WIDEBAND ANALOG FRONT-END FOR MULTI-STANDARD SOFTWARE DEFINED RADIO RECEIVER

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ABSTRACT

Software Defined Radio (SDR) is a concept that has been giving momentum in realizing a wireless multi-mode, multi-band, multi-standard radio terminal capable of operating according to a variety of different mobile communication standards. This paper investigates a number of architectural issues and trade-offs involved in the design of receiver analogue front end for a multi-standard SDR with a fundamental objective of expanding the digital signal processing (DSP) toward the antenna. Receiver topologies such as heterodyne, direct conversion, low IF, wideband IF and bandpass sampling receiver configurations are described and summarized, and also a suitable analog front-end architecture for SDR is suggested.

I. INTRODUCTION

A goal in software defined radio is to push the digitization point as close as possible to the antenna [1]. An ideal architecture of a software radio receiver with minimum analogue components in analogue front-end is shown in Figure 1 [2]. The only analogue components are the antenna, the bandpass filter, and the low noise amplifier (LNA). Analog-to-digital conversion is done immediately at RF in order to digitally elaborate the signal on a completely reprogrammable board. The flexibility of the radio terminal to adapt to different types of signals having different symbol rates is made possible by using reconfigurable and reprogrammable hardware such as Field Programmable Gate Array (FPGA). More radio function can be written in software and embedded in programmable logic. But this ideal receiver is at the moment far from realizable since it is not reasonable to use a single RF stage for a multi-band system due to the impossibility of building antennas and LNAs on a bandwidth ranging from hundreds of megahertz to units or tens of gigahertz. Analog-to-digital converter (ADC) performance still isn't sufficient enough to perform digitization at RF. Particularly, the analogue input bandwidth, sampling rate, dynamic range, and therefore resolution need considerable amounts of improvement if wideband front-end and sampling at RF are to become reality.

The ability to process signals corresponding to a wide range of frequency bands and channel bandwidths is a critical feature of multi-standard radios and impacts heavily on the design of both analogue and digital segments of the receiver. The work presented in this paper describes a short overview of different analogue front-end architectures for the implementation of multi-standard SDR with respect to the current emerging technologies. Section II reviews receiver architectures, including heterodyne, direct conversion, low IF, wideband IF and bandpass sampling techniques. Section III suggests a suitable architecture, wideband IF sub-sampling receiver, with respect to the fundamental idea of expanding digital signal processing toward the antenna and section IV summarizes and concludes the suitability of the suggested architecture with todays technology.

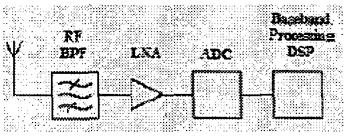

Figure 1: The ideal software radio receiver

II. RECEIVER ARCHITECTURES

Many issues are involved when attempting to consider a suitable architecture for analogue front-end in SDR terminal. To understand some of the barriers in different types of receiver architectures, a review is given and analyzed.

A. Superheterodyne Receiver

The superheterodyne receiver is a traditional receiver architecture, and the one most often used owing to its high selectivity and sensitivity [3]. The heterodyne receiver is depicted in Figure 2. At first, the RF band is selected and the out-of band signals are attenuated using a passive band selection filter. The signal is amplified by means of a LNA and the image signal is filtered with a passive bandpass filter. First the signal band is translated down to some IF which is usually much lower than the initially received frequency band. This relaxes the requirements for the channel selection filter. As the first mixer down-converts frequency bands symmetrically located above and below the local oscillator (LO) frequency to the same center frequency, an image-reject filter in front of the mixer is needed. In a dual IF topology, the resulting signal is subsequently down-converted again to baseband and the last down-conversion generates in-phase (I) and quadrature (Q) components of the signal. The quadrature I and Q channels are necessary in typical phase and frequency modulated signals because the two sidebands of RF spectrum contains

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different information and result in irreversible corruption if they overlap each other without being separated into two phase.

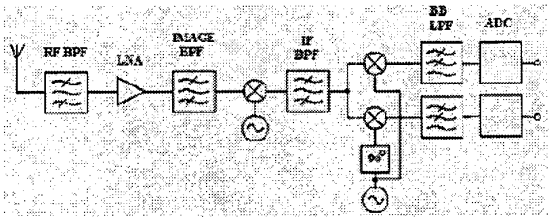

Figure 2: Superheterodyne architecture

The adaptability to many different receiver requirements is a major advantage of the heterodyne receiver. The effect of DC offsets of the first few stages is removed by bandpass filtering, and that of the last stage is suppressed by the total gain in the proceeding stages. Also I/Q mismatches occur at much lower frequencies and are therefore easier to control and correct [4]. As for the LO leakage, since the first mixer LO frequency is out of the band of interest, it is suppressed by the front-end bandpass filter and its radiation from the antenna is less objectionable.

However, the need for a large number of external components and the complexity of the structure make problems if a high level of integration is necessary. This is also the major drawback from the costs point of view. Furthermore, amplification at a high IF frequency can cause high power consumption. Even though this architecture is widely used now, it is difficult to change system parameters such as bandwidth because RF and IF signals are processed by fixed narrowband analog components.

B. Direct Conversion Receiver

Direct conversion is an alternative wireless receiver architecture to well established superheterodyne, particularly for highly integrated, low power terminal [3]. In a direct conversion, also called zero-IF or homodyne conversion [5], the incoming RF signal is down-converted to baseband (zero IF) in one step by mixing with an oscillator output of the same frequency. A direct conversion receiver is shown in Figure 3. The RF band is selected by an external passive filter and the signal is amplified by an LNA, as in the superheterodyne architecture. The signal is then mixed directly to DC by a RF mixer, hence, the rest of the passive filters and mixing stages are unnecessary. The resulting baseband signal is then filtered by analog baseband lowpass filters to select the desired channel before the A/D conversion. The direct conversion can be real or complex. While the first is more expensive with respect to the mixer, it circumvents filters that would be necessary for the suppression of RF images in the second case [1].

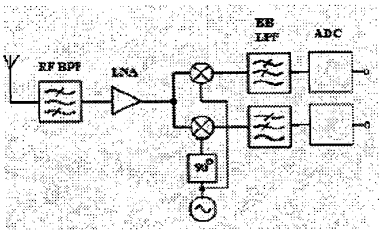

Figure 3: Direct conversion architecture

The main advantage of a direct conversion receiver is that it does not suffer the image problem as the incoming RF signal is down-converted directly to baseband without any IF stage. Another advantage of the direct conversion architecture is its simplicity. Since it does not require any high frequency bandpass filter, which is usually implemented off-chip in a super-heterodyne receiver for appropriate selectivity, the direct conversion architecture requires less number of external components. However, there are a number of issues in the implementation of the direct conversion receiver. The major disadvantage is that severe DC offsets can be generated at the output of the mixer when the leakage from the LO is mixed with the LO signal itself. This could saturate the following stages and affect the signal detection process leading to I/Q mismatch and even-order distortion [5]. Also, since the mixer output is a baseband signal, it can easily be corrupted by the large flicker noise of the mixer, especially when the incoming RF signal is weak. As a result, homodyne receivers are extremely difficult to implement.

C. Low-IF Receiver

The low IF receiver architecture combines the advantages of heterodyne receivers and direct conversion receivers. The RF front-end of the low-IF receiver [6] is similar to the direct conversion in Figure 2.2. A difference is that the RF signal is down-converted using quadrature RF down conversion to an IF of around a few hundred kilo-hertz up to several mega-hertz depending on the channel spacing, instead of the DC frequency. In contrast to direct conversion receiver, the channel select filter must be a bandpass filter.

As a non zero IF is used, the image frequency problem cannot be avoided. A complex signal processing is then needed to suppress the image components. The most common techniques to remove the image in low-IF receivers are to use image rejection architectures or polyphase filters [8]. After A/D conversion the signal is digitally down-converted to baseband before digital filtering.

Since the wanted signal is not situated around DC, there is absolutely no DC problems such as DC offset, flicker noise and LO self mixing in low IF receiver [7]. At the same time high level integration can be achieved. But the main disadvantage is that the image signal suppression required is

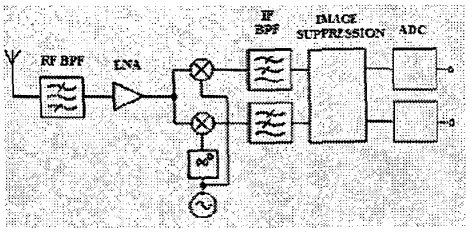

Figure 4: Low IF architecture

larger. In direct conversion receiver, the mirror signal is the wanted signal itself, while in the low-IF case it may be larger than the wanted signal. In addition, this receiver architecture has higher demand for I/Q balance or more complicated analogue part. I/Q imbalances cause interference that cannot be removed in later stages and so directly decrease the image-reject capabilities of the front-end [6].

D. Wideband IF Double Conversion Receiver

An alternative architecture well suited for integration of the entire receiver is wide-band IF with double conversion [9]. In a wide-band IF double conversion receiver architecture, signal down-conversion is performed in multiple phases, as in the superheterodyne receiver, but the discrete image and IF filters are avoided. This receiver system takes all of the potential channels and frequency in a wide signal band, translates them from RF to a IF using a mixer with a single frequency LO and, after that, the high-frequency components are filtered using a simple lowpass filter, allowing all channels to pass to the second stage of mixers. The second mixer stage is tunable to perform the channel selection and furthermore it is a quadrature type to accomplish the image rejection. All of the channels at IF are frequency translated directly to baseband and channel filtering is performed at the baseband.

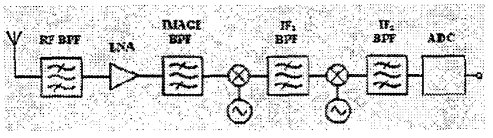

Figure 5: Wideband IF Sub-Sampling Architecture

The most important advantage is the fact that neither of the LOs is at the RF frequency reducing the risk of LO mixing which degrades the overall receiver's dynamic range. In addition, this architecture achieves image rejection without a passive phase shifting filter in the signal path. However, the additional mixers make it difficult to achieve a low power, low noise figure and low distortion receiver. The image rejection mixer requires highly accurate phase and gain matching between the quadrature LOs and the signal path.

E. Bandpass Sampling Architecture

Bandpass sampling offers an attractive alternative solution. It is a special form of under-sampling [10]. Ideal goal of an SDR approach is to move the ADC as close as possible to the antenna, minimizing the number of required front-end components. The minimal set would contain the antenna, the amplifier for the necessary gain towards the ADC, band limiting filters, and the ADC (Figure 1). The sampled RF signal, generated by the ADC operated at a rate slightly higher than twice the highest frequency, would be fed to the signal processors, in order to extract the channels among the available ones. However, this approach requires a huge amount of computational power, particularly if the RF frequencies are of some gigahertz. Bandpass sampling, instead, intentionally aliases (under-samples) the signal thus reducing the resulting processing rate and at the same time can still successfully recover the information bandwidth by adopting a sampling rate matched to its bandwidth. This process converts the information RF band down to a very low IF without any LO mixing and image filtering. First, the signal entering the antenna passes through a narrow bandpass filter centered on the carrier frequency and matched to the size of the information band. Next, the signal is processed by a LNA. The amplified signal is then sampled using ADC. The selection of ADC sampling frequency, fs, defines the resulting sampled bandwidth as $[0, fs/2]$. After sampling, the analog information bandwidth is folded into the resulting sampled bandwidth.

The major advantage of bandpass sampling is the sampling frequency and processing rate is proportional to the information bandwidth rather than the carrier frequency. A bandpass sampling ADC works like a mixer and also ADC. So, there is no need for a mixer, thus, reduces design complexity. However, the input bandwidth of the ADC must include RF carrier and this requires a huge amount of computational power. Another drawback is the filter at RF must have a steep roll-off, because it must attenuate the energy outside the information bandwith. The filter at RF must have a programmable
center frequency and this basically represents the major disadvantage of the technique.

III. WIDEBAND IF SUB-SAMPLING RECEIVER

By considering all the above mentioned architecture, a suitable concept for a wideband multimode software defined radio receiver analog front end is suggested in this paper which is a *wideband IF sub-sampling* architecture. This architecture performs transformation of analogue RF signal to digital IF signal. The sub-sampling approach can be thought of as generating a signal replica at much lower IF frequency close to DC. The analogue segment consists of superheterodyne section where the received signal under goes two stages of down-conversion to a low intermediate frequency of IF_2. The signal is subsequently sub-sampled and digitized at IF, extending the boundary of the digital domain one stage closer to the antenna.

The digitization can be performed as Full Band Digitization or Partial Band Digitization (Figure 6)[1][12]. While in the case of Full Band Digitization the whole bandwidth comprising all services to be supported is digitized, in Partial Band Digitization just a part of the whole bandwidth (e.g. an equivalent to the largest channel bandwidth of all services to be supported) is digitized. Since the whole bandwidth to be supported can easily extend to some 100 MHz while the dynamic range mobile communications standards may be well above 100 dB, Full Band Digitization does not seem to be feasible, not even in the near future. Therefore Partial Band Digitization is the most promising candidate for SDR terminals.

Wideband IF sub-sampling requires dual stage IF down-conversion of RF signal to a fixed IF. For a multi-standard terminal capable of processing standards like GSM and DECT the entire frequency band present at the RF filter is about 200MHz wide spanning from 1700 – 1900MHz. The RF filter rejects the image frequencies of the first mixer. The transition bandwidth of the RF filter can be made broad if IF_1 is chosen to be sufficiently large, at least a couple of hundred MHz. On the other hand with regard to subsequent sampling, IF_1 should not be chosen too high. The bandpass and anti-alias filters at IF_1 and IF_2 respectively are designed for Partial Band Digitization bandwidth, Ba, of each standard. Passband Ba of the analogue front-end needs to be sufficiently large to accommodate the air-interface with the widest channel bandwidth (e.g., Ba = 1.6MHz for GSM and Ba = 20MHz for DECT). Since signal sampling is done at IF_2, the required IF_2 is determined by the Nyquist bandwidth to maintain faultless sampling. The following relationship between the sampling frequency and the final intermediate frequency IF_2 holds:

$$fs = \frac{4}{2M-1} IF_2 \quad M = 1,2,3.... \quad (1)$$

The IF_2 signal sub-sampling is performed in the 2nd Nyquist zone, M=2, is applied to ensure suitable conditions for the digital signal processing in the baseband signal, giving fs=4IF_2/3. Either of the images centered on fs/4 or 3fs/4 may be down-converted to baseband. However, for even values of M, an additional spectrum reversal is necessary for the down-conversion of the former image, while no such operation is needed for the latter image. As a result, it is more convenient to down-convert the image centered around 3fs/4 since quadrature digital down-conversion for this centre frequency can be achieved efficiently. This signal is later going to be processed digitally to shift it and center it at DC. Digital quadrature down-conversion to baseband eliminates some of traditional drawbacks associated with I/Q mismatch [11].

A high fs relaxes the required steepness of the analogue bandpass and anti aliasing filter frequency responses, but places additional demands on the ADC and the subsequent DSP. This important trade-off between the analogue and digital domains needs to be carefully considered, particularly with respect to the expected radio channel conditions and the typical levels of interferers and blockers. The choice of IF_1 is more or less independent of IF_2 and can be optimized with respect to implementation of the bandpass filter. In addition to alleviating the dynamic range problems of the ADC, this approach would allow a reduction in the sampling rate fs in accordance to the channel bandwidth of the target standard, hence achieving significant savings in power consumption. A drawback of this architecture is that two analogue filters with demanding requirements and two analogue mixers contributing to intermodulation distortions are required. Furthermore, fs and IF_2 are related according to the sub-sampling equation.

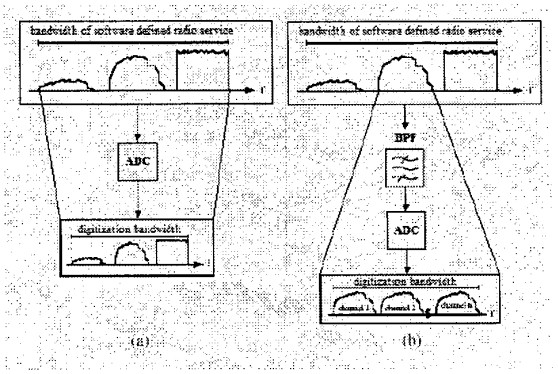

Figure 6: (a) Full Band Digitization (b) Partial Band Digitization.

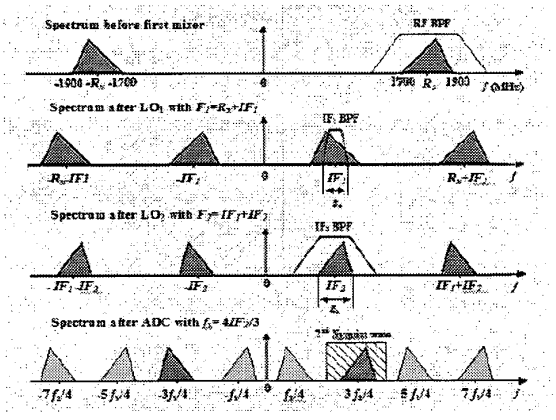

Figure 7: Spectral representation of signals in wideband IF sub-sampling architecture.

IV. CONCLUSION

A number of different architectures for the use of analogue front end for multi-standard software defined radio

receiver is discussed and analyzed in this paper. A suitable architecture with regard to moving the digitizing point one stage closer to the antenna, wideband IF sub-sampling, is presented. Fixed bandwidth with Partial Band Digitization technique is a solution for 'high-end mobile terminals', where power consumption is a most restrictive constraint and strong interferers are present. This applies digital signal processing as much as possible with today's technologies. Digital down-conversion is an efficient way of down-converting signal to baseband and the logic behind this approach is to eliminate the need for flexibility in the analogue segment at the expense of additional signal processing in the digital domain. The suggested method of digital down-conversion at a quarter of the sample rate is certainly a restriction and a trade-off in order to minimize cost. However, as long as Full Band Digitization is not realizable the signal has to be converted to an IF by appropriate mixing with a variable synthesizer before ADC, and in this case it is not really a restriction to fix the IF with respect to the sample rate.

V. REFERENCES

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