Performance Evaluation of LoRaWAN Applied to Smart Monitoring in Onshore Oil Industries

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Abstract—A performance evaluation of the physical layer of the long-range (LoRa) technology is presented in this paper. An experimental setup with off-the-shelf LoRa wide area network (LoRaWAN) devices were prepared to demonstrate the feasibility of this technology. Feasible communication between a central oil-producing process used to monitor several oil wells, located in a rural area, was achieved at distances up to \( \approx 2.7 \) km, according to measurements of the average received signal indicators around \(-100\) dBm for an average SNR \( \approx 5.6\) dB. It is possible to conclude from the experimental results that LoRaWAN is a suitable long-range and low power wide area network for smart monitoring in oil industries.

Index Terms—Long range, low power wide area network, performance evaluation, received signal indicator.

I. INTRODUCTION

The concept of Industry 4.0 is worldwide growing, also due to the rapid development of the information technology [1]. Industrial equipment in systems like manufacturing, smart metering and smart monitoring in industries of automation already demand, among others, intelligent communication and data processing through smart and low power networks. Indeed, long-range coverage, low data rates, energy and cost effective end devices are important requirements attended by some low power wide areas network (LPWAN) technologies.

The application of LPWAN technologies such as Long Range Wide Area Network (LoRaWAN), Sigfox, Narrowband-IoT (NB-IoT) and Long-Term Evolution MTC (LTE-M) is in continuous growth [2]. Taking advantage of an already installed and mature infrastructure and, in theory, with better coverage, NB-IoT and LTE-M has the disadvantage of operating in frequencies of the licensed bands. Low-cost deployment and short time-to-market are important advantages of LoRaWAN and Sigfox, due to the use of owned licensed or license-free bands, like the industrial, scientific and medical (ISM) band. The fair coverage and capacity comparison between LoRaWAN and Sigfox detailed in [3] shows that LoRaWAN has better performance in outdoor environments with external interference. Indeed, LoRaWAN is being employed in various use-cases, exciting investigations like those outlined in [4], [5].

Long range (LoRa) is a wireless narrowband technology using low cost and low power devices for low data rate transmission in long ranges, even with the extremely low receiver sensitivity and signal detection with negative signal-to-noise ratios (SNR) [6]. Commonly, it explores a kind of chirp spread spectrum (CSS) modulation technique that is robust against interference, multipath fading, and Doppler effect. In its turn, LoRaWAN is the media access controller (MAC) layer protocol that uses LoRa as its physical (PHY) layer [7]. By employing multiple LoRaWAN gateways, communicating through an Internet connection with a specific server, it is possible to build public and private wireless networks [6].

However, it should be stressed that important details of the LoRa PHY layer is still unknown due to the corporate property and patents that characterize the technology [3], [7]. Therefore, a performance evaluation on the PHY layer of the LoRa technology is presented in this paper. An experimental setup with off-the-shelf LoRaWAN equipment was used to demonstrate the feasibility of this promising technology in the communication between a central monitoring station and several oil wells located in a rural area. Communication in distances up to \( \approx 2.7 \) were achieved, showing the reliability of the technology for control and supervision of the relevant process variables in Industry 4.0.

II. BASIC ASPECTS OF THE LORA MODULATION FORMAT

Because of the robustness against noise interference, multipath fading, and Doppler effect provided by the modulation format, LoRa presents itself as a strong candidate for transmissions over a long distance, while being energy efficient [7]. Usually operating in unlicensed bands, chirp spread spectrum is considered as the modulation scheme used in the LoRa physical layer [6]. Also known as frequency shift chirp, the CSS generates chirp signals with a variable frequency that linearly increases or decreases over a certain amount of time, basically going from a minimum frequency \( (f_{min}) \) to a maximum \( (f_{max}) \), or in the opposite direction [3], [6].

To modulate a symbol (a number of bits between 7 and 12) into a chirp, CSS uses a frequency offset \( f_{off} \) for every chirp, which is the start frequency of the chirp. The frequency of the chirp increases until the higher bandwidth boundary \( (f_{max}) \), from which its value is cyclically shifted to the lower boundary \( f_{min} \). Again, the frequency increases, until it gets
back to \( f_{off} \), were the symbol completes one cycle. The time it takes to complete one chirp cycle is also denominated as a symbol period \( T_s = \frac{2^{SF}}{T} \), for \( SF \in 7, 8, ..., 12 \) the spreading factor and \( T = 1/BW \) a sample (also known as a chip) time. With a chirp composed of \( 2^{SF} \) samples, a discrete time LoRa symbol can be expressed as

\[
s_k(nT) = \sqrt{E_s} \cdot z_k(nT)
\]

\[
= \sqrt{E_s} \cdot \exp \left( j2\pi (k + n) \mod \frac{2^{SF}}{n} \right)
\]

for \( k \in 0, 1, 2, ..., 2^{SF} - 1 \), \( E_s \) the chirp energy, \( z_k(nT) \) the quasi orthogonal basis functions of the signaling space and \( \mod \) the modulo operator [3].

Considering the quasi orthogonality of the chirp signals and perfect time and frequency synchronizations, the LoRa demodulation can be executed by the correlation process

\[
\sum_{n=0}^{2^{SF}-1} r_k(nT) \cdot z^*_k(nT) = \begin{cases} \sqrt{E_s} + \eta_i & i = k \\ \eta_i & i \neq k \end{cases}
\]

(2)

where \( r_k(nT) = s(nT) + \eta(nT) \) is the received waveform degraded by the zero mean white Gaussian noise \( \eta(nT) \) of an AWGN channel and \( z^*_k(nT) \) the complex conjugate of \( z_k(nT) \) [3]. The received symbol with the highest correlation with the corresponded transmitted waveform can be detected as

\[
Y_k = \arg \max \left( \delta_{k,i} \sqrt{E_s} + \eta_i \right),
\]

(3)

in which \( \delta_{k,i} = 1 \) for \( i = k \) and 0 otherwise. The bit rate can be defined as \( R_b = SF \cdot \frac{B}{c} \) in b/s [6]. Considering a channel coding at a rate \( \frac{4}{7} \), the useful bit rate is \( R_b = SF \cdot \frac{B}{c} \cdot \frac{4}{7} \), for CR the code rate.

Received signal strength indicator (RSSI) and signal-to-noise ratio (SNR) are measurement parameters that reflects the quality of a LoRaWAN link [6]. Thus, considering that

\[
\text{SNR} = S + 174 - 10 \cdot \log_{10}(BW) - NF
\]

(4)

for \( S \) the receiver sensitivity and \( NF \) the receiver noise figure, we can estimate the SNR from measured RSSI considering that \( S = \text{RSSI} - P_{tx} \), for \( P_{tx} \) the transmitted power.

A. Urban, Suburban and Open Area Channel Models

The Hata model is one of the most popular used to calculate path loss for microwave radio links up to 1500 MHz and

100 Km [8]. According to the Hata model, the path loss for a distance \( d \) (in meters) in Urban areas can be calculated as

\[
P_{L_{Hata,U}}(d) [\text{dB}] = 69.55 + 26.16 \times \log_{10}(f_c) - 13.82 \times \log_{10}(h_{TX}) - C_{RX}
\]

\[
+ (44.9 - 6.55 \times \log_{10}(h_{TX})) \times \log_{10}(d),
\]

(5)

for \( f_c \) the center (operation) frequency in MHz, \( h_{TX} \) the transmitter antenna height in meters and \( h_{RX} \) the height of the receiver antenna. For large coverage, the correlation coefficient \( C_{RX} \) of the receiver antenna is given as

\[
C_{RX} = 3.2 \cdot \left( \log_{10}(11.75 h_{RX}) \right)^2 - 4.97, \quad 0.2 \leq f_c \leq 1.5 \text{ GHz}.
\]

(6)

Moreover, for open areas, the path loss can be obtained as

\[
P_{L_{Hata,O}}(d) [\text{dB}] = P_{L_{Hata,U}}(d) - 4.78 \times (\log_{10}(f_c))^2 + 18.33 \times (\log_{10}(f_c))^4 - 40.94.
\]

(7)

III. EXPERIMENTAL EVALUATION

A. The Experimental Setup

Fig. 1 shows a block diagram of the experimental setup used to measure RSSI and SNR. A global positioning system (GPS) module located at the transmitter (LoRa end device) measures the current device location, supported by an ATSAMD21 micro-controller. The measured coordinates are transmitted every minute to the receiver LoRa Gateway via a RFM95W LoRaWAN chip. Fig. 2 shows the oil Industry map with the locations of the central monitoring station (Gateway location) and several oil wells (end devices locations).

At the receiver, the LoRa concentrator chip SX1301 measures the values of RSSI and SNR at each end device position. A Raspberry Pi micro-controller sends the measured values to a LoRaWan server. The used LoRa devices were configured according to the parameters shown in Table I.

B. Experimental Results

Fig. 3 shows the RSSI values measured in all considered oil wells. To compare the measurements with analytic approximations, Fig. 3 shows the curve of equation (7). The gateway sensitivities for \( SF = 10 \) is also shown for fair comparisons. It is clear from Fig. 3 that the behavior of open areas can be distinguished from the RSSI measurements. This was expected due to the fact that the monitoring plant is located in a rural area. The few measurements that belongs to suburban
TABLE I
PARAMETERS CONFIGURED IN THE DEVICES.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>$B_W$</td>
<td>125</td>
<td>kHz</td>
</tr>
<tr>
<td>Spreading Factor</td>
<td>$SF$</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Frequency</td>
<td>$f_c$</td>
<td>902.3; 902.5; ...; 903.7</td>
<td>MHz</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>$P_T$</td>
<td>20</td>
<td>dBm</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>$N.F.$</td>
<td>7</td>
<td>dB</td>
</tr>
<tr>
<td>Antennas Gain</td>
<td>-</td>
<td>3</td>
<td>dBi</td>
</tr>
<tr>
<td>Gateway Antenna Height</td>
<td>-</td>
<td>20</td>
<td>m</td>
</tr>
<tr>
<td>End-Device Antenna Height</td>
<td>-</td>
<td>1.5</td>
<td>m</td>
</tr>
</tbody>
</table>

Fig. 2. Map showing the central monitoring station and the oil wells.

areas can be explained by the mountains and high trees that exist between the monitoring station and the oil wells.

Fig. 3 also shows that, for all measurements, the acquired $RSSI$ values are above the receiver sensitivity. This shows the robustness of the technology in such scenarios.

Fig. 4 shows a comparison between the measured values of SNR and the SNR quantities estimated from the measured $RSSIs$. It can be seen from Fig. 3 that, almost all the estimated values are close to measured SNRs. The discrepancy registered in the first measurements are due to the fact that they were measured underneath the gateway antenna tower, whereas the last three depicted discrepancies can be explained by multipath gains not considered by the theoretical analysis.

IV. CONCLUSION

Important mechanisms of the LoRa physical layer that can support the design of a LoRaWAN are still unknown due to its corporate property nature. Hence, a performance evaluation of the PHY of the long-range (LoRa) technology was presented in this paper. An experimental setup with off-the-shelf LoRa devices was prepared to demonstrate the feasibility of LoRaWAN in long-range rural areas.

Communication in distances up to $\approx 2.7$ km were achieved, according to measurements of the average received signal indicators around $-100$ dBm for an average SNR $\approx 5.6$ dB. Thus, we conclude that LoRaWAN can be considered a suitable LPWAN technology for smart monitoring in oil Industries.

V. ACKNOWLEDGEMENTS

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