Preprint

LoRa Transceiver With Improved Characteristics

Nikola Jovalekic, Vujo Drndarevic, Iain Darby, Marco Zennaro, Ermanno Pietrosemoli, Fabio Ricciato

***Abstract*—In this letter we present a novel design and implementation of a LoRa transceiver with improved characteristics which operates in two Industrial, Scientific, and Medical (ISM) bands, 868 MHz and 434 MHz. Comparative tests with two widely utilised commercial transceivers were carried out to demonstrate the enhanced characteristics of the new transceiver. Laboratory tests revealed significant improvement in sensitivity, 15 – 25 dB, while field tests demonstrated the higher immunity to interference. Field tests were performed by establishing very long Line-of-Sight (LOS) over land link of 112 km. The main achievements of the work are: *(i)* the design of a novel, high sensitive, low-cost, and miniaturized LoRa transceiver, *(ii)* establishing a very long LoRa link using only low-cost, of-the-shelf, omni-directional, rubber duck antennas with standard output power in ISM 868 MHz band, and *(iii)* temporal analysis of the link for three different spreading factors (7, 10, 12) within a fixed LoRa bandwidth of 125 kHz.**

***Index Terms*—LoRa, transceiver, sensitivity, interference, IoT, LPWAN.**

I. Introduction

LORA is a proprietary modulation, developed by Semtech, which utilizes spread spectrum techniques and limited throughput to increase receiver sensitivity [1].

Several research groups have investigated LoRa until now by logging the Received Signal Strength (RSS), Signal-to-Noise Ratio (SNR), and packet loss. A range of test scenarios have been examined, e.g. in [2], [3] insights into LoRa system behavior in both indoor and urban scenarios are given, while in [4] communication range, link consistency, impact of vegetation and different antennas were examined. LoRa channel characterization in the Antarctic was reported in [5], while range evaluation and channel attenuation model over land and sea is given in [6].

The conclusions drawn from those experiments are limited by the several factors. The use of commercial general purpose LoRa development kits masks the real capabilities of LoRa transceivers, since the kit design is not optimized for low-noise operation. Unspecified antenna parameters such as gain, radiation pattern and RF front end matching, limit the insight into the LoRa links since those parameters significantly influence the performance of wireless links. The reporting of grossly aggregate performance metrics, typically limited to long-term average values of RSS and packet reception rate (PRR) cannot give information about short term variations and link behavior over the time. Finally, there is often no information provided about RSS indicator calibration, leading to questions on the validity some of the conclusions obtained from those experiments.

To overcome such limitations and provide a deeper insight into LoRa technology, we have developed a new low-cost LoRa transceiver capable of standalone operation with significantly improved characteristics in terms of sensitivity and immunity to interference. Furthermore, we performed comparative verification tests in both the laboratory and field to demonstrate the specified improvements. Finally, we used the data obtained from the field experiments to analyze and assess LoRa performance for very long distance links.

N. Jovalekic and V. Drndarevic are with School of Electrical Engineering, University of Belgrade, Serbia. (e-mail: jovalekic@gmail.com, vujo@etf.rs)

M. Zennaro and E. Pietrosemoli are with Telecommunications/ICT4D Lab, ICTP, Italy. (e-mail: mzennaro@ictp.it, ermanno@ictp.it)

I. Darby is with the IAEA Nuclear Science and Instrumentation Laboratory, Physics Section, A-2444, Seibersdorf, Austria. (e-mail: I.Darby@iaea.org)

F. Ricciato is with Faculty of Computer and Information Science, University of Ljubljana, Slovenia. (e-mail: fabio.ricciato@fri.uni-lj.si)

II. Transceiver Design

The design of the transceiver is illustrated in the block diagram given in Fig. 1. Transceiver operation is controlled by an Energy Micro $EFM32GG990F1024$ microcontroller while a Semtech $SX1276$ Integrated Circuit (IC) is used as a LoRa modem. The transceiver features 32 MB of NAND flash memory (Micron NAND256-A) for logging purposes and has a port expander to enable connection to other boards via GPIO, I^{2}C or SPI. A push button and two LEDs enable interaction with the transceiver, while the UART port allows direct connection to the microcontroller. A debug port enables programming and debugging of the transceiver. The transceiver is equipped with two antenna ports: 868 MHz, and 434 MHz, enabling 14 dBm and 20 dBm of output power, respectively.

We combined several methodologies to improve the transceiver sensitivity and immunity to interference. By utilizing a low-dropout linear regulator with a dedicated noise reduction feature to power the transceiver's chipset, we lowered the output noise significantly. In addition, we divided the Printed Circuit Board (PCB) into two regions using a moat separating a digital and RF part, providing connection between them using a bridge, thereby preventing the switching noise from the digital part interfering with the RF part. Furthermore, we properly filtered and decoupled both the digital and analog power supply for the RF IC.

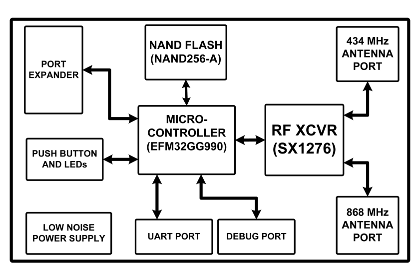

Figure 1. LoRa transceiver block diagram.

The four layer PCB provided one ground, one power supply and two signal layers. The core material separating the power and ground plane was selected to be only 0.2 mm, which enabled additional decoupling of the whole board due to the resultant formation of a PCB parallel plate capacitor. Thanks to the very small serial inductance of such a capacitor, decoupling was improved resulting in further lowering of the transceiver's noise floor. The mechanical strength of the PCB was provided by use of a thicker pre-impregnated (prepreg) material between the signals and power layers, which also provided decreased capacitive coupling between signal traces and power planes, thus consequently reducing crosstalk.

RF front end impedance matching was performed via simulations in SPICE and experiments, wherein we took advantage of known complex impedances on the RF IC's ports to calculate and implement our own impedance matching to PCB microstrips and to design harmonic filters. To reduce the effects caused by the reflections that occur when the RF signal is injected into the PCB, we placed the matching network as close as possible to the IC's RF pins, at a distance significantly shorter than the signal wavelength ($\approx \lambda/100$). The microstrips have an impedance of 50 Ω and chamfered corners to compensate for discontinuities when changing the routing direction.

Finally, we adapted the original Semtech driver to use interrupts instead of a polling mechanism to check if the packet is received, thus improving the resource usage on the microcontroller and lowering the power consumption of the transceiver. The dimensions of the transceiver are 35x58 mm and the physical appearance with marked sub-blocks is given in Fig. 2.

III. Verification Experiments

Verification experiments were conducted to evaluate the characteristics of the new transceiver and to compare it with two commercial transceivers under the same operating conditions. Additional experiments were carried out to explore the feasibility of LoRa links over the very long trajectory (> 100 km) using low-cost, off-the-shelf, rubber duck antennas in ISM 868 MHz band with our optimized and commercial transceivers.

A. Experimental transceivers

Besides our Own Developed Transceiver (OdT), we used two additional commercial transceivers in the experiments:

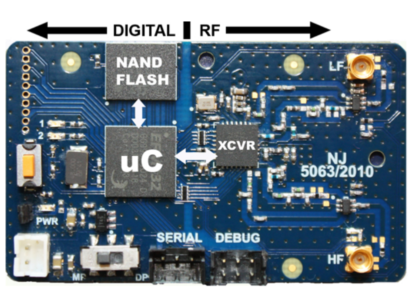

Figure 2. LoRa transceiver physical appearance with marked sub-blocks.

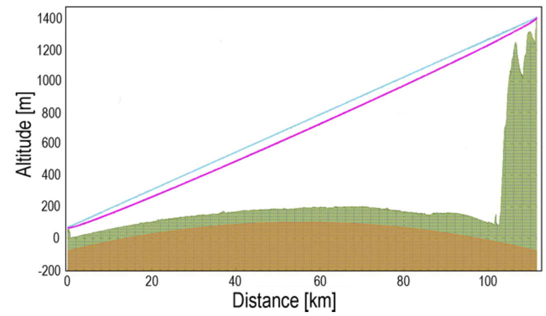

Figure 3. LOS over land Terrain Profile: Brown area indicates the curvature of the earth, modified by the refraction index; Green area is the terrain profile as seen by the radio wave; Magenta line is the 60% of the first Fresnel zone; and the blue line is the optical line of sight.

Libelium $SX1272$ RF transceiver $v0$, and Uputronics RF transceiver $v2.5$ (hereafter "LiT" and "UpT", respectively). The LiT was mounted on Seeeduino Stalker $v2.3$ carrier board, whereas UpT was mounted on Raspberry Pi3.

Since all three transceivers are equipped with different RF ICs, we examined their sensitivities in the corresponding datasheets to compensate for possible differences, and maintain valid comparison conditions. OdT and UpT have identical sensitivities and in comparison LiT has an improved sensitivity of 1 dB.

B. Experimental Setup

In the laboratory tests, the RSS indicator on each transceiver was calibrated and interoperability between OdT and commercial transceivers confirmed. For the noise floor comparison measurements, one OdT was set up as a transmitter and the same number of packets was sent to each transceiver under test. The transmit and receive sides were connected by a coaxial cable and attenuator and the attenuation was set so that the OdT sporadically loses packets. The tests were executed consecutively for each transceiver and under the same operating conditions.

In the field, tests were carried out for three different spreading factors (7, 10, and 12) in three consecutive measurements. All transceivers were equipped with the same low-cost, off-the-shelf, rubber duck, omni-directional antenna with nominal gain of 4.5 dBi.

C. Field Experiment Location

The field experiments were carried out in a LOS over land channel condition on a 112.5 km long trajectory. Suitable test sites were identified and modelled using BotRf [7], which provides a graph of the terrain profile and calculates the path loss for different atmospheric refraction indexes using the Longley-Rice Irregular Terrain Model. The terrain profile obtained with the BotRf is given in Fig. 3, whereas the geographical details of the test sites along with the path loss are provided in Table I. During the measurements the weather conditions were clear and sunny with an average temperature of 28°C.

Table I
GEOGRAPHICAL DETAILS OF TEST LOCATIONS AND CALCULATED PATH LOSS.

Site	Latitude	Longitude	Altitude	Toponym, Country	Path distance from A	Path Loss (Longley-Rice)
A	45.7035	13.7207	76 m	ICTP, Trieste, Italy	-	-
B	46.0392	12.3629	1406 m	Monte Pizzoc, Italy	112.5 km, LOS over land	131.91 dB

D. Traffic Setup

The trasmitting OdT was configured to send packets comprising an 8 byte preamble and 9 bytes of payload with CRC and explicit header enabled. After transmitting a packet, the transmitter waited $T_w = 200$ ms before sending the next packet. Consequently there was a high packet sending rate, violating the European maximum duty cycle regulation [8] and therefore such a rate should not be adopted for commercial solutions to be deployed in Europe. However, for these experiments this setting was required in order to properly explore the short-term temporal variability in reception quality, critical to understanding the present work. Transmission power was set in software to 14 dBm, whereas actual measured output power was 12.6 dBm, due to losses in the RF front end.

In each experiment 20 000 packets were sent. For the field experiments the following parameters for Bandwidth (BW), Spreading Factor (SF), and Coding Rate (CR), $(BW - SF - CR)$ were used: *(i)* $125\,kHz - 7 - 4/6$, *(ii)* $125\,kHz - 10 - 4/6$, and *(iii)* $125\,kHz - 12 - 4/6$; whereas for the laboratory experiments a $125\,kHz - 10 - 4/6$ setting was used.

On the receiving side, for each correctly decoded packet, m, the receivers logged the time-stamp, the packet identifier, RSS $r[m]$ and SNR $s[m]$ values, reported in the corresponding transceivers' registers.

IV. Experimental Results & Discussion

Figure 4 presents data obtained from the laboratory test, while data acquired in the field measurements are given in Figs. 5 - 7. In each test RSS, SNR, and PRR are recorded over time. The individual data-points are drawn with low intensity color, whereas the thicker curve represents the short-term average value in a sliding window of 1 minute.

Comparative results for RSS, SNR and PRR obtained in the laboratory measurements are shown in Figure 4, with exactly 20 000 packets sent in the each test. From this data it was found that: LiT received 4 525 packets, UpT 17 402, and OdT 19 398 packets; yielding packet losses of 77.38 %, 12.99 %, and 3.01 %, respectively.

The OdT transceiver has 4 times less packet loss than the UpT, and 25 times less than LiT. The mean values of RSS over the entire measurement interval are −132 dBm, −125 dBm, and −139 dBm for LiT, UpT, and OdT respectively. Since the packet losses are not the same, sensitivities of the transceivers cannot be directly compared.

Using a conservative comparison approach, from the data it can be concluded that the OdT has at least 15 dB better sensitivity than UpT, and 25 dB better than LiT. Furthermore, OdT sensitivity is equal or exceeds the one specified in the datasheet for the RF IC used to develop new transceiver, since the datasheet states −132 dBm for 1 % packet loss.

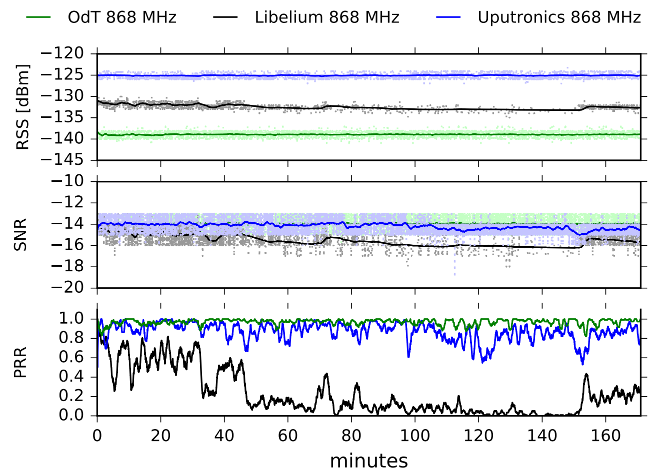

Figure 4. RSS, SNR and PRR in the laboratory test for OdT, LiT and UpT at 868 MHz. LoRa test parameters: $BW = 125$ kHz, $SF10$.

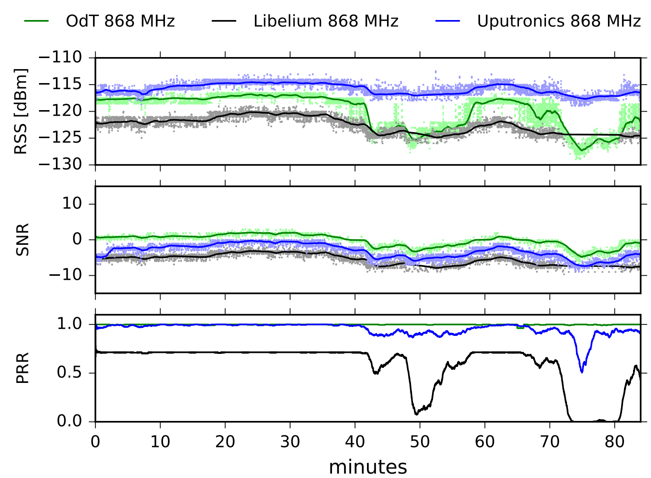

Figure 5. RSS, SNR and PRR for 112 km LOS link over land for OdT, LiT and UpT at 868 MHz. LoRa test parameters: $BW = 125$ kHz, $SF7$.

Field tests revealed improvements also in terms of sensitivity and, additionally, susceptibility to interference bursts. Figure 5 shows how interference affects the PRR of all three transceivers for $SF = 7$. The first interference burst occurs between the 40th. and 60th. minute of the test. During that interval, the RSS values drop for all three transceivers and OdT actually reaches the lowest value. Despite exhibiting the largest drop in RSS value OdT maintains the highest SNR, which clearly indicates that its noise floor is lowest. Moreover, packet loss is evident only on LiT and UpT, whereas OdT does not experience packet loss. The same situation repeats between the 70th. and 85th. minute.

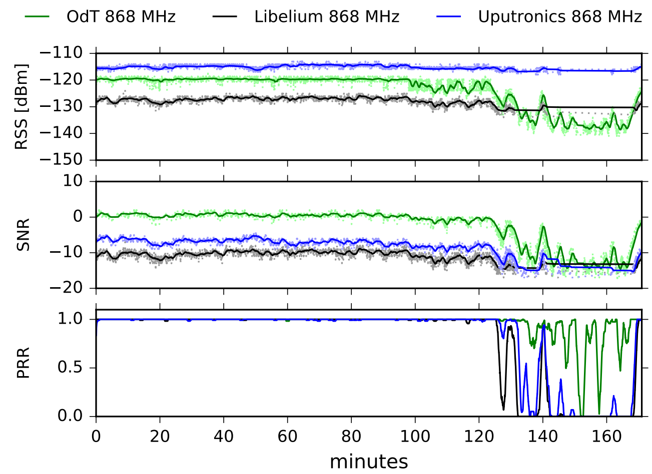

Figure 6. RSS, SNR and PRR for 112 km LOS link over land for OdT, LiT and UpT at 868 MHz. LoRa test parameters: $BW = 125\,\mathrm{kHz}$, $SF10$.

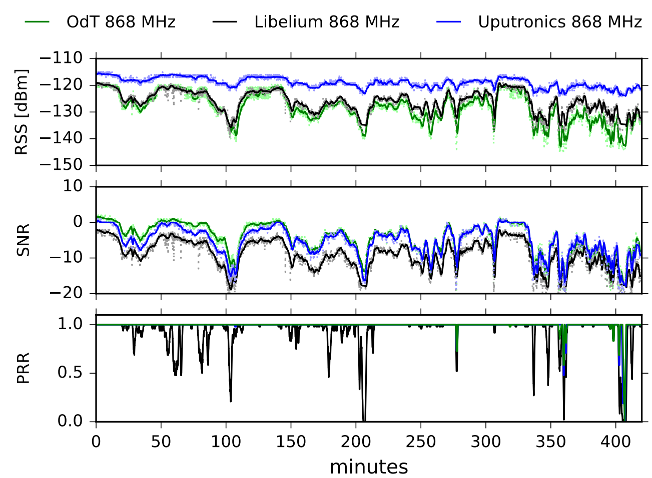

Figure 7. RSS, SNR and PRR for 112 km LOS link over land for OdT, LiT and UpT at 868 MHz. LoRa test parameters: $BW = 125\,\mathrm{kHz}$, $SF12$.

Further examination of the data reveals interesting behavior of the transceivers during a strong burst of interference which occurred between the 130th. and 170th. minute of the test, see Fig. 6. The interference was so strong that it affected the PRR of all three transceivers. It can be seen that while LiT and UpT experienced almost zero packet reception, OdT maintained a relatively high PRR.

We also investigated the feasibility of long range LoRa links and their properties for three characteristic spreading factors $SF \in (7, 10, 12)$ within a fixed LoRa bandwidth of 125 kHz. The field experiments clearly show that very long distance LoRa links (> 100 km) are entirely feasible using low-cost, off-the-shelf, rubber duck, omni-directional antennas in ISM 868 MHz band. This confirms assumptions that LoRa can be used in such scenarios. Although the links can be established using commercial transceivers, higher link reliability is achieved using OdT transceiver.

Analyzing RSS and PRR for different SFs, we make the following observations. For lower SFs (Figs. 5 and 6), multipath propagation effects are not dominant. This can be confirmed with reference to the low short term fluctuations of the RSS. Contrariwise, for $SF = 12$, results show that short term fluctuations are pronounced, implying a strong multipath effect. Furthermore for $SF = 12$, a small but almost constant packet loss is observed during the entire experiment. Such packet loss is unexpected since LoRa RF ICs have the highest sensitivity in this mode, and it has already been showed that transceivers can receive packets on the same trajectory without packet loss for lower SFs. Considering the duration of the experiment (7 hours), this phenomenon could be explained by very long packet air time which is 1057 ms and consequently higher probability for environment noise to be coupled during packet reception.

SNR follows PRR in all experiments and its minimum values are in accordance with minimum values specified in corresponding datasheets. This implies that SNR values reported by the transceivers are reliable and can be used to asses link quality.

V. Conclusion

We have presented a novel low-cost and miniaturized LoRa transceiver with improved characteristics. Experiments in both the laboratory and field were carried out to verify the transceiver's characteristics. We showed that the new LoRa transceiver has improved characteristics in terms of sensitivity and immunity to interference in comparison with two widely adopted commercial transceivers. Furthermore, we demonstrated that very long distance links in LOS scenario over land (112.5 km) are fully feasible using only low-cost, off-the-shelf, rubber duck, omni-directional antennas in ISM 868 MHz band, for three different spreading factors: 7, 10, and 12. Experiments also revealed potential downside of using higher spreading factors due to very long packet air times and increased susceptibility to interference. Our future work will focus on very long distance links and correlation between SFs and transmission reliability within fixed bandwidth.

References

[1] B. Reynders and S. Pollin, "Chirp spread spectrum as a modulation technique for long range communication," in *Symp. on Comm. and Veh. Technol.*, 2016.

[2] P. Neumann *et al.*, "Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study," in *Proc. IEEE 12th Int. Conf. on Wireless and Mobile Computing, Networking and Commun*, 2016.

[3] A. Augustin *et al.*, "A study of lora: Long range & low power networks for the internet of things," *Sensors*, vol. 16, no. 9, 2016.

[4] O. Iova *et al.*, "Lora from the city to the mountains: Exploration of hardware and environmental factors," in *Proc. of the 2017 Int. Conf. on Embedded Wireless Systems and Networks*, 2017, pp. 317 – 322.

[5] J. Gaelens *et al.*, "Lora mobile-to-base-station channel characterization in the antarctic," *Sensors*, vol. 17, no. 8, 2017.

[6] J. Petajajarvi *et al.*, "On the coverage of LPWANs: Range evaluation and channel attenuation model for LoRa technology," in *Proc. 14th Int. Conf. ITS Telecommun. (ITST)*, 2015.

[7] M. Zennaro *et al.*, "Radio link planning made easy with a telegram bot," in *Proc. of the 2nd EAI Int. Conf. on Smart Objects and Technol. for Social Good*, 2016.

[8] ETSI. [Online]. Available: http://www.etsi.org/deliver/etsi_tr/103000_103099/103055/01.01.01_60/tr_103055v010101p.pdf

[9] U. Raza *et al.*, "Low power wide area networks: An overview," *Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 855 – 873, 2017.

[10] A. Wixted *et al.*, "Evaluation of LoRa and LoRaWAN for wireless sensor networks," in *Proc. IEEE SENSORS*, 2016.