, etc.). Every year the number of RFID applications grows, and the number of research works on various issues of this subject increases accordingly.

The survey [1] listed the following areas of utilizing RFID: transport, agriculture and livestock farming, healthcare and welfare, environmental applications, and protection and security. These areas can be extended and refined: RFID is utilized in construction, transportation of materials and cargoes, tracking and controlling the speed of special vehicles, and their parking [2].

Logistics can be considered an independent large area of RFID applications. Dozens of papers have been devoted to this issue; for details, see the overview [3]. Effective RFID applications for object positioning, navigation, as well as labeling and searching various objects indoors, where GPS is difficult to use, were described in the survey [4]. Labeling is performed by placing low-cost passive RFID tags on identified objects that contain information about their exact position. Often such systems are used as an assistant for visually impaired people in public spaces such as subways [4].

In the recent decade, an intensively developing line of RFID applications is the radio frequency identification of fast-moving vehicles (cars, trains, and unmanned aerial vehicles (UAVs)). However, the corresponding theoretical and practical studies have been poorly overviewed in the world literature. This paper is intended to fill the gap.

The remainder of this paper is organized as follows. Section 1 briefly describes RFID technologies and standards, including the relevant terms. In Section 2, the features of signal propagation are considered and the performance characteristics of wireless communication between an RFID tag and a reader are estimated. Also, the works on the mathematical methods of radio channel design in RFID systems are surveyed. In Section 3, we overview publications on utilizing RFID on the base of ground transport (car roads and railways). Theoretical and experimental results, as well as the architecture and hardware and software tools for the practical implementation of ground vehicle identification systems, are described. Finally, Section 4 covers publications on utilizing RFID on the base of UAVs.

1. RFID STANDARDS

RFID is a technology that labels and automatically identifies objects: the data stored in RFID tags are read or written using radio signals. The simplest RFID system consists of at least two parts: tags (radio electronic devices placed on an identified object) and readers (active devices initiating the procedure of data exchange). An important feature of RFID systems is that, as a rule, tags are passive devices without a built-in power source that wait for the initiation of data exchange by a reader. Therefore, tags are cheap and simple and can be placed on most everyday items in retail stores (clothing labels, book covers in libraries, and so on. Also, an RFID system possibly contains other devices to extend its functionality or is part of a larger system. For example, data received by a reader can be sent via other communication protocols to a remote database.

Semi-passive and active tags were developed to increase the number of tasks fulfilled by RFID systems. Semi-passive tags have an energy source (lithium or solar battery) supplying power to the embedded chip. Accordingly, they receive and transmit signals to significantly greater distances compared to their passive counterparts. Semi-passive tags cannot generate a high-frequency signal to initiate a communication session. They can only modulate the reader's field similar to the passive ones. Active tags have another principle of operation because they include an active transmitter and sometimes a receiver. They emit a high-frequency electromagnetic field to transmit data to the reader instead of modulating the reader field.

There are three main transmission bands in RFID, each with particular standards:

– *The low frequency* (LF) *band*, 30–300 kHz, is used for close communication between a tag and a reader at a distance of up to 1 cm [5].

– *The high frequency* (HF) *band*, 3–30 MHz, is used for communication at a distance of 0–1 m [6].

– *The ultra-high frequency* (UHF) band, 860–960 MHz, is used for communication and identification at a distance of above 1 m [7].

RFID has been widely used in various areas since the late twentieth century. In addition to classical applications (identifying objects in stores and warehouses, creating electronic access cards, etc.), this technology can be used for positioning mobile objects [8–10] or assisting to find handicapped people lost in a city [11]. For a detailed description of RFID, we refer to Finkenzeller's handbook [12]. The further presentation deals with UHF RFID only since exactly this technology identifies objects equipped with RFID tags at significant distances from a reader placed on a UAV or above the roadbed.

The EPC Class 1 Generation 2 standard [7] (ISO/IEC 18000-6C, GOST R 58701-2019) [13] describes the physical (PHY) and channel (MAC) layers of an RFID system for passive and semi-passive tags. At the physical level, the standard specifies signal modulation and coding methods; at the channel level, the data exchange protocol between a reader and tags. This protocol is based on the Slotted ALOHA standard [14]. It eliminates collisions when several tags are located in the reader region and contains means for reading and writing data to tags.

Standard protocols supported by most suppliers are used to connect RFID readers to control systems. Low Level Reader Protocol (LLRP) [15] defines a low-level interface between a reader and a controller. This protocol allows executing arbitrary access and inventory operations, tuning the reader's radio interface parameters, as well as receiving the radio channel's status data and diagnostic data on the reader's operation. LLRP is supported by most existing readers. The standard defines the possibility of protocol operation over *transport layer security* (TLS) channels. Besides LLRP, the EPCglobal organization published several standards [16–19], which can be used when designing a reader and a control system. The Reader Management 1.0.1 (RM) standard [16] defines a system model and *Management Information Base* (MIB) for collecting reader's status data via the SNMp protocol. Discovery, Configuration, and Initialization (DCI) for Reader Operations [17] is a standard allowing a reader, controllers, and LLRP clients to find each other in a network, authenticate between controllers and readers, manage the operation of readers, download new software images, and perform other service functions. The Application Level Events (ALE) Specification [18, 19] describes recommendations for middleware development.

RFID standards are being improved: new additions and specifications appear. In 2020, RAIN RFID Alliance proposed a specification for the interface between a reader and a controller [20]. This specification has a higher level compared to LLRP. It describes basic actions including reader configuration and status retrieval, radio protocol settings, and tag access. The specification defines messages transmitted between a reader and a controller in the JSON format, as well as their use to identify transport vehicles [21].

2. STUDIES OF THE WIRELESS COMMUNICATION CHANNEL OF RFID SYSTEMS

Signal attenuation in the wireless communication channel of a UHF RFID system significantly affects the identification range of an object (the distance between a tag and a reader). The identification range is one of the most important performance indices of RFID systems: the fundamental possibility of utilizing RFID in transport depends on this parameter.

The works of K.V. Rao and P.V. Nikitin considerably contributed to studying signal attenuation in the channel and characteristics of the communication protocol of the UHF RFID standard. In particular, the publications [22–24] described the parameters and structure of passive tags, as well as antenna devices in their composition, which have the greatest impact on the reading range in a UHF RFID system. They include the following:

- The tag chip sensitivity threshold P_{th}, i.e., the minimum power required to activate an RFID chip. The lower this threshold is, the greater the distance of tag identification will be.
- The tag antenna gain G_r, which depends on the directional pattern and is limited by the operating frequency and the tag size.
- The polarization matching coefficient χ, which characterizes the coincidence between the polarizations of the tag and reader antennas. The polarizations must match in order to increase the range.
- The power transfer coefficient τ characterizes the impedance matching between the antenna and the chip, also affecting the range.

The power P_{tag} required to activate a tag satisfies the inequality [25, 26]

$$P_{tag} = P_t G_t Pl G_r \chi\tau \geq P_{th},$$

where P_t is the power radiated by a reader; G_t is the reader antenna gain; Pl is losses on the signal propagation path. Note that the maximum permissible value of the reader power is limited by legislation (e.g., 4 W in the USA).

The probability of successful tag detection significantly depends on the characteristics of the communication protocol and noisy signals from other readers and tags. An ideal reader can always detect a passive RFID tag if it receives sufficient energy for activation and backscattering. As a rule, in the UHF band, the required power received by a tag is estimated using the free-space signal propagation model based on the Friis transmission formula [27]

$$P_r = \frac{P_t G_t(\theta,\phi) G_r(\theta,\phi)\lambda^2}{(4\pi)^2 r^2},$$

where P_r is the power received by the tag; λ is the wavelength; r is the distance between the antennas; θ and ϕ are the angles of azimuth and elevation, respectively, showing the dependence of the directional pattern on the position in space; finally, the subscripts t and r indicate "*transmitter*" (usually refers to a reader) and "*receiver*" (usually refers to a tag), respectively. Nowadays, the estimates can be essentially refined through the complex modeling of electromagnetic wave propagation considering various parameters of the receiver, transmitter, and signal propagation channel [28].

Since passive tags dominate due to their low cost and simplicity, their sensitivity and design features are the main limiting factors for the communication range of an entire RFID system. Therefore, numerous studies have been devoted to their design; see the survey [29]. The paper [30] presented the results of testing many types of tags on a laboratory bench. Several parameters were investigated as follows: the correctness of tag responses to the corresponding reader commands, input impedance, the operating power range of the tag chip, and backscattering efficiency. In the publication [31], the authors considered the tag parameters responsible for the budget of a communication channel to a reader. Also, the equipment necessary to experimentally measure the performance of an RFID channel was described. The impact of the Gen2 protocol [7] on the sensitivity of the tag and its backscattering efficiency was analyzed in [32]. An experiment was conducted to measure the values of these characteristics for different UHF RFID tags.

Many researchers examined the characteristics of the communication protocol and mathematical models of the channel between a reader and a tag. Multibeam signal propagation and the quality of communication depending on the Doppler effect were considered. For example, the papers [33, 34] described a method for visualizing signal propagation in a UHF RFID system. This method was applied to estimate the tag reading speed in the presence of various obstacles, as well as depending on the reader's antenna suspension height and the tag location height. A mathematical model was developed based on the Friis equation modified for two- and three-beam cases of signal propagation. The paper also described the experiments on determining the power necessary for tag activation in an anechoic chamber.

The papers [35–38] presented communication channel models for estimating the required power transmitted by a reader to activate a tag, as well as different options for organizing antenna systems responsible for transmitting and receiving signals in an RFID system. Some channel models are created not only to calculate the attenuation level but also to determine the probability of successful data exchange. For example, the channel model [39] considers the polarization of the antennas and the materials of the objects reflecting the signals. This model allows determining the density of the probability of successful reading at any point of the space by considering the set of reflected rays. The theoretical results were compared with the experimental ones. In [24], the reader-tag-reader communication channel was discussed. Different configurations of reader antennas were described, and their disadvantages and advantages were analyzed. In addition, polarization issues of the reader antenna were addressed. The model of losses in the wireless communication channel with multi-beam signal propagation was described.

A significant contribution to wireless RFID channel studies was made by the research work [27]. The authors investigated the issue of determining the reading range in RFID systems considering the tag interrogation cycle and regional power constraints, as well as the directional patterns of the reader and tag antennas. This paper also presented channel models for estimating the reading range of UHF RFID systems with different levels of detail and computational complexity.

Numerous papers on the topic of this section can be classified as follows.

Table 1

The wireless communication channel in RFID systems: Classification of papers

The subject of study	Papers
Factors affecting tag reading range	[22, 24, 32]
Channel characteristics	[23, 27, 33–39]
Design and parameters of tags	[25, 29–32]
Nonstandard applications	[26]

3. RFID ON THE BASE OF GROUND VEHICLES

Historically, one of the pioneering applications in transport was utilizing RFID on toll roads to identify cars and collect tolls. Such systems were first used in the 1980s in the USA. In the 1990s, RFID systems on toll roads became ubiquitous not only in the USA but also in European countries [40, 41].

A significant number of publications have been devoted to the identification of ground vehicles using RFID. Information about identified vehicles can be effectively used for many purposes: for example, for barrier control and transit payments, traffic light adjustment, search for stolen vehicles, etc. [42–45]. One application of an RFID system was presented in [46], i.e., a hardware-software complex to monitor car access to a university campus. The authors described an experiment in which the performance and stability of the system were tested. It involved 20 cars equipped with RFID tags. As a result, the load of passages and the time of stay of cars in the campus were assessed. Active tags can be used to increase the range of an identification system [47].

Another problem was solved in [48–50], where the principles of designing and implementing an automated traffic offense control system using RFID technologies were described. A large-scale experiment was conducted involving 800 cars: passive RFID tags were mounted on their license plates, and the readers were placed above the roadbed. According to the three-month tests in winter time [51], RFID ensures the probability of vehicle detection at a level of about 0.95. The experiment results match the theoretical studies on estimating the probability of vehicle detection using RFID presented in [52–55]. The vehicle travel time was also studied in [56], where data from RFID readers were used. The theoretical results of the model were compared with experimental data.

The papers [57–59] proposed a method for measuring vehicle speed by estimating the power of the signal received by the reader from an RFID tag. In particular, the authors [57, 58] described a corresponding method when RFID tags are placed on the roadbed and RFID readers on cars. The paper [59] suggested using RFID to monitor traffic and determine the speed of cars in the case of placing an RFID tag on the car's license plate and a reader above the roadbed.

Vehicular ad hoc networks (VANETs) [60, 61] have recently become topical. They provide high-speed communication from various devices on roads, including RFID readers, to control center's databases. VANETs are a main component of an *Intelligent Transportation System* (ITS) [61–63]. In such systems, numerous technologies and various communication systems are used, with RFID occupying a special place [50, 52, 54, 64–69]. In [64], a traffic flow monitoring system was presented; it detects traffic accidents using RFID. The problem of optimal locations of readers in order to minimize the cost of system deployment was solved. The research works [62, 70, 71] considered an optimal placement method for wireless network base stations in long transport highways to collect information from video monitoring systems and prompt transmission of traffic offense data to a control center. This method was applied to design an effective implementation of a broadband high-speed wireless network along the Kazan bypass road (the Russian Route M7, also known as the Volga Highway).

The paper [65] presented a traffic jam detection method in urban areas that utilizes RFID-based vehicle positioning. By assumption, all vehicles can communicate with each other and form clusters within a VANET network. A prototype vehicle traffic monitoring system was described in [66]. This system consists of piezoelectric transducers placed under the roadbed to estimate the flow density and RFID readers receiving information from tags mounted on vehicles. The system provides priority to special service vehicles (ambulance, police, etc.) at intersections. The authors [67] described the architecture of a system that identifies very many vehicles per unit time and also considered the reading regions of RFID tag and their dependence on the speed of vehicles. The corresponding mathematical model takes into account the peculiarities of the RFID protocol, traffic speed, and other parameters. Finally, the analytical results were compared with experimental data. The performance of vehicle identification systems based on UHF RFID was assessed in [72]. The possibility of identifying tags placed on both cars and trains was investigated. In addition, models were developed to determine the optimal location of a tag on different vehicles.

Several works were devoted to determining the position of a vehicle using RFID technologies. Despite the currently widespread satellite navigation systems (GLONASS and GPS), improving their accuracy, particularly with the help of RFID, remains a relevant issue. A vehicle positioning method using RFID-refined GPS data was presented in [73]. The idea is to mount a reader on a moving vehicle whereas tags storing information about their exact position on various road infrastructure objects. Mathematical models were developed to calculate the positioning error. In the publication [74], RFID was used to determine the position of a vehicle and then transmit this data via a VANET network to a server for real-time route planning and estimation. The results were compared for two cases: using GPS only and using RFID together with VANET. A system for localizing and identifying obstacles in low-visibility conditions was considered in [75]. An analytical model of a communication channel was described, including the case of two-beam propagation. The system was mathematically modeled, and laboratory and field experiments were conducted.

Tags can be placed not only on road infrastructure but also directly in the roadbed; see the paper [76]. As a result, vehicles equipped with readers can determine their position. The authors studied algorithms for avoiding collisions when multiple readers attempt to read the same tag simultaneously. The effectiveness of the proposed algorithms was assessed using computer simulation.

Positioning is important not only on car roads but also on railways for localizing trains accurately. The research works [77, 78] considered the issues of identification of ultrahigh-speed trains (up to 500 km/h). The idea is to mount readers between sleepers and fix a set of tags along the entire length of the train. Another positioning method for railroad vehicles was proposed in [79]: a reader is attached to the train to receive location data from tags distributed along its route. A similar method was discussed in [80]: it was suggested to use RFID in a subway system to refine the location data of the odometry method, traditional for underground railways.

Also, RFID can be applied to other problems in transport, not directly related to object identification. Many traffic accidents occur due to driver fatigue and falling asleep at the wheel. Currently, driver anti-sleep systems are beginning to be actively used in public transport [81]. A similar system utilizing RFID was proposed in [82]. Another example was presented in [83], i.e., a motion algorithm and a laboratory bench for a small-sized robot equipped with an RFID reader to move along a trajectory labeled by RFID tags.

In 2022, for the first time in world practice, the paper [68] described a hybrid vehicle identification complex based on the joint use of video detection systems and RFID technologies. The hybrid complex was designed for implementing pilot zones of the new safety improvement system on the roads in Moscow, St. Petersburg, and Kazan. It was successfully tested at an experimental ground of the State Road Safety Inspectorate (GIBDD) of Tatarstan.

Publications on utilizing RFID on the base of ground vehicles can be classified as follows.

Table 2

RFID on the base of ground vehicles

Application	Papers
Vehicle identification	[42–47, 56, 67, 84–88]
Vehicle speed measurement	[57–59]
Smart car roads	[48–54, 60–70, 72]
Railway transport	[77–80]
Vehicle positioning	[73–76]
Non-standard applications	[82, 83]

4. RFID ON THE BASE OF UNMANNED AERIAL VEHICLES

UAVs are widely used in civil and defense industries [89–91]. In recent years, RFID and UAVs have been actively applied for various purposes. Here, a common scenario is to mount a reader on a UAV in order to interrogate tags located on identified objects. For example, the papers [92, 93] considered the collection of plant data in agricultural fields using UAVs. Experiments were described to determine an optimal UAV altitude and other parameters with a significant impact on the probability of reading RFID tags. The authors [93] also presented experiments on studying different UAV flight algorithms with an RFID reader, carried out to determine the speed of flight over each tag to read it with a given probability. RFID and UAVs can also be used to perform some sea fishery tasks. For example, the problem of abandoned oyster fishing tackle located in southwestern Taiwan was considered in [94]. The idea is to mount RFID tags on the tackle and detect it using UAVs with a reader.

Soil conditions in large open spaces can be determined from UAVs by interrogating tags with built-in sensors (temperature, moisture, etc.) [95]. (Note that only one specific parameter can be measured.) Such tags can be passive or semi-passive; see the websites of their suppliers [96, 97]. The paper [98] considered data collection using a UAV that flies along a route with known coordinates of sensor RFID tags. Upon reaching an appropriate point, the UAV descends to an altitude of up to 1 m, hovers for collecting information from the tag, and then flies to the next point. An algorithm was developed to transmit information from the tag to the server via a UAV-mounted repeater.

Sensor RFID tags and UAVs can also be applied to collect temperature or humidity data of air masses [99–101]. A spatial map of the environment can be built using a swarm of ultra-small UAVs with onboard sensor RFID tags and a larger drone equipped with an RFID reader; for details, see [100, 101]. A mathematical model was constructed, and the computational results were compared with experimental data on air temperature measurements at different altitudes. The paper [102] compared the parameters of the communication channel between an RFID reader on the base of a UAV and different types of tags (passive and semi-passive).

The author [103] addressed the issue of assessing the condition of food packaging in large warehouses. It was proposed to use a UAV with an onboard RFID reader to collect information from specially designed tags to determine the condition of the packaging material.

In [104–106], the issues of object positioning by the joint use of RFID and UAV technologies were discussed. An algorithm was developed to find tags in unknown locations using UAV position and flight path data. For this purpose, a UAV is equipped with an RFID reader, a Wi-Fi module for ground control, and also with a GPS module. Mathematical models of a positioning system were described, and the modeling results were compared with those of field experiments.

In [107], a localization method based on *Received Signal Strength* (RSS) measurements was discussed. This method solves the UAV tracking problem by collecting RSS values between a UAV with an onboard RFID tag and a ground-based reader. The authors [108] also estimated the probability of reading fixed tags located on the ground from a UAV-mounted reader using both analytical and simulation modeling. As a result, the optimal UAV flight parameters and RFID protocol settings for successful tag reading were determined.

It is also possible to determine the position of labeled objects indoors. The publication [109] proposed a system for stock positioning in large warehouses where various objects are stored on several levels of vertical racks. An algorithm was developed to find objects using an RFID reader on a UAV. This algorithm identifies the rack as well as the shelf number where the desired object is stored. In [110], machine learning methods were applied to increase the accuracy of positioning. In addition, it was suggested to use two RFID reader antennas so that the flying UAV can identify objects on the shelves on both sides simultaneously. The conducted experiments confirmed the high accuracy of this approach.

RFID in combination with UAVs can be applied to authenticate drones at military facilities. This issue was addressed in [91]. The paper described a secure communication algorithm between a UAV-mounted tag and a ground stationary reader.

According to the smart parking concept presented in [111], available parking spaces can be found using a UAV-mounted RFID reader. A practical implementation of such a system was developed by Exponent [112]. In addition to determining an available parking space, the system shows the position of a car relative to other cars. Another project of the same company was to identify and localize metal structures in a warehouse using active tags. Similar services are provided by the companies [113, 114] that have UAVs with special equipment, including RFID equipment, for various monitoring and identification purposes.

Note that several important studies are absent in the existing literature, in particular, RFID applications for accurate landing of UAVs and the local navigation of high-altitude unmanned platforms in the absence of satellite navigation signals. They can be considered a subject of further R&D work. Also, a promising line of future studies is the RFID-based recognition of unidentified UAVs [115–118].

The joint use of RFID and UAVs can be classified as follows; see Table 3 below.

CONCLUSIONS

This survey has addressed publications in the intensively developing area of utilizing RFID for fast-moving vehicle identification, a topic poorly reflected in the literature.

RFID standards have been considered, as well as numerous papers devoted to the peculiarities of signal

Table 3

The joint use of RFID and UAV technologies: Classification

Utilizing RFID on the base of UAVs	Tag mounting point	Papers
Data collection from hard-to-reach locations	Identifiable object	[92–94, 99, 100, 102, 109]
Collecting data from sensor tags	Identifiable object	[95, 98, 101, 103]
	UAV	[99, 100]
Positioning	Walls and surfaces	[104–107, 109, 111]
Military applications	UAV	[91]

propagation in the wireless communication channel between RFID tags and a reader. Publications on assessing the key parameters of the reading range of RFID systems (those affecting the fundamental possibility of utilizing RFID in transport) have been overviewed. Theoretical and experimental results, as well as the architecture and hardware and software tools for the practical implementation of ground vehicle identification systems, have been described. In addition, this survey has covered publications on utilizing RFID on the base of unmanned aerial vehicles.

At the end of each section, the related papers and their distribution by the subject of study have been analyzed. According to the analysis results, RFID on the base of ground vehicles is most widely used for the following purposes: identification of vehicles on toll roads, detection of cars offending traffic rules, traffic control at intersections, etc. Another promising line is utilizing RFID in railways and subways to localize vehicles and improve traffic safety.

Modern literature contains almost no description of utilizing RFID to solve the following topical problems: identification of unauthorized UAVs, precise landing of UAVs, local navigation of tethered high-altitude unmanned platforms, etc. They can be the subject of further research in the area.

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