Flexible Multi-Standard Digital Front End for LPWA Technologies

Patrick Savelli, Vincent Savaux, Pauline Desnos, Ali Zeineddine, Matthieu Kanj, and Christophe Delacourt

Abstract – This article proposes a flexible multi-standard digital front-end (DFE) hardware architecture designed for three main low-power wide-area technologies: LoRa, Sigfox, and narrowband Internet of Things. We demonstrate the feasibility of a unified DFE architecture that fits the requirements of these technologies. The proposed DFE architecture has been implemented on a Spartan-6 field-programmable gate array within a base station receiver and tested using a platform based on universal software radio peripherals. We show that the expected performance can be achieved with low hardware complexity in terms of memory and logic requirements.

1. Introduction

The development of the Internet of Things (IoT) market has led to a great diversity of wireless connectivity solutions. This article addresses low-power wide-area (LPWA) solutions, targeting IoT networks with coverage in the kilometer order, using low-power end devices that have a battery-life autonomy of multiple years. Various LPWA technologies and standards have emerged, with different air interfaces, including LoRa, Sigfox, narrowband IoT (NB-IoT), LTE-M, DASH7, Weightless, NB-Fi, RPMA, and MYTHINGS [1–3]. In this context where multiple options are possible, there is a need for technical components that are flexible enough to support different technologies.

In this article, we focus on the main LPWA technologies that have been widely adopted and deployed by operators, as part of large ecosystems [4]: LoRa, Sigfox, and NB-IoT.

The LoRa technology introduced by Semtech uses a chirp-based patented modulation scheme, while the network can be deployed by any third-party entity based on the LoRa 2017 open specifications [5] maintained by the LoRa Alliance (https://lora-alliance.org/). Sigfox technology proposed by Sigfox S.A. also uses the unlicensed spectrum, and is based on the differential binary phase-shift keying (D-BPSK) and Gaussian frequency-shift keying (GFSK) modulation schemes. Moreover, the network deployment of this technology is controlled by Sigfox. NB-IoT, initially published in release 13 of the third-generation partnership project (3GPP; https://www.3gpp.org/news-events/1785-nb_iot_complete), is based on a cellular mobile network, using resources within frequency bands allocated to LTE (in-band mode) or dedicated to NB-IoT (stand-alone mode). This diversity increases LPWA network deployment costs, in case each technology is independently deployed.

To solve the problems of a heterogeneous network and efficiently exploit virtualization techniques, interoperability between these LPWA technologies should be maximized. On the radio front-end level, this is achieved by providing LPWA gateways that are capable of supporting the largest number of technologies. This type of gateway requires a digital front-end (DFE) implementation that provides the flexibility needed to meet the requirements of these different technologies.

This article proposes a generic approach to building a flexible multi-standard DFE for LPWA technologies. A focus on the hardware implementation of the DFE is presented. A common architecture for the three considered LPWA solutions is proposed, respecting the constraints imposed by their specifications.

The rest of the article is organized as follows. In section 2, the flexible DFE architecture is presented based on the requirements of the different LPWA technologies. Section 3 presents the hardware implementation of this flexible DFE. And Section 4 concludes the work.

2. Multi-Standard DFE Design Approach

2.1 Overview

A preliminary analysis phase of the three protocols allowed us to design the DFE around three blocks, as shown in Figure 1:

1. Rate adaptation: the sampled signal at the output of the analog-to-digital converter (ADC) is subsampled from sampling frequency f_0 (ADC frequency) to frequency f_1, with $f_1 \leq f_0$. A very efficient and low-complexity rate adaptation is implemented based on [6, 7].
2. Filtering: A low-pass finite impulse response (FIR) filter operating at frequency f_1 allows rejection of neighboring interferers and blocking signals, as well as performance of a pre-

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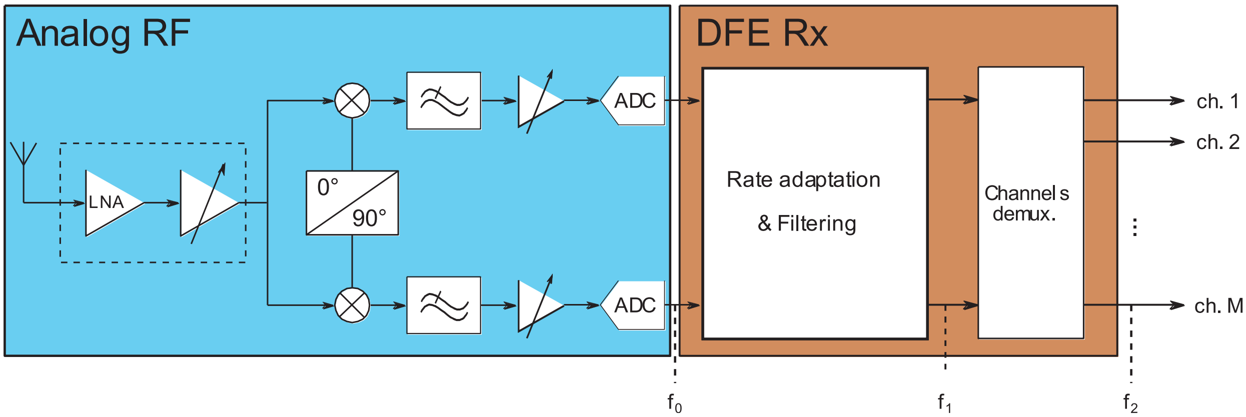

Figure 1. General DFE block diagram, including rate adaptation, filtering, and channel demultiplexing (demux.).

equalization in the band-pass area. Since the computational cost of the filtering step is directly related to the length of the filter (i.e. its number of taps), it is designed as short as possible while respecting the requirements. We used our own FIR filter design tool (available at https://wirelesslibrary.labs.b-com.com/FIRfilterdesigner/) to generate equiripple filters [8].

3. Channel demultiplexing: The aim of the channel demultiplexing block is to split the whole band into different channels, e.g., channels of 125 kHz for LoRa (i.e., $f_2 \geq 125$ kHz) or of 180 kHz for NB-IoT (i.e., $f_2 \geq 180$ kHz). The channel demultiplexing is performed thanks to a filter bank with a polyphase filter implementation, which is easily configurable (number of channels, channel bandwidth). The result is that all output channels have the same bandwidth. It must be noted that there is no default channel split defined in Sigfox, so we propose applying several channel demultiplexing blocks in parallel, using the same input signal with a different frequency shift, so as to use a similar architecture.

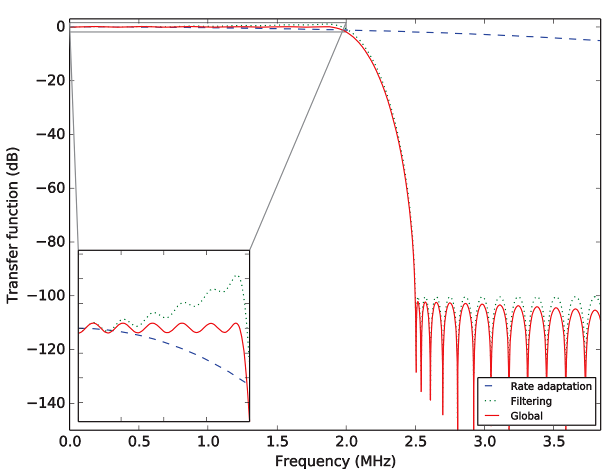

Figure 2. Filter shapes at each step and global filtering. Note that the FIR filter compensates the rate adaptation attenuation in the passband.

These blocks are common to the three technologies, and require only specific parameters to be adapted to each. This then allows for rapid hardware development of flexible DFEs. Figure 2 shows an example of frequency response for the rate adaptation, the low-pass filter, and their combination (referred to as “global”). In this example, the DFE is adapted to the reception of NB-IoT within an LTE band, considering a 5 MHz bandwidth. The ADC frequency is set to $f_0 = 60.8$ MHz and the output frequency of the rate adaptation and filtering stage is $f_1 = 7.68$ MHz, corresponding to the sampling frequency of the 5 MHz LTE band. The filter has been designed for a 100 dB rejection and a ripple below ± 1 dB. Furthermore, it can be observed that the filter applies equalization in the passband to counterbalance the attenuation due to the rate adaptation block.

2.2 Design Constraints

We provide in this section the list of RF performance parameters that affect the DFE design for the targeted air interfaces.

2.2.1 *LoRa:* LoRa networks are operated in unlicensed bands using a proprietary physical layer (PHY) designed by Semtech.

The LoRa PHY main characteristics are listed in Table 1. The European industrial, scientific, and medical (ISM) frequency band used for LoRa operation is indicated for the sake of example, but other unlicensed frequency bands are also used according to the geographical area [9].

Based on these characteristics, we have derived the design parameters of our DFE for the LoRa mode of operation as indicated in Table 2. The parameters have been carefully adjusted to achieve high channel selectivity, assuming parallel reception of eight LoRa RF channels with 200 kHz channel raster. The output rate of the DFE in this case is 250,000 samples/s, which

Table 1. LoRa PHY characteristics

Parameter	Value (Europe)
Frequency band (MHz)	863-870
Duplex mode	Half duplex
Channel bandwidth (kHz)	125
Channel raster (kHz)	200
Number of channels	3 mandatory, typically 8
Gateway Tx power (dBm)	20
Modulation	Chirp spread spectrum
Spreading factor	7-12
Coding rate	4/5, 4/6, 4/7, 4/8

corresponds to a data rate of 1 MB/s per channel when using 16 bits for each of the I and Q paths.

2.2.2. *Sigfox:* Sigfox has released its proprietary radio specifications in [10], including the air interface description and the different regional parameters. Table 3 summarizes the radio parameters of the European region.

As indicated in the table, the available frequency range for uplink and downlink transmissions spans 192 kHz in both directions. Within this bandwidth, guard bands are reserved at the lower and upper parts to account for inaccuracies in the reference frequency at the end node (20 ppm assumed) and at the network gateway (1.62 ppm assumed) sides. The usable frequency band when considering these guard bands is reduced to 154.462 kHz, centered at 868.13 MHz. For the sake of clarity, let us consider a usable frequency band of 150 kHz in the rest of this article.

It is also important to note that the channel bandwidth occupied by the Sigfox signal (100 Hz) is low compared to the channel frequency inaccuracies of the transmitter and receiver ends.

For this reason, the Sigfox gateway receiver cannot assume a fixed channel raster, and must be able to demodulate an uplink-modulated signal present at any frequency within the usable bandwidth. In addition, the average RF channel frequency drift observed during a transmission is as high as ±20 Hz/s due to the reference frequency source drift, and the typical burst duration exceeds 1 s. This constraint needs to be addressed when designing the filtering and channel demultiplexing in the DFE.

In order to fulfill these constraints, our proposal is to consider 300 Hz wide channels every 200 Hz, using two parallel filtering and channel demultiplexing entities. Each parallel entity processes a different version of the received signal shifted by a 200 Hz offset. In total, there are 750 channels at the output of the DFE to cover the 150 kHz band.

Table 2. DFE configuration for LoRa, 8 channels

Parameter	Value
DFE design parameters	
ADC output rate f_0 (MHz)	60.8
Rate adaptation output rate f_1 (MHz)	1.6
Channel demultiplexing (1000 samples/s)	250
Output rate f_2	Per channel
Number of filter taps	500
Achieved channel selectivity	
Carrier offset (kHz)	±85
Rejection (dB)	75

Table 3. Sigfox PHY characteristics

Parameter	Value (Europe)
Frequency band (MHz)	
Uplink	868.034-868.226
Downlink	869.429-869.621
Duplex mode	FDD
Channel bandwidth (Hz)	100 uplink and downlink
Modulation	
Uplink	D-BPSK
Downlink	GFSK

The DFE parameters set to implement this Sigfox configuration are provided in Table 4. Note that at the DFE output, the channel bandwidth is 300 Hz, so the output of the DFE must be further processed to demodulate the 100 baud D-BPSK signal.

2.2.3 *NB-IoT:* NB-IoT is a cellular LPWA technology introduced in release 13 of the 3GPP specifications. In this contribution, we target the NB-IoT in-band operation mode, where some LTE resource blocks of 180 kHz bandwidth are allocated to NB-IoT. For instance, four specific resource blocks are defined when NB-IoT is transmitted in the 5 MHz LTE band.

Our proposal for the NB-IoT operation mode is to use the DFE for the extraction of 180 kHz wide physical resource blocks (PRBs) within the LTE band. Tables 5 and 6 summarize the NB-IoT constraints and the corresponding configuration, respectively, considering the LTE 5 MHz bandwidth and in-band mode.

3. Hardware Implementation

3.1 Test Platform

Our gateway experimentation platform is composed of an off-the-shelf NI USRP B205mini board. This software-defined radio platform contains the RF transceiver and an Xilinx Spartan-6 FPGA with an 83.3 mm × 50.8 mm × 8.4 mm form factor. The DFE function has been implemented in the user-programmable FPGA.

The receiver also includes, prior to the B205mini RF receiver, an analog front-end board of our own

Table 4. DFE configuration for Sigfox

Parameter	Value
DFE design parameters	
ADC output rate f_0 (MHz)	60
Rate adaptation output rate f_1 (MHz)	150
Channel demultiplexing (1000 samples/s)	400
Output rate f_2	Per channel
Number of filter taps	24,000
Achieved channel selectivity	
Carrier offset (Hz)	±200
Rejection (dB)	60

Table 5. NB-IoT PHY characteristics (in-band mode)

Parameter	Value
Frequency bands	Same as LTE
Duplex mode	Half duplex
	FDD
	TDD (release 15)
Channel bandwidth (kHz)	180
Waveform	
Uplink	SC-FDMA
Downlink	OFDMA
Modulation	π/2-BPSK, π/2-QPSK, QPSK
Subcarrier spacing (kHz)	3.75, 15

design that includes a low-noise amplifier achieving 30 dB gain with a 3 dB noise figure in the 868 MHz ISM band and LTE band 8.

The functional and performance tests are done using IoT (LoRa, Sigfox, or NB-IoT) commercial devices.

3.2 FPGA Implementation and Results

Table 7 summarizes the Rx DFE hardware resource utilization for each of the targeted IoT standards. Four key resources are detailed: registers used to save temporary results and variables, lookup tables (LUTs) that determine the combinatorial behavior, memory (RAM) to store parameters such as the filter taps, and digital signal processors (DSPs) that are specialized units for multiplication/addition computation. Note that the DFE has been designed to be optimized in terms of resource utilization. Since the input rate is low in IoT standards, it allowed us to focus on the module size from the design stage.

This table shows that any of the LoRa, Sigfox, or NB-IoT DFEs fits in the small cost-effective B205mini board. The different technologies use similar resources, except for the much higher RAM requirement for the Sigfox mode. This is mainly due to the number of channels to be processed in parallel, requiring a large number of filter taps. The RAM requirement is also higher for NB-IoT compared to LoRa. The worst case in the NB-IoT in-band mode is indeed the 20 MHz LTE bandwidth case, where 18 PRBs are dedicated to NB-IoT and need to be extracted in parallel. This affects the number of filter taps that need to be stored within the block. In the case of LoRa, the number of parallel channels is set to eight, hence the lower memory needs. Moreover, it must be emphasized that a small (cost-effective) FPGA has been used for our test, allowing for the embedding of at most two technologies on the same board. However, the three technologies could be easily embedded on a larger board, allowing for a true multi-standard DFE.

Table 6. DFE configuration for NB-IoT in-band mode, 5 MHz bandwidth (25 PRBs)

Parameter	Value
DFE design parameters	
ADC output rate f_0 (MHz)	60.8
Rate adaptation output rate f_1 (MHz)	7.68
Channel demultiplexing (1000 samples/s)	240.10
Output rate f_2	Per channel
Number of filter taps	256
Achieved channel selectivity	
Carrier offset (Hz)	±200
Rejection (dB)	60 0

Table 7. FPGA DFE complexity figures

Technology	Registers	LUTs	RAM	DSPs
Available	184,304	92,152	268	180
LoRa	12,055	10,162	24	68
Sigfox	12,282	11,019	153	68
NB-IoT	13,585	10,936	48	74

The integration of the DFE within the complete network infrastructure has been initiated and preliminary measurements conducted. Figure 3 shows some of the sensitivity measurements obtained for the LoRa case. The curves represent the block error rate as a function of the input signal level, for spreading factor configurations 7 and 9. The performance results obtained through simulations (the whole LoRa transmission/reception chain has been simulated) and through measurements (testing our Lora receiver against an RF signal generator loaded with LoRa waveforms) are compared. It can be observed that the curves almost match, validating our implementation.

4. Conclusion

In this article, we present a flexible multi-standard digital DFE for the main LPWA technologies: LoRa, Sigfox, and NB-IoT. The solution is based on three hardware subsystems that can be configured and tuned according to the targeted technology: rate adaptation, filtering, and channel demultiplexing. In the future, we plan to assess and further improve the full RF receiver performance for the three technologies, and particularly immunity to adjacent signals and blockers. We are also working on the integration of hardware detection blocks

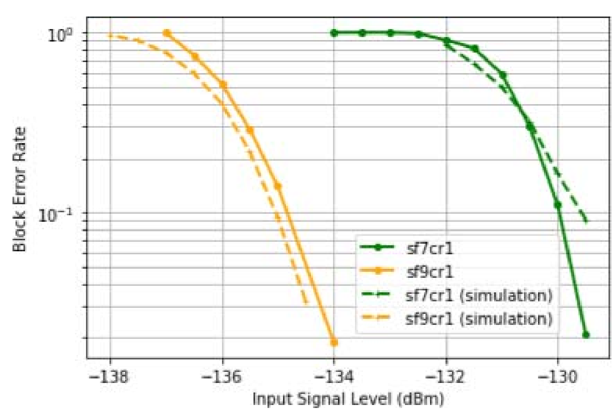

Figure 3. Sensitivity preliminary measurements for the LoRa system.

dedicated to the technologies mentioned, with encouraging preliminary results.

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