CHAPTER THREE

Receiver Filter Design for Sensitivity Boosting

5 Introduction

Any fast transition (whether it is amplitude, phase or frequency) in a modulated signal, will require a wide bandwidth for its faithful transmission. Whereas, filtering of signal slows down or smoothen the signal and that helps to reduce the transmission bandwidth without losing the digital data content. This filtering operation improves spectral efficiency of signal, which is very important for a bandwidth limited communication systems. On the receiver side, the reduced bandwidth helps to improve receiver sensitivity, because the front-end filter rejects unwanted blocking signals and out of band noise signal. The sensitivity level of a receiver can be expressed by equation (1.5). According to that, lesser the bandwidth (B), lesser the thermal noise generated in the receiver system. Also, narrower bandwidth helps to choke or block the unwanted signals (e.g. interferers or blockers) in the received signal and that helps for better desired frequency channel selection. So, selecting the proper receiver filter structure plays very important role for achieving the optimum receiver sensitivity and selectivity level.

5.1 Objective

The objective of this part of the work is to explore and find out the best possible filter structure, type and design parameters for achieving the optimum receiver sensitivity
level. In [21] many receiver down-conversion architectures (like, Low-IF, Wide-IF, and Zero-IF) and their respective pros and cons are discussed in detail. Because of the cost, size and good multi-standard ability, here only the Zero-IF homodyne receiver architecture is considered for this analysis. As GSM system, which is most widely deployed mobile system today, uses GMSK modulation, so, here the study is limited to the GMSK modulation only. But, the same method can be extended to other systems which uses other modulation schemes.

5.2 Simulation method

A GSM system simulator is used to explore different possible options and to select the best possible filter parameters. First the filter structure and the candidate bandwidths (one sided) are chosen from 125-140 kHz, with a step size of 0.5 kHz and then for different roll of factors. A binary search strategy is adopted here. The raw bit error rate (BER) after the demodulations (and before the channel decoding) as well as the FER, RBER or BLER statistics are used to evaluate the options and to speed up the initial optimum solution search process. After the best solution candidate has been identified, full simulations with 100000 frames for some critical test cases are executed to verify the performance to meet the 3GPP standard requirements.

3GPP has recommended several wireless channel propagation conditions. Here, in this work, the following channel conditions are studied (these are also explained in table 2.1):
- Static channel with AWGN (for sensitivity only): S1
- Fading channels with Typical Urban (TU3), Typical Urban with speed 50 km/h (TU50), Hilly Terrain with speed 100 km/h (HT100) and Rural Area with speed 250 km/h) RA250 profiles.
- P-GSM band (900MHz band) is used for bandwidth search.

In a noise-limited condition, the \( \frac{E_b}{N_0} \) is set to realistic values (e.g., 10dB) whereas the 
C/I is set to 200 dB. In an interference limited scenario, Eb/N0 is set to 200 dB whereas 
C/I is set to realistic values around the 3GPP required cross-over points for the respective logical/physical channels. The simulation set up is already depicted and discussed in the 
Figure 2.1.

6 Different filters in the receiver structure

Filters are applied at multiple stages inside a communication receiver. In order to select 
the desired channel and better selectivity, sensitivity gain, all other unwanted / undesired signals have to be removed or suppressed in the received signal. In practice, this is done by combining multiple stages of filtering and decimation in receive and transmit chain. In 
figure-3.1, simple homodyne receiver architecture is shown. The band-pass (BP) filter 
placed before the LNA allows a particular band of frequency (like, 900 MHz band) to 
pass inside the receiver. Then the amplified received input signal is mixed with local oscillator (LO) signal to generate intermediate (IF) or baseband signal. This is then passed through analog filter, placed before the ADC. Next the signal is sampled and 
passed to the digital filter and then that digital signal is passed to the digital baseband.
Figure-3.1, Direct conversion RF receiver architecture

In homodyne RF receiver architecture, the input signal is frequency translated to baseband by mixing the incoming received signal with local oscillator signal prior to any channel filtering. The channel selection can be performed in analog domain (e.g. before ADC) or in digital domain (e.g. after ADC). Both options have some advantages as well as some disadvantages.

Analog domain channel selection: Here, the channel selection is performed with the help of analog filter placed before ADC module, this filter is commonly known as anti-aliasing (AA) filter. This analog filtering might help to avoid the need of digital filters and it helps to stop or block the interference/unwanted signals before the ADC. But, the analog domain channel selection process needs high R-C dynamic range and linear channel select filter. Also, analog filter is difficult to program the filtering options or change the filter parameters dynamically, but it offers one advantage of having relatively simpler analog-to-digital conversion by employing low cost ADC circuit.
Digital domain channel selection: Digital channel selection requires ADC with high dynamic range. But advantages are it helps for using on-chip programmable filter structures to adjust variable channel bandwidth and dynamic parameter selection. Generally, FIR or IIR filters are used as digital filters. IIR filters relatively instable and shows non-linear phase responses, so are avoided due to these issues. In such cases, FIR filters are preferred instead of going for IIR filters.

Generally, as discussed above, in a mobile communication receiver, a channel select filter is added for removing interference or blocking signals from other frequency channels and radio access systems (RATs). To avoid the high cost and power consumption (due to sharp cut off requirement), high delay etc. the analog filter is kept relatively poorer in quality in most of the receiver design. Due to this, significant amount of adjacent channel interference (ACI) signal passes to the digital base-band. Then in digital base-band this is treated adaptively by introducing adaptive filtering or FIR filtering or applying whitening method using SAIC or other associated technique. Digital Adjacent Channel Interference (ACI) cancellation method significantly relaxes the design of analog front-end filters specifications and helps to reduce the system design complexity and cost. And also it improves receiver’s average bit error rate performance. But, the ACI cancellation in the base-band digital domain can be performed, only when the ACI condition is detected properly by the receiver base-band algorithm. At the input of the matched filter, the ACI may be considered as coloured noise, as its power spectral density is not uniform across all frequencies. This fact imposes a noise floor on the system based on two factors: (a) amount of spectral overlap between the adjacent channels and the channel of interest, (b) the ratio of the adjacent channel to desired channel power. This above issue results in an
irreducible bit error rate (BER), irrespective of SNR value, that means the BER value remains almost same e.g. flat, though the SNR per bit is increased. One objective of the proposed filtering technique is to reduce (or remove) this irreducible bit error rate by proper detection of the ACI scenario and then adopting different solutions to combat that. In present day’s GSM receiver, SAIC algorithm is implemented for mitigating the effect of co-channel and adjacent channel interference and these receivers are called as DARP-I (Downlink Advanced Receiver Algorithm) receiver. For better detection of ACI, CCI conditions e.g. whitening decision in SAIC receiver, the bandwidth of the received baseband signal set to an optimum bandwidth instead of the bandwidth of the GSM carrier frequency, 200 KHz.

So, for achieving optimum receiver performance, generally both the filters (analog and digital) are used in the mobile phone receiver structure. Now, for this type of design, there is a challenge to find out the optimum bandwidth, roll-off and other filter design parameters for both the type filters (e.g. analog and digital filters) in order to achieve the optimum receiver sensitivity level without sacrificing the ACI and CCI performance as discussed above.

The typical frequency response of a filter is shown in figure 3.2.
Figure-3.2, typical response of a real filter

The ‘sharpness of a filter’ is described by a parameter called - alpha ($\alpha$). Which is computed as, occupied bandwidth (BW) = symbol rate * (1 + $\alpha$). This ‘$\alpha$’ parameter gives a direct measure of occupied system bandwidth. For ‘$\alpha$’ value of zero, the filter shows a perfect brick wall type of characteristic, which has sharp transitions, in this case the occupied bandwidth will be (BW) = symbol rate * (1 + 0) = symbol rate. Though practically, an alpha of zero value is impossible to implement in real circuit. Occupied bandwidth for $\alpha$ value of 1 is: occupied bandwidth = symbol rate * (1 + 1) = 2 x symbol rate.

Figure-3.3, filter response for variation of alpha ($\alpha$)

7 Filter parameters optimization for optimum sensitivity level

Nowadays in a mobile receiver RF ASIC, lower order sigma delta ADC (2$^{nd}$ order) is used instead of higher order sigma-delta ADC (5$^{th}$ Order) for cost complexity reduction.
Due to the lower Sigma-Delta ADC order, the ADC sampling rate has been increased from 13 MHz to around 312MHz to achieve the similar SNR performance. Here in this work, first the analog anti-alias filter is set to a bandwidth of 290 KHz (both sided) and then the effected of bandwidth and roll factor factors for digital filter are studied to achieve the optimum sensitivity level.

The candidate digital filters are designed by Matlab code as given in Appendix and also some filters with different bandwidth and roll-off factors are provided. The 15 tap filter coefficients are quantized into 11 bits and scaled down. The maximum value of the scaled version is 310. The scaling is used to avoid the ADC clipping effect for large input signal level. There are several logical channels exists in GSM system, but for quick exploration here only TCH/Full Rate (FR) channel is studied. The same can be extended to other logical channels. As mentioned in the earlier sections, the receiver FER and BER performance at different 3GPP recommended channel propagation conditions are studied to find out the best possible design options to achieve optimum sensitivity level.

7.1 Optimum BW search

First the effect of bandwidth is studied by varying the bandwidth of the digital filter keeping the analog filter bandwidth as fixed to 290 KHz (two sided) and measuring the BER (or FER, RBER and BLER) characteristics for a fixed roll off factor of 0.2.

As specified in earlier, the required filter bandwidth for GSM system will be around $1/PW_{min} = 1/0.369 \text{ us} = 270.833 \text{ KHz}$, whereas the carrier 3 dB bandwidth is 200 KHz. So, considering the facts discussed earlier, ideally a bandwidth of 200 KHz to 280 KHz will be the right one. Here, in this work the optimum bandwidth is searched in a simulated environment for different wireless channel propagation conditions. In figures
3.4 to 3.7, the BER performance vs $E_b/N_0$ requirements for the receiver are shown for different bandwidths in different channel conditions for GSM full rate traffic channel.

Figure 3.4, GMSK Sensitivity with Static (S1) Channel (TCH/FR: Traffic channel / Full Rate Speech)
Figure-3.5, GMSK Sensitivity with TU50 (S2) Fading (TCH/FR)

Figure-3.6, GMSK Sensitivity with HT100 (S5) Fading (TCH/FR)
7.2 Optimum Roll-off factor Search

From the above results for bandwidth variation, it is evident that bandwidth 140 KHz (one sided) provides the best BER performance for this reference receiver. So, here the bandwidth 140 KHz is now fixed and then roll-off factor is varied from 0.1 to 0.5 to find out the optimum candidate. In figures 3.7 to 3.10, the BER performance vs Eb/No requirements for the receiver is shown for different roll-off factors with a fixed bandwidth of 140 KHz in different channel conditions for GSM full rate traffic channel (TCH/FR).

![Figure-3.7, GMSK Sensitivity (S1) for AWGN (TCH/FR)](image-url)
Figure-3.8, GMSK Sensitivity for TU50 (S2) Fading (TCH/FR)

Figure-3.9, GMSK Sensitivity for RA250 (S4) Fading (TCH/FR)
Figure-3.10, GMSK Sensitivity for HT100 (S5) Fading (TCH/FR)

8 Result analysis and conclusion

The filter type, shape, bandwidth and other parameters selection plays an important role in determining the sensitivity level of a receiver. This also affects the overall size, cost and performance of a mobile receiver. So, selection of the proper filter type and its parameters are very vital for obtaining the best receiver performance. Here, in this work the proper methodology for obtaining the right filter parameters, like bandwidth and roll-off factors are explored and found out for a specific type of mobile receiver. This helps for finding out the best possible design solution. Here in this work, it is found that the filter with coefficient values \{-1,1,0,-5,8,11,-33,-16,144,255,144,-16,-33,11,8,-5,0,1,-1\} e.g. filter 140 KHz Bandwidth and roll-off factor of 0.3 gives best performance for
achieving the best sensitivity, CCI, ACI, as well as DARP I performances for GSM receiver. In figure-3.11, the frequency response of this filter is shown.

The matlab program for designing the digital filter is given is the appendix: A1.

Nowadays, most of the smart phone receivers are multi-band and multi-RAT receiver. In a multimode or multiband mobile phone, the same filter might not be optimum for all bands and in all environments. So, in such case the best option is use of reconfigurable filter. Another option is download different filter co-efficient adaptively based on the RAT type or detected channel environment type to get the optimum performance in all scenarios. That means the filter parameters can be reconfigured between the changing communication standards or during a call or data session. Because of that, based on the types of transmission, many receivers switch to different filters structures. This can be achieved, either automatically as part of mode switch, or by employing a filter switch. This will help to achieve best performance in all the time irrespective of any channel conditions and receiver operating modes.

Figure-3.11, Filter response for 140 KHz with roll-off factor 0.3
9 Publications and Patents

The above obtained results are published in papers [47] and [41].