Wideband Digital Receivers for Multi-Standard Software Radios

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Abstract: *Multi-standard software-definable radios which are capable of operation according to a variety of different mobile radio standards represent an extremely powerful tool for evolution towards future third-generation cellular systems. This is particularly the case in Europe where the emergence of advanced UMTS air-interfaces needs to be accompanied with some degree of backward compatibility with the well-established GSM/DCS systems. This paper examines a number of the architectural issues and trade-offs involved in the design of wideband multi-standard GSM/UMTS digital radios and presents an examination of the filtering and ADC technology requirements for their implementation.*

This work has been undertaken in the context of the FIRST project (Flexible Integrated Radio System Technology) as part of the ACTS mobile line.

1. Introduction

The ability to process signals corresponding to a wide range of frequency bands and channel bandwidths is a critical feature of 3rd generation cellular multi-standard radios and impacts heavily on the design of both analogue and digital segments of the radio. In Europe, cellular frequency bands are concentrated in the neighbourhoods of 1 and 2 GHz, while channel bandwidths can vary from 200 kHz (GSM/DCS) to around 1.6 MHz (DECT, FRAMES mode-1 UMTS proposal) and even up to 6.4 MHz and beyond (FRAMES mode-2 and other wideband UMTS proposals) [1]. A primitive approach for the implementation of a multi-standard radio is characterized by the use of distinct transceiver chains, each optimized to support one of the above radio standards. However, such a “stacked-radio” or “velcro” approach is inflexible and increasingly infeasible for the support of more than two standards. It should however be noted that depending on the frequency coverage of the radio, some degree of duplication in the RF components (e.g. preselect filter, PA, LNA…) may be inevitable.

A more advanced approach involves the use of a single wideband transceiver which is sufficiently flexible for the support of multiple standards [2]. One possible option involves the use of *programmable analogue selectivity* whereby the bandwidth of the analogue segment of the transceiver is adapted to accommodate a single channel of the target air-interface. The programmability of the analogue filtering may be at a coarse level, followed by fine digital channel-selection filtering. In this paper, however, we focus on the more challenging option of using *fixed analogue selectivity* whereby the fixed bandwidth of the analogue front-end equals the width of the widest channel of interest. This latter option is also of interest in the context of advanced base stations capable of digitizing entire operator frequency bands. The implications of this approach with respect to current and emerging technologies in the context of wideband multi-standard GSM/UMTS receivers are investigated.

2. Characteristics of Wideband Receivers

An important feature of a wideband muli-standard radio is that the passband B_a of the analogue front-end needs to be sufficiently large to accommodate the air-interface with the widest channel bandwidth. This implies that, unlike traditional narrowband designs, the latter stages of the receiver and the ADC can be potentially exposed to a large number of carriers when processing signals from narrowband standards. The situation may be readily quantified for the case of a GSM/UMTS wideband receiver. The large channel bandwidths of the proposed UMTS air-interfaces (>1.6 MHz) imply that the dynamic range of the receiver needs to cope with the multiple GSM carriers as well as possible blocking signals (caused by sources external to the network) which can be present within the bandwidth B_a . The power levels of these blockers are detailed in the GSM specifications 5.05 [3] and are summarized in Table (1). The figures are relative to a wanted carrier at +3dB above the receiver sensitivity level (–100 dBm for DCS mobiles and –104 dBm for other radio types).

Blocker Offset δf [MHz]	DCS-MS [dBc]	DCS-BTS [dBc]	GSM-MS [dBc]	GSM-BTS [dBc]
0.6 - 0.8	+54	+66	+63	+75
0.8 - 1.6	+54	+76	+68	+85
1.6 - 3.0	+64	+76	+78	+85
> 3.0	+71	+76	+78	+88

Table (1) - GSM/DCS blocker specifications.

The above specifications are used in the following sections in order to evaluate the filtering and ADC requirements of wideband GSM/UMTS receivers.

2.1. Analogue Filtering

The objective of filtering in the analogue domain is not only to isolate the channel of interest but also to suppress adjacent channels which may alias as co-channel interferers due to the ADC sampling action. The situation is depicted in Figure (1) for a GSM receiver with an analogue passband of B_a = 1.6 Mhz.

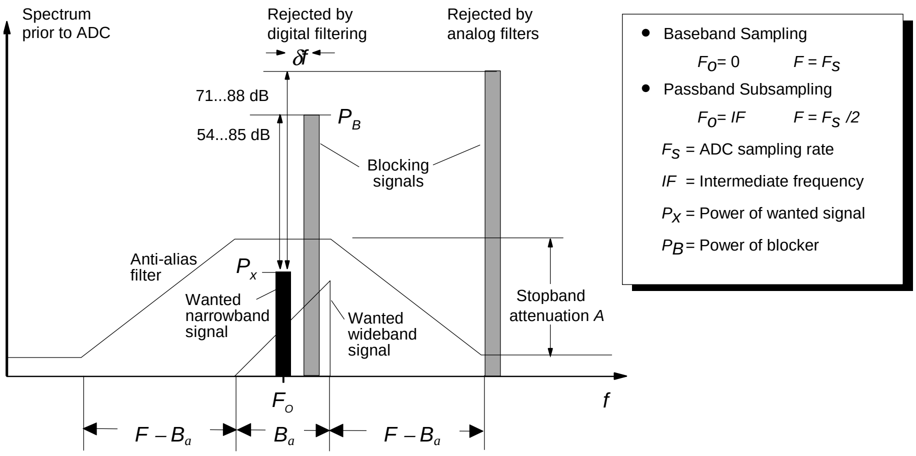


Figure (1): Rejection of blocking signals

The diagram applies irrespective of whether the receiver architecture deploys baseband or passband digitization (see Section 3). While blocking signals which appear outside the analogue pass/transition bands must be rejected by analogue filtering, those appearing within the analogue passband can be rejected by digital filtering following analogue-to-digital conversion. The extent of stopband attenuation is determined by the amount of tolerable co-channel interference caused by the aliasing of large blockers. Co-channel interference power is typically specified to be at a level of about 10 to 20 dB below that of the wanted signal depending on the modulation scheme ($SNR_{CO\text{-}CHANNEL}$ > 9 dB for GSM). Consequently, depending on the radio type and the sampling rate used, the required stopband attenuation is given by:

$$A = P_{B\text{-}dB} - P_{x\text{-}dB} + SNR_{CO\text{-}CHANNEL\text{-}dB} = [54\ldots88] + [10\ldots20] = 64\ldots108 \text{ dB} \qquad (1)$$

The above values represent the combined effect of all analogue filters. The large values of stopband attenuation, in conjunction with wide passbands, demand very steep transitions in the frequency response, therefore requiring additional stages of filtering compared with narrowband designs. Apart from size and cost issues, an increase in the number of stages also contributes to the receiver noise figure and non-linearities. Filter complexity may be traded off against power consumption and DSP load (for digital decimation and channel selection) via an increase in the ADC sampling rate F_s.

2.2. Analogue to Digital Conversion

As in the case of analogue filtering, the ADC requirements for a GSM/UMTS multi-standard radio are heavily influenced by the GSM blocker specifications. Two scenarios considered for the evaluation of ADC parameters are depicted in Figure (2) below:

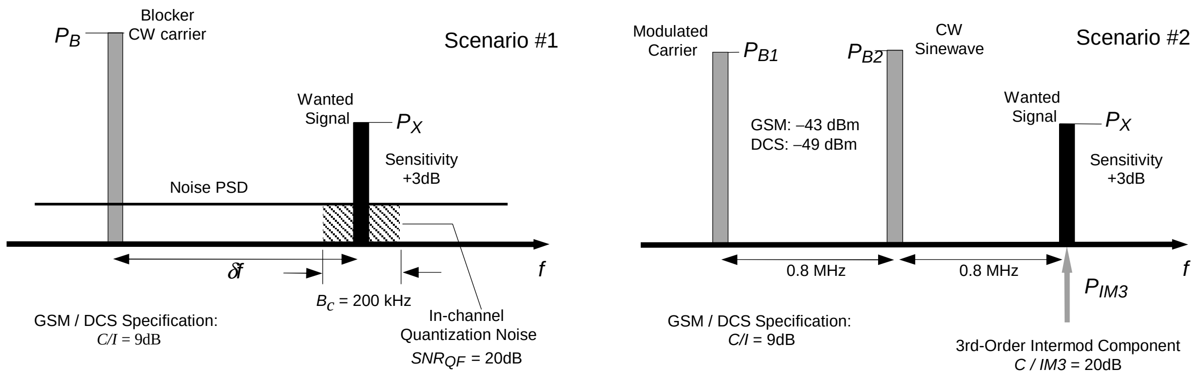


Figure (2): Scenarios for evaluation of ADC requirements.

In the first scenario, a large CW carrier at an offset frequency of δf (see Table 1) is considered to cause blocking of the wanted carrier (at 3dB above sensitivity) [3]. Since $\delta f \leq B_a$ for a wideband receiver, the ADC is exposed to the full amplitude of the blocker, i.e. the dynamic range of the ADC needs to simultaneously accommodate the blocker (as well as other adjacent-channel carriers) and provide adequate signal-to-noise ratio within the bandwidth of the wanted carrier. The ADC full-scale range X_m needs to be sufficiently high to prevent clipping when the signals add in phase and may be written as:

$$X_m \cong \sqrt{2P_B} \tag{2}$$

where the sinusoidal blocker is assumed dominant and no allowance is made for headroom. The required number of bits b (or quantization step-size Δ) can then be found for a specific value of quantization SNR_{QF} (following digital filtering) where:

$$P_{QF} = \frac{\Delta^2}{12} \times \frac{2 \times B_c}{F_s} \quad \text{(3a)} \qquad SNR_{QF} = \frac{P_x}{P_{QF}} = 3 \times 2^{2b} \times \frac{P_x}{X_m^2} \times \frac{F_s}{2 \times B_c} \quad \text{(3b)}$$

The last ratio in Equation (3b) represents the *processing gain* which results from digital filtering under the assumption of a white quantization noise spectrum [4]. To ensure that the quantization noise power is negligible compared to that of interferers and other sources of thermal and device noise, a value of SNR_{QF} = 20 dB may be assumed. The *spurious-free dynamic range SFDR* is defined as the ratio of X_m to the rms amplitude of the largest spurious component over the entire Nyquist band. *SFDR* represents all sources of noise and distortion (including integral and differential non-linearities, sampling jitter etc.) caused by the ADC. Assuming that the largest spurious component falls within the bandwidth of the wanted carrier and assuming a total SNR of 20 dB, the *SFDR* may be computed as:

$$SFDR_I = 20 \log \left[\frac{X_m}{\sqrt{2P_x}} \right] + 20 \quad \text{dBFS} \qquad \text{(relative to full-scale)} \tag{4}$$

In the second scenario, two large carriers at an offset of 800 kHz are considered to cause intermod products which fall within the bandwidth of the wanted carrier [3]. If B_a is sufficiently large to pass the two large carriers, this scenario dictates the two-tone linearity requirements of the ADC. The *two-*

tone SFDR is defined here as the ratio of the amplitude sum of the two large carriers (nominally equal to full scale X_m) over that of the third-order intermod component. Again assuming a 20 dB margin:

$$SFDR_{II} = 20\log\left[\frac{2\times\sqrt{2P_{B1}}}{\sqrt{2P_x}}\right] + 20 \quad \text{dBFS} \qquad \text{(relative to full-scale)} \qquad (5)$$

The ADC parameter values required for receivers intended for two different UMTS channel bandwidths of 1.6 MHz and 6.4 MHz are presented in Tables (2a) and (2b) where B_c = 200 kHz.

Table (2a)	RESOLUTION [Bits]	$SFDR_I$ [dBFS]	$SFDR_{II}$ [dBFS]
DCS MOBILE	9 - 10	74	—
DCS BTS	13 - 14	96	—
GSM MOBILE	12 - 13	88	—
GSM BTS	15 - 16	105	—
• Analogue channel bandwidth B_a = 1.6 MHz as specified in the FRAMES mode-1 proposal.			
• Sampling Frequency F_s = (2×2B_a)= 6.4 MHz .			

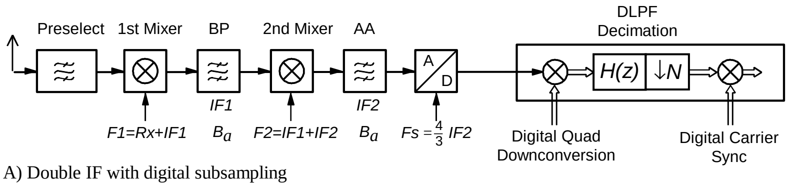
The ADC dynamic range is dictated by the GSM blocker at an offset of 0.8 MHz from the wanted carrier. Note that $SFDR_{II}$ figures are not quoted since one of the intermod test carriers (1.6 MHz away from the wanted carrier) falls outside the analogue passband.

Table (2b)	RESOLUTION [Bits]	$SFDR_I$ [dBFS]	$SFDR_{II}$ [dBFS]
DCS MOBILE	11 - 12	91	74
DCS BTS	12 - 13	96	78
GSM MOBILE	12 - 13	98	84
GSM BTS	14 - 15	108	84
• Analogue channel bandwidth B_a = 6.4 MHz as specified in the FRAMES mode-2 proposal.			
• Sampling Frequency F_s = (2×2B_a) = 25.6 MHz .			

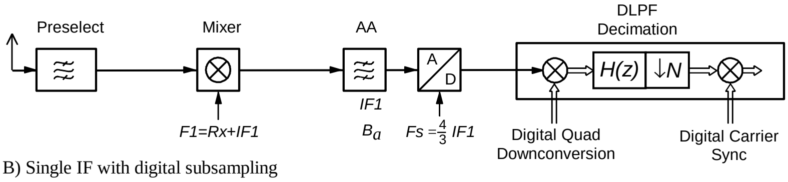
The ADC dynamic range is now dictated by the blocker at an offset of 3 MHz from the wanted carrier. Note that despite an increase in the blocker level, the quantization resolution requirements have fallen compared to Table (2a). This is due to the increased processing gain resulting from the higher sampling rate (see Equation 3). The *SFDR* figures are not subject to any processing gain and have accordingly increased. The current state of the art in commercially available ADCs (b=11, $SFDR$=80 dB and F_s=40 MHz) falls significantly short of the values presented above for GSM base stations but approaches those required for DCS radios. It should be emphasized that the analysis presented here involves worst-case test scenarios. It has been argued, based on experience in commercial systems that a moderate relaxation in the stringent GSM blocking specifications may be feasible without a significant impact on system performance [5]. Furthermore, measures such as frequency hopping, adaptive beamforming, and improved detection algorithms may somewhat alleviate the demands on the ADC.

3. Survey of Receiver Architectures with Fixed Analogue Bandwidth

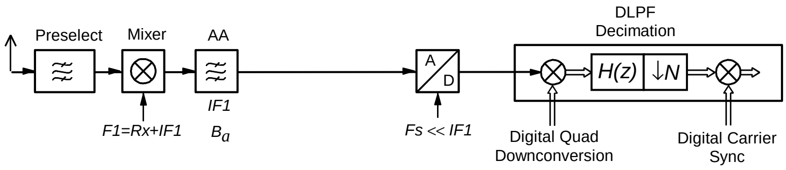
Having considered the filtering and ADC requirements, the merits of a number of receiver architectures for wideband multi-standard radios will be examined in this section. Figure (3) illustrates four different architectures, showing the path from antenna to the digital demodulation unit (includes decimation, low-pass channel selection filtering and complex phase rotation for carrier synchronisation). Several methods for sampling at IF followed by digital down-conversion are listed as types A, B, C. The architecture of type D employs analogue quadrature down-conversion and sampling at baseband, usually known as direct down-conversion. For a multi-standard terminal capable of processing standards like DCS or UMTS land mobile segments 3/6, the entire frequency band present at the preselect filter is about 500 MHz wide spanning from 1710 to 2170 MHz.



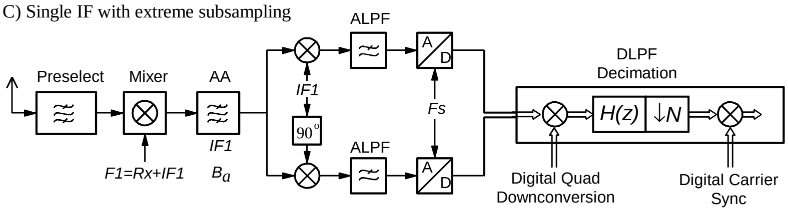
A) Double IF with digital subsampling



B) Single IF with digital subsampling



C) Single IF with extreme subsampling



D) Sampling at baseband (direct down conversion / single IF / double IF)

Figure (3): Alternative analogue front-end architectures

Architecture A (double IF with digital subsampling). This approach was described in [2]. See also Figure (4) for a spectral representation of the signals in the receiver chain. Sampling is performed at an appropriate IF_2 and the down-conversion process is realized completely via DSP. Subsampling in the second Nyquist zone given by the relation $F_s=(4/3)\times IF_2$ implies a sampling rate F_s which is less than twice the highest frequency component in the sampled signal. The preselect filter rejects the image frequencies of the first mixer. The transition bandwidth of the preselect filter can be made broad if IF_1 is chosen to be sufficiently large (i.e. at least a couple of hundred MHz). The bandpass (BP) and anti-alias (AA) filters at IF_1 and IF_2 respectively are designed for bandwidth B_a (eg. B_a = 1.6 MHz). The BP filter rejects the image frequencies of the second mixer and requires a transition bandwidth of $(2\times IF_2) - B_a = (3/2)\times F_s - B_a$. The AA filter suppresses the components which can be aliased due to sampling and requires a transition bandwidth of $F_s/2 - B_a$. A high F_s relaxes the required steepness of the analogue BP and AA 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 BP filter. A drawback of architecture A, is that two analogue filters with demanding requirements (see Section 2) and two analogue mixers contributing to intermodulation distortions are required. Furthermore, F_s and IF_2 are related according to the subsampling equation. Finally, apart from the subsampling, the architecture is very similar to that of conventional receivers.

Architecture B (single IF with digital subsampling). This is similar to architecture A with the difference that only a single intermediate frequency IF_1 is employed. This allows a reduction in the analogue component count as well as a reduction in nonlinear distortions. However, according to the subsampling equation $F_s = (4/3)\times IF_1$ from architecture A, IF_1 is a direct function of F_s and thus it is difficult (in comparision to architecture A) to achieve a compromise between a high IF_1 (to ease analogue filtering, particularly image rejection) and a low IF_1 (to ease ADC and DSP complexity and improve attenuation of nearby blocking signals). However, since the preselect filter cannot achieve a steep frequency response, a low IF_1 design is not really feasible, and a high IF_1 will cause infeasible DSP requirements. Consequently, architecture B seems unrealistic.

Architecture C (single IF with extreme subsampling). The concept of extreme subsampling implies the use of a sampling rate F_s which is considerably lower than IF_1. This corresponds to subsampling in the Mth Nyquist zone (i.e. $F_s = [4/(2M-1)]\times IF_1$) where M>>1. An important implication is that extreme subsampling requires a fast ADC with a broad bandwidth (such ADC technology is now becoming available, eg. bandwidth of 450 MHz for F_s =20 MHz from Analog Devices). This technology is in contrast to that of conventional ADCs where the bandwidth is usually limited to $2\times F_s$. Architecture C is similar to architecture A with respect to the two separate design tradeoffs for IF_1 and F_s: High IF_1 to widen the preselect transition bandwidth, low IF_1 to ease AA. High F_s to widen AA and to achieve high stopband attenuation, low F_s to ease ADC and DSP. As an advantage, the analogue component count is reduced to that of architecture B. However, the requirements on the stopband attenuation of the analogue filter(s) are similar for architectures A,B and C.

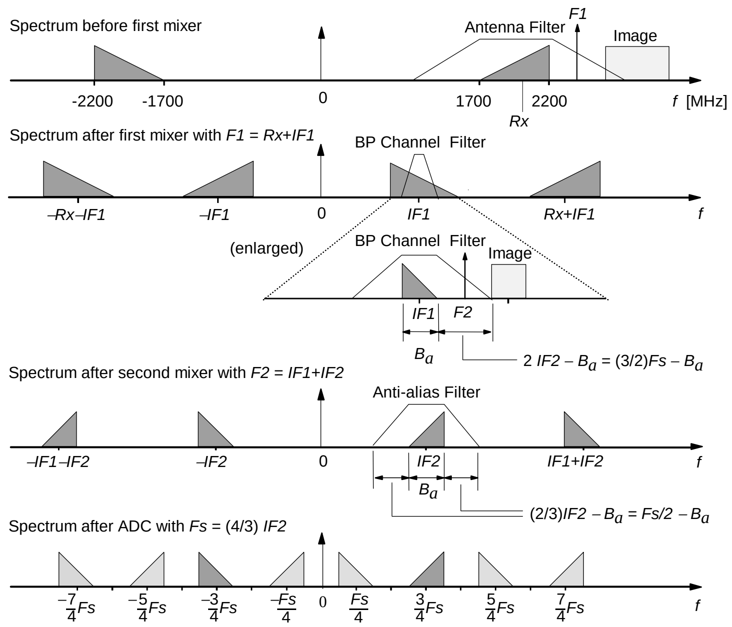


Figure (4): Spectral representation of signals in double-IF receiver (type A).

Architecture D (sampling at baseband). Sampling performed at baseband is an alternative to passband subsampling and represents a traditional approach. Sampling can be preceded by either direct- (zero IF), single-IF or double-IF downconversion stages. The main advantage of this architecture is that the AA filtering operation can be performed at baseband (instead of passband) with an analogue low-pass filter (ALPF) transition bandwidth of $F_s - B_a$ (instead of $F_s/2 - B_a$). Filter requirements are thus relaxed. The analogue component count is reduced, particularly for zero-IF. A drawback is the need for an analogue quadrature down-converter which introduces the associated problems of gain/phase mismatch in the I and Q branches. This problem could be significant when dealing with multi-level modulation schemes proposed for pico-cellular modes of UMTS.

From a conceptual point of view, the use of analogue down-conversion may be argued to be contradictory to the spirit of an ideal software-definable digital radio. However, from a practical point of view, architecture D can be seen to provide a number of advantages in the context of multi-standard radios. The most important advantage is that programmable analogue selectivity can be readily implemented through the use of tunable active low-pass AA filters (bandpass IF implementations using SAW technology is unrealistic). In addition to alleviating the dynamic range problems of the ADC, this approach would allow a reduction in the sampling rate F_s in accordance to the channel bandwidth of the target standard, hence achieving significant savings in power consumption.

4. Digital Carrier Synchronisation and Related Tradeoffs

For a multi-standard terminal capable of processing standards like DCS or UMTS, the entire frequency band can be about 500 MHz wide. According to the GSM specifications, the transmit frequency must be generated with an error less than 90 Hz (0.1 ppm) and this demands the ability to generate around five million distinct frequencies. In order to enable a simple and cost-effective synthesizer design, it is possible to increase the frequency quantization step-size by several orders of magnitude, if complex phase rotation is performed at baseband in the digital segment of the transceiver (depicted in Figure 3). A total frequency error F_E representing all imperfections due to control algorithms and Doppler shifts would require passband extensions of $2\times|F_E|$ for analogue AA filtering and $4\times|F_E|$ for digital low-pass filtering respectively. Frequency errors of the order of some percentage of B_a are not critical and thus the quantization step-size of the local oscillator can be increased to 10…100 kHz, thereby allowing considerable simplifications compared to the case of analogue carrier control.

5. Conclusions

The concept of fixed-bandwidth analogue selectivity for the design of wideband multi-standard GSM/UMTS digital radios was presented and the implications of this approach with regards to current and emerging filtering and ADC technologies were examined. Also the merits of a number of receiver architectures for the implementation of such radios were discussed. It was seen that the performance of current ADC technology falls significantly short of that required for wideband GSM/DCS base stations, although the issue is less severe for the case of mobiles. From the receiver architectures considered, it was seen that while double-IF subsampling is readily feasible, the more compact single-IF subsampling architecture is only feasible with extreme subsampling and is the preferred option once fast ADC technology becomes available (the same applies to subsampling directly at RF). Baseband sampling architectures are most suitable for implementation of programmable-bandwidth multi-standard radios.

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