A robust, selective, and flexible RF front-end for wideband sampling receivers

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Abstract

In this paper, we describe the design and evaluation of a second-generation front-end unit for wideband sampling radio receivers. The unit contains a surface acoustic wave (SAW) filter to protect the receiver from strong out-of-band signals, an RF limiter to protect both the filter and the receiver from physical damage due to strong signals, and a bias tee with a DC limiter to provide DC power to a masthead low-noise amplifier, if one is used. The unit allows receivers such as those of the universal software radio peripheral (USRP) N-series type to be effectively used in RF environments with weak signals and strong in-band and out-of-band interferences.

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1. Introduction

The flexibility of implementing most of the signal processing of a radio system in software, coupled with the availability and low cost of wideband sampling receivers and transceivers, has led to an incredible range of applications of software defined radios (see, [1–9] for examples in the areas of cognitive radio, satellite navigation, and localization). In many cases, the sampling radio must cope with weak signals and RF interference, which requires a quiet and selective front-end. Many popular wideband sampling radios lack such front-ends. In this paper, we describe the design and evaluation of a simple but effective front-end unit for such radios, and in particular for universal software radio peripheral (USRP) N-series radios that operate in the license-free UHF bands. The design that we describe is a second-generation design that builds on the experience gained from designing and operating a first-generation design for several years. As a result, the design is not only quiet, selective, and robust (in a sense that will be described later), but also flexible, inexpensive, and easy to deploy.

2. Background and objectives

A USRP radio\textsuperscript{1} consists of an up/down converter, analog-to-digital converters (ADCs), digital-to-analog converters (DACs), a field programmable gate array (FPGA), and a computer interface (Ethernet or USB). In radios from the N and X series, and in some of the radios from the B series, the ADCs, DACs, and FPGA are on a motherboard and the up/down converter is on a daughterboard. On the other hand, low-end USRPs utilize a single chip that combines the up/down converter, ADCs, and DACs (the Analog Devices AD9364). Current up/down converters, as well as integrated USRPs are wideband and have linear responses; that is, they have no RF selectivity. For example, the WBX daughterboards cover 50–2200 MHz and the UBX daughterboards cover 10–6000 MHz.

The absence of RF selectivity permits out-of-band signals to overload RF amplifiers and/or mixers leading to non-linearity, intermodulation, or loss of sensitivity due to automatic gain

\textsuperscript{1} By Ettus Research, http://www.ettus.com.
control (AGC) action that places attenuators in the signal path. In addition, the noise figures of the downconverters are good but not superb (typically around 5 dB), further limiting their abilities to process weak signals. These considerations suggest that one or more circuits be placed between the receiving antenna and the input of the USRP and similar radios. We refer to such circuits as front-end units.

At the very least, the front-end unit should include a filter to attenuate out-of-band signals. However, a filter between the antenna and the input of the receiver will degrade the noise figure of the system; this can be addressed by placing a high intercept low-noise amplifier (LNA) between the antenna and the filter, ideally close to the antenna (to prevent long cable runs from degrading the system’s noise figure).

We designed two generations of such front-end units for a time-of-arrival wildlife localization system [10,11]. The first-generation units, which have been deployed for over 3 years now, consist of a commercial LNA with modest of selectivity (single LC pole in the input, a second at the output) and a boxed front-end unit consisting of a helical LC filter, an integrated wideband LNA, a limiter, and a SAW filter [12]. Most of the selectivity is provided by the SAW filter; the helical filter was intended for the most part to prevent overload of the integrated LNA by far out-of-band signals. The limiter has two functions. Firstly, to protect the SAW filter, which can only tolerate about 10 mW of power; the two LNAs have a combined gain of about 35 dB, and because of their high IP3 intercept points, they can produce about 250 mW of power. Therefore, a power of more than 10 mW at the input of the SAW filter is not unlikely. The limiter also protects the down converter from excessive power. Moreover, most USRP down converters do not have built-in RF limiters, so their input power is limited to 10 mW (or less, depending on the model). Initially, power to the masthead LNA was provided by a dedicate power cable, but we later converted some of the sites to use bias tees so that a single cable can carry both DC to the masthead LNA and the RF signal, simplifying the logistics.

The experience we gained from operating 9 sites with first-generation units led to several conclusions:

- The combined gain of the two LNAs was usually much more than needed. The AGC algorithm usually placed attenuation in the signal path to avoid overloading the ADCs.
- If the integrated LNA is dropped, the helical filter can also be dropped, since its sole function is to protect the integrated LNA. The helical filter is relatively expensive (about $18 US) and difficult to source.
- The RF limiter that we used (Mini-circuits RLM-33+) allows a little more than 10 mW to pass through, requiring an additional fixed attenuator between the SAW filter and itself.
- Providing DC at the input connector of the front-end unit via a choke proved problematic. This was because many commercial antennas present a DC short (this prevents static buildup and eliminates the need for a blocking capacitor in some antenna designs). Users sometimes connected the front-end unit to such an antenna rather than to the masthead LNA, sometimes by mistake, and other times because they did not need the masthead LNA. This led to power failure in the front-end unit, whose DC supply was shorted, and sometimes destroyed the choke.
- The boxed front-end unit required a separate power supply from that of the radio, complicating the logistics.
- Manufacturing or adapting the box for the boxed front-end unit proved time consuming and fairly expensive.

These difficulties and lessons led us to define more appropriate requirements for the next generation of front-end units:

1. The front-end units should contain a limiter and a SAW filter but no LNA.
2. The front-end units should provide DC power to the masthead LNA, and should also continue to operate normally even if connected instead to an antenna that presents a DC short.
3. The DC power that the unit provides to the masthead LNA should come from the radio when possible, and not from a separate power supply.
4. When possible, the front-end unit should be packaged as part of the USRP radio, as opposed to being placed in a separate box.
5. To provide flexibility, the front-end units should be adaptable to different frequency bands (we also examined the possibility of switching filters in and out to allow band selection at run time but eventually decided to design simple single-filter units).

3. Design

Fig. 1 shows the design of the new front-end units. The signal from the antenna or from the masthead LNA passes through a limiter and a SAW filter. The limiter, SKY16602-632LF by Skyworks Solutions [13], is more conservative than the one used in first-generation units. It has minimal insertion loss for input powers of up to 0 dBm (up to 0.5 dB), and does not allow more than about 6 dBm to pass to the filter. It operates between 0.2 and 4 GHz. The SAW filter installed in the built units is Murata SF2136E, a 5 MHz-wide, 433.92 MHz center, 3 mm-by-3 mm filter [14]. Both the limiter and the filter are internally matched to 50 Ω, simplifying the design. The limiter also includes DC blocking capacitors. The footprint of the filter can accommodate a wide range of SAW filters that cover the 434, 868, 915, and 2400 MHz license-free bands, and the GPS band, among others. Table 1 lists some of these alternative filters.

The front-end unit also includes a bias tee that provides DC power to its RF input connector via a DC limiter integrated circuit, the Texas Instruments TPS2553-1 [15]. The $R_{\text{lim}}$ resistor programs the current limit; we use 180 kΩ resistors that imply a current limit of about 130 mA in our units, whereas other resistor values can program current limits ranging from 75 to 1500 mA. The limiter operates at DC input voltages of 2.5 to 6.5 V, serving well the USRPs that have power supplies providing 6 V. This voltage level allows the masthead LNA to regulate its DC voltage to 5 or 3.3 V, using an LDO. We use the
Table 1

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*a The part numbers are those used in our evaluation.

TL720M05 5 V regulator in the masthead LNA. The DC limiter comes in several variants and we use a latch-off variant that shuts off the DC to the masthead LNA if the current limit is exceeded for more than a few milliseconds. The same footprint also accommodates a variant that behaves like a constant current source when overloaded; it wastes more power when overloaded, but does not require resetting when the short or overload is removed. The limiter has a fault (overload) logical output that we do not use, and an enable pin that we normally pull up using a 10 kΩ resistor (shown in the photograph but not in the schematics).

We designed the form factor of the units so that they fit within USRP N200 and N210 radios. A card-edge SMA male connector on the input of the unit is secured to an existing hole in the front panel of the USRP, and a card-edge SMA male connector attaches to the cable that normally connects the daughterboard to the front panel. Power is delivered via a Molex connector that attaches to an unused DC supply connection on the motherboard.

4. Evaluation

Fig. 2 shows the frequency response of the unit. A comparison with the data sheet of the SAW filter indicates that the two responses are virtually identical, except for the stopband attenuation, which is about 40 dB in our unit and about 50 dB for the filter itself. We assume that the discrepancy is due to the design of the coplanar waveguide transmission line in the PCB and we plan to correct this in the next manufacturing run. Fig. 3 shows the response of a unit with a 915 MHz SAW filter (Murata SF2136E).
The unit delivers DC power as expected. Shorting its input shuts down the DC supply to the LNA but does not, in any way, disrupt the USRP that feeds the unit.

Fig. 4 shows how the unit fits within the enclosure of the USRP.

5. Related work

There have been a few efforts to develop complete up/down converter daughterboards for USRP radios [16,17]. Such boards are orders of magnitude more complex than the simple add-on board we describe here. We feel that in most settings it would be difficult to justify the development of a complete custom up/down converter. This is because using an off-the-shelf one and customizing it with external filters, amplifiers, and so on, requires much less effort.

An alternative approach to adding filters, bias tees and amplifiers is to use ready-made connectorized units, like the masthead amplifier that we use. An application note by Ettus Research (the manufacturer of the USRP line of radios) provides a few concrete designs of this type using Mini-Circuits connectorized building blocks [18]. This is an excellent approach for experimental setups, but the cost and packaging challenges make it less attractive when many units are required.

6. Conclusions

A $10 front-end unit like the one described in this paper,² coupled with a widely-available masthead LNA that costs less than $100 can turn a USRP that is very easily overloaded when connected to an external antenna, into a sensitive receiver with an excellent out-of-band blocking performance. The unit also eliminates the risk associated with operating a USRP with a high-linearity LNA (which can easily destroy the input circuits of the USRP). Moreover, it fits within the USRP, and allows the USRP to be used with or without an external LNA, even if the antenna presents a DC short.

The design is freely available and boards can be ordered directly from our manufacturer’s web site.³ Users can also fork (copy) the project on the web site, to order it with a different filter (or make other modifications).

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Conflict of interest The authors have no financial or other interest in the companies and the products mentioned in this paper.

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[13] Skyworks Solutions, SKY16602-632LF: Low-threshold PIN diode limiter 0.2 to 4.0GHz, data Sheet, 2016.

