Ultra-Low Power Identification in Explosive Environments

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***Abstract*—The paper focuses on design and validation of an active RFID platform, devoted to vehicle identification and authorization for the fueling in gas stations. The system is built on ANT communication protocol, which is intended for extremely low power consumption. The explosive environment of a filling station places special requirements on involved electronic devices – the preferred way is a hermetic sealing of the complete device in an epoxy resin.**

***Keywords*—radio-frequency identification, fleet services, ANT protocol, ultra-low power communication, identification in explosive environments, fuel tank, fuel dispenser**

I. Introduction

Radio frequency identification (RFID) technology uses various techniques, which differ in many attributes like power demand and management, communication range, mass production availability and cost, information capacity, etc. Technologies currently involved in fleet services management and related application fields are dividable into three groups:

A. Personal identification

Traditional personal identification systems use RFID chips in the form of a card or a sticker on goods, working in 125 kHz or 13.56 MHz frequency bands [1]. Low system cost and minimal tag dimensions lead to easy mass production and distribution. The price paid for the passivity of the tag (i.e. the tag do not require an internal power supply) is a limited communication range and low information capacity. In fact, a typical tag does not provide any other information except its unique identification code.

B. Vehicle transit inspection

Longer communication distance and higher information capacity are important for e.g. toll systems. Generally, the vehicles are equipped with an active identification device and the information are collected by gates during a vehicle pass-through. For a short period of time, the devices are able to exchange significantly higher amount of information via a radio link, typically in UHF band [2]. Today available systems are more expensive, with significantly higher energy and implementation demands compared to personal identification.

C. Fuel dispensers in filling stations

Systems for fuel tank authorization are not widely spread on the market. Some existing solutions [3] typically use technology similar to person identification, which is based on RFID at low frequencies. The tags are supposed to allow fueling only into correctly identified and authorized fuel tanks. However, since the technology does not allow any estimation of the mutual position of the fuel dispenser and the fuel tank itself, the correct identification is the main weakness.

This was basically the main motivation for the design of an advanced identification and authorization system. The aim of the development was to find a solution for a universal identification tag with compact dimensions attachable to various places on the vehicle, relatively long communication distance with reliable signal strength (RSSI) measurement, and battery lifetime of at least 5 years. Devices operating near fuel filling stations require special ATEX certification for explosive environments [4]. For a successful pass of these tests, it is advised to seal the complete device into an epoxy resin [5]. However, no further development or even battery replacement can take place after the potting. It was therefore necessary to create a very robust platform without any need for service during its lifetime. As far as we know, existing devices meet these attributes separately, but none of them combines them in a single device.

The following sections introduce the communication technology and protocol chosen for the system, describe the testing and measurement process, and discuss the results.

II. ANT Technology

Several technologies were considered for the tag RF communication. Requirements for relatively low communication distance, high directivity, energy efficiency, and small antenna dimensions lead to selection of 2.4 GHz band.

Communication systems working in this band include BLE (Bluetooth low energy or Bluetooth 4), ANT, ZigBee, Wi-Fi, and proprietary solutions (e.g. nRF24L01) [6]. The most important limiting factor is protocol support for TX-only low-power beacon mode. Together with the availability of development tools and possibilities of protocol customization, these requirements led to selection of the ANT standard, which is extensively described in [7].

The ANT chipsets are produced by two main manufacturers – Nordic Semiconductors and Texas Instruments. ANT is intended for a communication on short distances with extremely low power consumption, allowing battery lifetime in order of years [8]. The manufacturers portfolio also provides complex system on chip (SoC) solutions, merging the ANT transceivers with a microcontroller.

Small dimensions and especially the non-flammability requirement disqualify using off-the-shelf communication modules, because the integrated antenna is never optimized for the permittivity of the epoxy resin, which is used for potting the tag.

Nordic Semiconductor produces larger family of the ANT and BLE chipsets and provides better user support compared to the Texas Instruments portfolio. The processing of the ANT protocol is concentrated in a non-user part of the firmware (SoftDevice), which is provided in a binary form by the vendor. The development can be therefore focused only to the application part of the firmware.

The tag is based on nRF51422 chip, which includes the ARM Cortex-M0 core with some specifics due to the uncommon peripherals [9]. Both extensive documentation and a software development kit (SDK) for common toolchains are provided by the manufacturer. Hardware development kits are also available, e.g. development kit nRF51-DK and USB dongle nRF51-Dongle.

III. Tag Hardware

The required features of the tag include:

- Small dimensions of the tag to fit in the box, attachable on the vehicle's fuel tank.
- Potting the tag including antenna and battery with a non-flammable resin to allow future ATEX certification for explosive environments.
- Battery lifetime longer than 5 years.
- Parameter and firmware over-the-air (OTA) update.

The selected power source is CR14250 lithium ($LiMnO_2$) primary cell. While maintaining small dimensions, the battery gives a voltage from 1.9 V to 3.1 V (3.0 V nominal) even at low temperatures, has low self-discharging, long shelf lifetime, and sufficient nominal capacity of 850 mAh. The voltage operating range of the designed circuit is 2.1 V to 3.6 V, therefore it can be supplied directly from the battery with no additional voltage regulator, which helps to maintain low current consumption.

The circuit is also equipped with a reed switch for configuration and mainly for activation of the firmware during the deployment. This feature saves battery energy in the meantime between the tag fabrication and the system assembly on the vehicle, when the circuit has almost zero current consumption.

The assembled PCB is placed in a custom made box (outer dimensions 32×18×24 mm) and filled with the two-component epoxy resin. The box shape allows an assembly to a round neck of the fuel tank by screws or by a tape. The prototype of the box was made on a 3D printer.

An inverted F antenna (IFA) with the overall size of 5×10 mm was designed in the corner of the PCB with the help of CST Microwave Studio. The IFA satisfies both required properties: operational bandwidth and omnidirectional radiation. The antenna structure and position are obvious in Fig. 1. The IFA is connected to the transceiver through a 50 Ω grounded coplanar waveguide (GCPW) and a chip balun. The

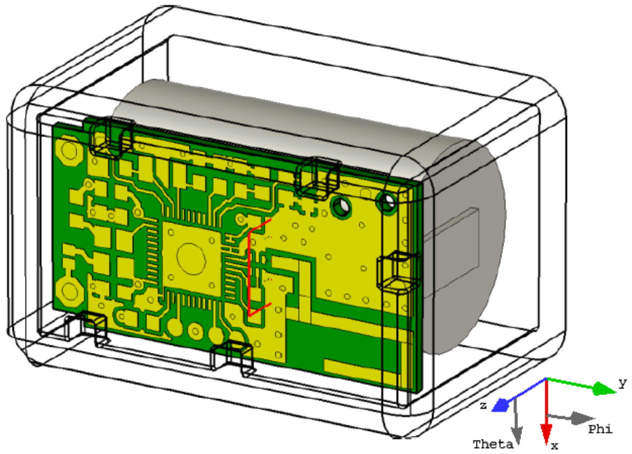

Fig. 1. Tag 3D model for antenna simulations.

model includes the detailed PCB layout, battery, plastic box, and epoxy filling. To ensure the faithful antenna simulation, the complex permittivity of the epoxy was extracted from scattering parameters of epoxy samples measured in a coaxial transmission line. For the simulation, the relative permittivity of 3.45 and the conductivity of 0.015 S/m at 2.45 GHz were used.

IV. Measurements and Results

The reflection coefficient of the IFA was measured using a vector network analyzer and a 50 Ω coaxial cable soldered to the GCPW. The influence of the cable was suppressed by the precise ground soldering and using ferrite cores placed over the full length of the cable. The IFA was tuned before epoxy resin sealing by trimming its length for the corresponding resonant frequency in free space according to the simulation. The reflection coefficient change during the tuning and sealing process is depicted in Fig. 2. The minimum reflection coefficient corresponds to the frequency 2.48 GHz. The measured sealed tag prototype with the coaxial cable is shown in Fig. 3.

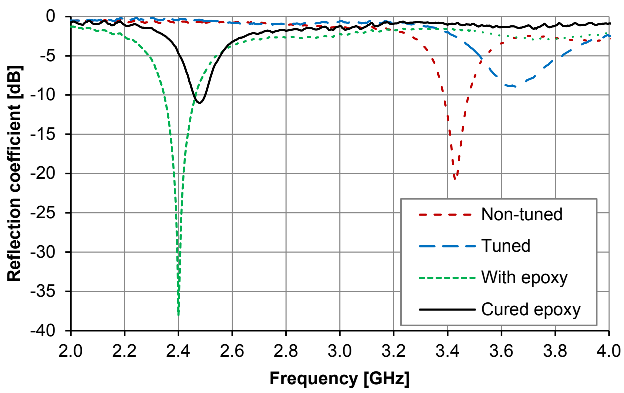

Fig. 2. Antenna reflection coefficient tuning.

Fig. 3. Modified tag with external connection for antenna measurement.

The equivalent isotropically radiated power (EIRP) of the tag was measured in a shielded anechoic chamber. Using custom firmware, the chip was transmitting a single-frequency continuous wave (CW) for radiation pattern measurement and a frequency-swept CW over the full frequency range 2.4-2.5 GHz for the impedance matching verification of the IFA with the chip. The tag was placed on a metal sheet, inside an open metal box shown in Fig. 4 to model the real placement on a metal fuel tank. In the case of the impedance matching measurement, the tag was also measured in free space. The measurement results are shown in Fig. 5 and 6. The peak EIRP values in Fig. 5 correspond to the best impedance matching of the IFA with the chip.

The complete testbed used for the measurement of the transceiver output characteristics is depicted in Fig. 7.

The output power and phase noise of the transceiver were measured in a setup similar to the antenna measurement, except the coaxial cable was connected by IPX/U.FL connector and no epoxy filling was needed. The transmitted power in full frequency band and CW mode was measured in several predefined levels. The results are summarized in Table I. After the attenuation correction of the balun and the coaxial cable (0.9 dB, resp. 0.5 dB), the output levels are in an acceptable range, sometimes even higher than the expected value. The phase noise, measured in CW mode at frequency 2.44 GHz and 0 dBm output power, is lower than –70 dBc from 1 kHz offset, as shown in Fig. 8.

Current consumption of the tag is highly dynamic, idle current is in order of μA, but the consumption during the transmission is in order of tens of mA. A modern IoT measuring solution with the X-NUCLEO-LPM01A development kit was selected, allowing measurement in the range from 100 nA up to 50 mA with 100 kHz bandwidth and supply voltage in the range from 1.8 V to 3.3 V.

The basic tag functionality is a beacon with 1 Hz repetition frequency. The detail of the transmission is depicted in Fig. 9, where the idle current consumption is about 4 μA. Such behavior follows the specification of the SoftDevice. The current consumption over a 10 second averaging window for each power level setting is summarized in Table II, where a simple battery lifetime estimation is calculated from the cell's capacity. In the beacon mode (ON), the theoretical tag lifetime is around 10 years, which is also the expected

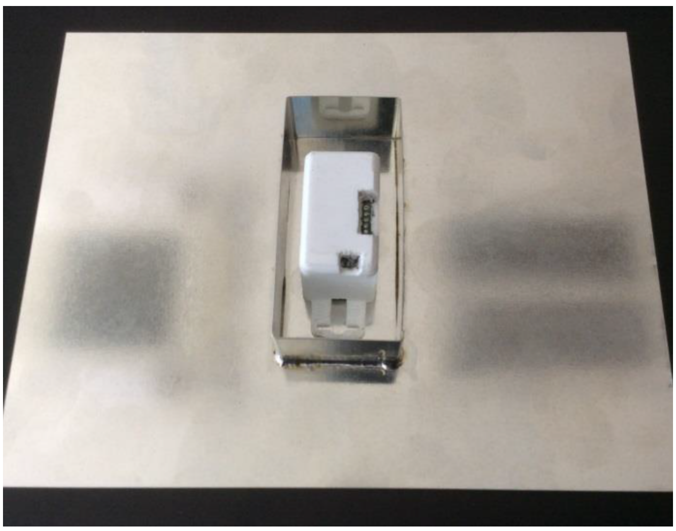

Fig. 4. Tag inside an open metal box.

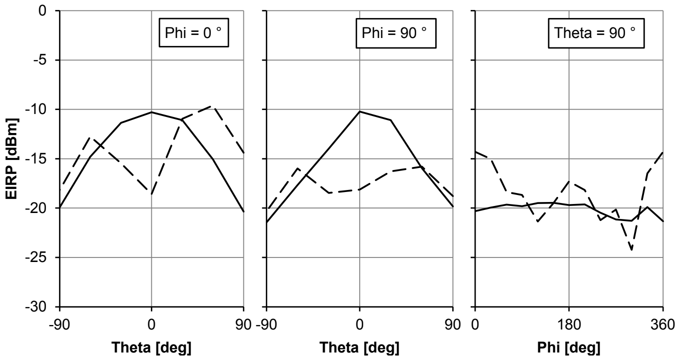

Fig. 5. Measured radiation pattern of the tag placed on a metal sheet (solid) and in an open metal box (dashed).

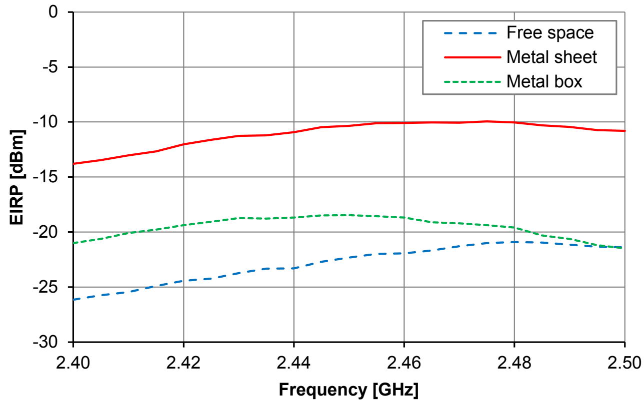

Fig. 6. Measured EIRP in z-direction of the tag placed in free space (long dashed), on a metal sheet (solid), and in an open metal box (short dashed).

TABLE I
TRANSCEIVER OUTPUT POWER FOR VARIOUS POWER LEVELS

Power level	Set output power [dBm]	Measured power [dBm]	Correction [dB]	Corrected power [dBm]
0	–20	–20.26		–18.86
1	–12	–12.23		–10.83
2	–4	–4.81	1.4	–3.41
3	0	–0.16		1.24
4	4	2.45		3.85

TABLE II
CURRENT CONSUMPTION OF THE TAG AND ESTIMATED BATTERY LIFETIME FOR VARIOUS POWER LEVELS

Power level	Set output power [dBm]	Mode	Average current [μA]	Lifetime [years]
0	–20	WAIT_REED	3.57	27.2
		ON	8.38	11.6
1	–12	ON	8.49	11.4
2	–4	ON	8.80	10.9
3	0	ON	8.97	10.8
4	4	ON	9.64	10.1

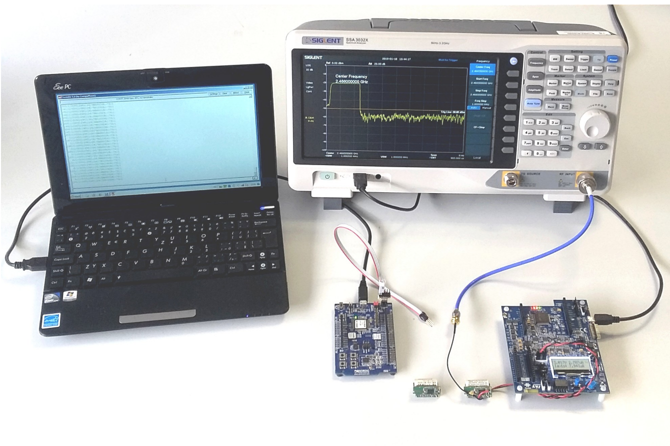

Fig. 7. ANT testbed: tag prototypes, nRF51-DK, X-NUCLEO-LPM01A, spectrum analyzer, and a laptop.

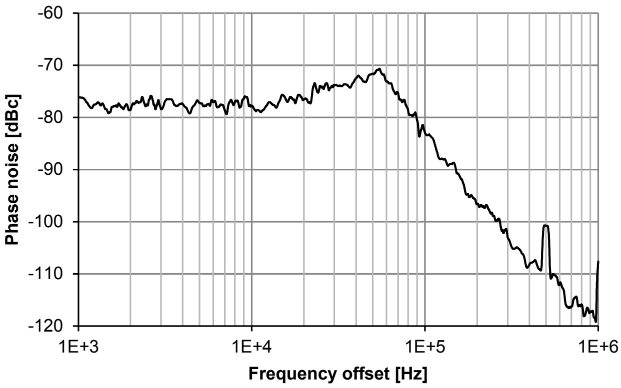

Fig. 8. Phase noise of a CW transmission at 2.44 GHz with 0 dBm power.

lifetime of the battery shelf. Just after the tag fabrication, the firmware is commanded to hibernate (WAIT_REED) until its deployment. The power consumption is almost negligible in this state.

V. Conclusion

The presented ANT identification tag is primarily intended to be used as a beacon, which periodically sends its unique identification and a status message with battery voltage and temperature. The design contains a reed switch, which provides a low-power way to activate the tag during deployment and enables an extended mode. In this mode, a newly opened service communication channel enables setting of output power, frequency, beacon period and unique identification code. It also allows the activation of the OTA bootloader for firmware update.

The measurements and tests performed so far show promising results, especially the low power consumption for different transmission power and thus the range of communication while keeping the physical solution compact and robust.

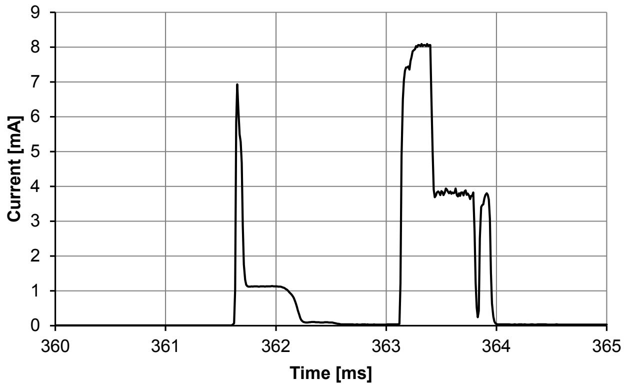

Fig. 9. Current consumption of the tag during the beacon transmission.

The system is still under evaluation. One of the open questions is the communication security. Most improvements require bi-directional communication between the tag and the fuel dispenser, which causes significant increase of tag power consumption (measured average current in such case is 20.48 μA for -20 dBm output power).

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References

[1] K. Finkenzeller, *RFID handbook: Fundamentals and applications*. Chichester: John Wiley & Sons, 2010.

[2] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in practice*. Burlington, MA (USA): Newnes, 2007.

[3] *ForeFuel: Automatic Vehicle Identification (AVI) for Fueling (Solution Description)*, ORPAK, 2018.

[4] *ATEX 2014/34/EU Guidelines*, 2nd ed., European Commission Services, Brussels, 2017.

[5] H. Panda, *Epoxy Resins Technology Handbook*. Delhi (India): Asia Pacific Business Press Inc., 2016.

[6] P. Christ, B. Neuwinger, F. Werner, and U. Rückert, "Performance analysis of the nrf24l01 ultra-low-power transceiver in a multi-transmitter and multi-receiver scenario," in *2011 IEEE SENSORS*, Oct 2011, pp. 1205–1208.

[7] *ANT Message Protocol and Usage*, Rev.5.1 ed., Dynastream Innovations Inc., 2014. [Online]. Available: https://www.thisisant.com/resources/ant-message-protocol-and-usage

[8] S. Khssibi, H. Idoudi, A. V. den Bossche, T. Val, and L. A. Saidane, "Presentation and analysis of a new technology for low-power wireless sensor network," *International Journal of Digital Information and Wireless Communications*, vol. 3, no. 1, pp. 75–86, 2013.

[9] *nRF51422: Multiprotocol ANT/Bluetooth low energy System on Chip (Product Specification)*, Nordic Semiconductor, 2014. [Online]. Available: https://www.nordicsemi.com/-/media/DocLib/Other/Product_Spec/nRF51422PSv32.pdf