Front End Architecture Design of Software Defined Radio Interoperable BTS between GSM and IS-95

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Abstract - Software Defined Radio aims at using the same hardware for different applications by the change in software parameters. The reconfigurable part in a Software Defined Radio is the Digital Front-end. The modifiable parameters for different standards and technologies include bandwidth, Sampling Frequency, down converted IF, up converted IF and filter cut-off frequencies. The major goal for an ideal Software Defined Radio is to place the ADC as close to the antenna as possible. This can be achieved by Band-pass Sampling. The main objective of this paper involves the design of RF front end of a Software Defined Base Transceiver Station (BTS) which can be configured to support different technologies (here GSM/IS-95) depending on the software modifications. The RF front end is dealt for both the transmitter and receiver with appropriate MATLAB models and the simulation results.

Keywords - Base Transceiver Station (BTS), Band-pass Sampling, Software Defined Radio (SDR), Reconfigurable, Global System for Mobile Communication (GSM), IS-95

1 Introduction

The advent of cellular communications is indeed a breakthrough in the chronology of wireless communication networks. The rapid growth in cellular communications has proved that wireless communication is viable for voice, data services and even more. From an age of wireless devices that were designed to deliver a single communication service using a particular standard, at present they have become obsolete. With the steady increase of new wireless services and standards, single purpose devices with dedicated hardware resources can no longer meet the user's needs. It is also expensive to upgrade and maintain a wireless system each time a new standard comes into existence.

A feasible solution to make communication systems more flexible and user friendly can be achieved through the software defined radio (SDR) concept. Software defined radio refers to the class of reprogrammable or reconfigurable radios in which the same piece of hardware can perform different functions at different times. Software defined radio is an emerging technology, for multi-service, multi-standard, multi-band, reconfigurable radio systems, which are reprogrammable by software. A working definition of a software defined radio is a radio that is considerably defined in software and whose physical layer behaviour can be significantly altered through changes to its software. Thus, the same piece of hardware can be used to realize different applications by modifying the software.

Software defined radio (SDR) uses programmable digital devices to perform the signal processing necessary to transmit and receive baseband information at radio frequency. Devices such as digital signal processors (DSPs) and field programmable gate arrays (FPGAs) use software to provide them with the required signal processing functionality.

A software defined radio system can operate in multi-service environments. This means that the system is able to offer services of any already standardized systems or future ones, on any radio frequency band. The system is not constrained to a particular standard. For that reason the software radio system is very flexible. The compatibility of a software radio system with any defined mobile radio standard is guaranteed by its reconfigurability, which is achieved by DSP processors. A software defined radio not only transmits and receives signals but it does more in an advanced application. Before transmission, SDR can distinguish the available transmission channel, select suitable channel modulation, direct the transmit beam in the direction of interest, check for proper power level and then transmit the signal. Similarly, on the receive path, apart from just receiving the signal, SDR can characterize the energy distribution in the desired channel and adjacent channels, provide adaptive equalization, null interference, approximate the dynamic properties of the desired signal, decode the channel modulation using appropriate schemes, correct errors through forward error correction, and hence help in obtaining the desired signal with less bit error rate.

Finally, software radio supports incremental service enhancements through a wide range of software tools. These tools assist in analyzing the radio environment, defining the required enhancements, prototyping incremental enhancements via software, testing the enhancements in the radio environment, and finally delivering the service enhancements via software and/or hardware.

A typical SDR Architecture consists of a digital subsystem and a simple analog subsystem.The analog subsystem consists of antenna, RF filtering, RF combination, receive preamplification, transmit power amplification and reference frequency generation.

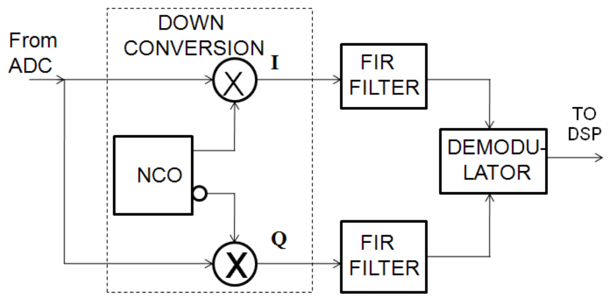

Fig.1 Digital front end of SDR receiver

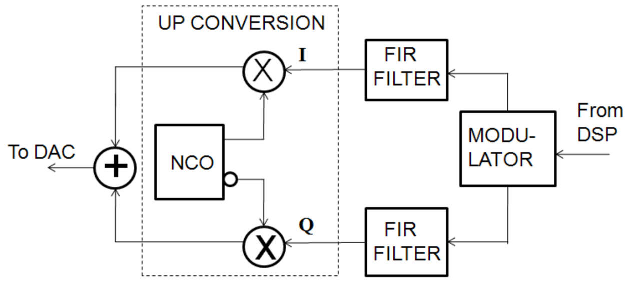

Fig. 2 Digital front end of SDR transmitter

The digital subsystem consists of up/down frequency conversion to baseband, IF filtering modulation/demodulation functions.

Fig. 1 and Fig. 2 illustrate the digital front end of a Software Defined BTS. Numerical Control Oscillator (NCO) is the digital counterpart of local oscillator. These oscillators generate very precise digital sine and cosine waveforms for use in the digital mixer, which performs the frequency translation function. The ADC in an SDR converts the incoming signal to a particular Intermediate Frequency (IF). The frequency of the NCO can be varied to bring the down converted IF to base band. Depending upon the incoming signals, the FIR filters are reconfigured accordingly.

Wireless communication standards are evolving very fast. Operators and system suppliers do not have the same philosophies when it comes to delivering the multitude of different mobile communication standards. Consider the situation where an operator has both global system for mobile communications (GSM) and code division multiple access (CDMA) radio mobile networks. Due to restrictions on transmission equipment, antenna feeder platforms and equipment room site selection, the common stations for both systems should be used for the purposes of fast construction and cost reduction. If there is no detailed plan to solve the disturbance or interference between the systems, then serious consequences such as poor network communication quality will occur. The practical solution to overcome this problem is to use a single base station that can adapt to different technologies. We believe that this can be made possible using software defined radio, since it represents a radio that uses a reprogrammable hardware to create a generic hardware base. As a result, a single BTS will support both GSM and CDMA (IS – 95 standard here) with a high degree of flexibility.

2 Band pass sampling

The design of a software radio is based on two simple design goals. First, the analog to digital and digital to analog converters should be placed as near the antenna as possible, in the chain of RF front-end components as shown in Fig. 3.

Second, the resulting samples should be processed on a reconfigurable digital domain via digital signal processors or field programmable gate arrays. One way to achieve this is by direct down conversion of the desired RF signal bands to baseband frequency using band pass sampling.

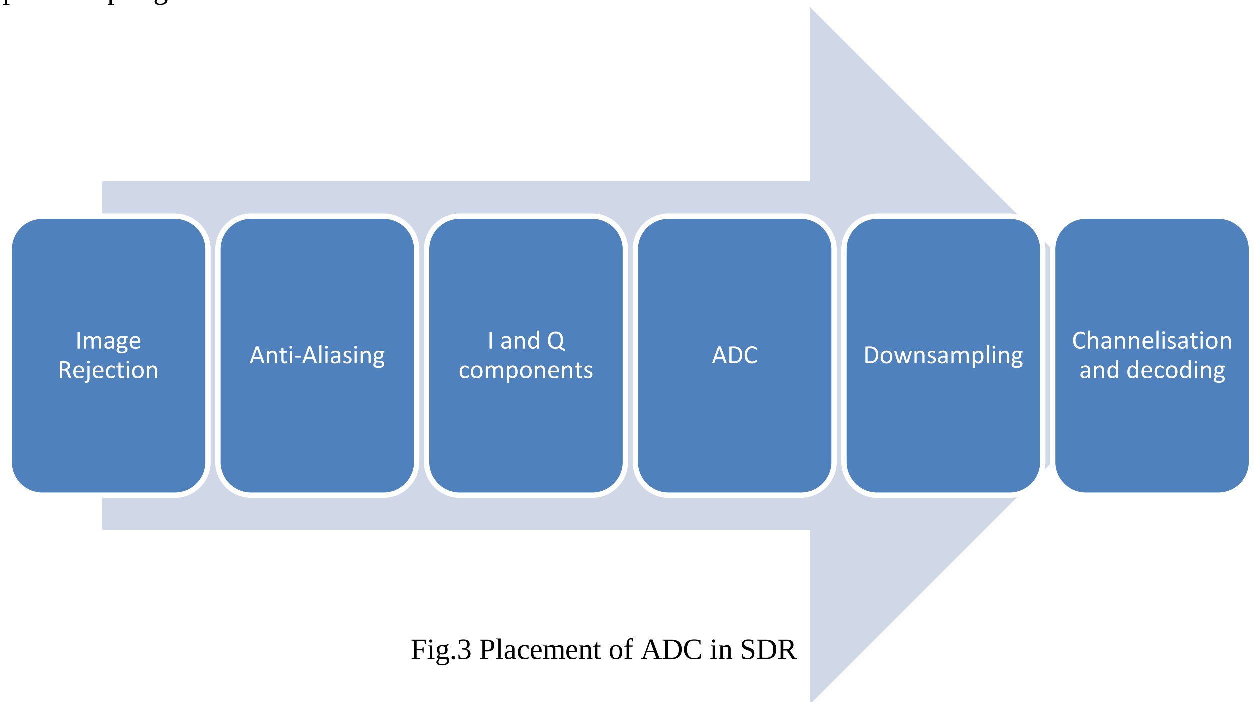

Fig.3 Placement of ADC in SDR

Band pass sampling is a method that down converts analog band passes signals to baseband or low intermediate frequency (low-IF) digital signals without analog mixers. It is a special form of under sampling that translates a high frequency band pass signal to a low pass one near the zero frequency via intentional aliasing.

The band pass sampling theorem says that *the sampling rate can be lowered from* $f_s > 2 f_2$ *to* $f_s > (f_2 - f_1)$ *if the signal being sampled is band pass, i.e. only has non-zero frequency content in the bands* $[-f_2, -f_1]$ *and* $[f_1, f_2]$.

According to the Nyquist sampling theorem, *the sampling rate should be equal to or higher than twice the maximum information signal frequency present*. When the sampling theorem is not obeyed, it leads to under sampling or over sampling and aliasing may be produced. For most radio applications, the required sampling rate for the ADC would be impractically high if Nyquist sampling is employed. For example, the GSM 900 digital cellular telecommunication system uses carrier frequencies of about 0.9 GHz. Therefore, Nyquist sampling frequency for a GSM 900 signal is about 1.8 GHz. Such a high sampling rate is infeasible even with the present technology. Alternatively, by the band pass nature of the radio signal, one can use band pass sampling to directly down convert the desired RF signal to an IF signal.

According to the band pass sampling theory, the minimum samplingrate is dependent on the bandwidth, but not the maximum frequency of the RF signal. Theoretically for a band pass signal, the minimum sampling frequency is twice its bandwidth. This significantly relaxes the requirement on the analog to digital converter sampling rate, as the required sampling frequency depends on the signal bandwidth, rather than on the highest frequency component. This leads to reduced requirement of the associated signal processing capability and power consumption.

Several methods have been proposed for band pass sampling. A novel method has been proposed to obtain valid sampling frequency ranges for direct down conversion of multiple RF signals as in [9]. Here one can adopt this method to determine all the possible orders of spectral replicas in the spectrum of the sampled signal. For each possible order of spectral replicas, we use the formula to find its valid sampling frequency range. For a particular band of incoming signals, there are many possible valid sampling frequency ranges. Any frequency lying within the valid frequency range can be chosen as the sampling frequency for the ADC, which in turn dictates the down converted IF. The value of the IF of the down converted signals is given as follows:

$$f_{IF} = \begin{cases} \text{rem}(fc,fs), & \text{if floor}(fc/(fs/2)) \text{ is even} \\ fs - \text{rem}(fc,fs), & \text{if floor}(fc/(fs/2)) \text{ is odd} \end{cases}$$

Where c is the centre frequency of the RF signal and fs is the sampling frequency.

Two RF signals of different standards (here GSM 900 and IS-95A uplink bands) are taken. For a given set of bands, there are many possible values of valid sampling frequency ranges. Some of them are shown in Table I for GSM 900 and IS-95A.These values are obtained through the above algorithm. From the range of sampling frequencies, a particular value is chosen as a sampling frequency. Also the values of down converted IF are obtained through the equation given above. These values are shown in Table II. The same concept can be extended to N band case. This concept is unavoidable in this case because in practice the BTS will be supporting more than two bands.

TABLE I
THE RANGES OF VALID SAMPLING FREQUENCIES FOR TWO BAND CASE FOR DIFFERENT STANDARDS

STANDARD	CHANNEL RANGE	SAMPLING FREQUENCY RANGE (MHz)
GSM 900	890 - 890.2MHz 900 - 900.2MHz	0.8165079 -
		0.9272917 -
		1.025576 - 1.025641
		1.318409 - 1.318519
IS 95A	824 - 825.25MHz 840 - 841.25MHz	5.750871 - 5.753425
		6.385057 - 6.387597
		7.039749 - 7.042735
		8.641361 - 8.659794

The N band algorithm can be obtained by using a repetitive process of finding the ranges of sampling frequencies by considering two bands at a time. From the valid ranges of sampling frequencies obtained, any one value can be taken and used in the receiver architecture. The sampling frequency ranges are tabulated in Table III.

TABLE II
SAMPLING FREQUENCY CHOSEN AND THE DOWN CONVERTED IF

SAMPLING FREQUENCY USED	IF_1 (Hz)	IF_2 (Hz)
0.816509MHz	105190	307082
0.92730MHz	108000	308300
1.025590MHz	112120	368020
1.318456MHz	142200	405448
5.75120MHz	1349950	2852530
6.386079MHz	2435019	337139
7.039749MHz	974367	2894869
8.641361MHz	3695705	2412983

TABLE III
THE RANGES OF VALID SAMPLING FREQUENCIES FOR N (THREE) BAND CASE FOR DIFFERENT STANDARDS

STANDARD	CHANNEL RANGE	SAMPLING FREQUENCY RANGE (MHz)
GSM 900	890 - 890.2 MHz 891.2 – 891.4 MHz 892.6 – 892.8 MHz	1.811371 - 1.811382
		2.136766 - 2.137170
		3.621907 - 3.622764
		5.63280 - 5.640506
IS 95A	824 – 825.25 MHz 830.25 – 831.5MHz 837.75 – 839MHz	10.00299 - 10.00301
		21.24051 - 21.28846
		31.66038 - 31.93269
		47.94286 - 4.83824

The same procedure is followed (as in the case of two bands) to calculate the intermediate frequencies. The intermediate frequencies are calculated using the above formula. The sampling frequency chosen and the corresponding IFs obtained are tabulated in Table IV.

TABLE IV
SAMPLING FREQUENCY CHOSEN AND THE DOWN CONVERTED IF

SAMPLING FREQUENCY USED	IF_1 (Hz)	IF_2(Hz)	IF_3 (Hz)
1.811371 MHz	7.1706e+05	1.0569e+05	3.0569e+05
2.136766 MHz	931422	268578	468188
3.621907 MHz	889122	310878	1710878
5.632808 MHz	116336	1316336	2716336
10.00299 MHz	4.379e+06	0.62e+06	1.87e+06
21.24051 MHz	3754890	2495110	9995110
31.66038MHz	1455120	7705120	15205120
47.94286 MHz	9596380	15846380	23346380

3 SDR Receiver Architecture

The concept of flexibility in a receiver breaks down into two main areas: that of flexibility in the modulation format, coding, and framing and that of flexibility in terms of RF (i.e., the ability to cover multiple bands, or provide general coverage, which is defined as covering all bands between a declared minimum and maximum frequency). This latter area, frequency flexibility, is certainly the more challenging of the two and is a concept which is the subject of our research. The former area has been much more widely addressed and most commercial communications receiver designs employ many of its basic principles, even if they do not aim to provide a wide choice of modulation formats. The ideal SDR radio architecture would allow digitization of the full bandwidth covering all the radio channels to be supported by the terminal. The ADC's performance (i.e. bit resolution, sampling rate) and the architecture for the RF to IF conversion require a trade-off among performance, power consumption and cost. An example of a practical SDR receiver using IF sampling is shown in Fig.4 as in [1].

This figure shows two possible locations for the ADC within the down conversion path. In one case, the ADC is placed after the in-phase and quadrature (IQ) demodulator. This configuration requires more analog circuitry and two ADC channels at the baseband or low-frequency IF. As ADC speeds improved, the ADC may also be placed before the IQ demodulator. In this case, the IQ demodulation occurs completely in the digital domain. We follow the second approach which removes much of the analog circuitry and the architecture begins to approach that of an ideal SDR as the transition point to digital occurs much closer to the antenna.ADC is critical for the system operation. Base station architectures may take into consideration either baseband sampling or IF sampling.

For a given frequency band (dependant on the air interface) the analog front end can be optimized; it is, however, kept fixed, which is more cost effective today than having a frequency agile and bandwidth programmable front end SDR implementation. Band pass sampling has the advantage that the signal is also frequency down converted in the same action, thereby reducing the need for an additional analog down conversion stage prior to sampling or a digital conversion stage following sampling. However, this approach assumes that the analog gain of the converter is not significantly diminished across the sampled signal's passband and that gain and phase distortion are within specification. Our receiver architecture shown in figuses pipelined ADC because of its potential advantages like inherent single-path sampling of the signal, good high frequency effective bit performance, and the capability of using dynamic comparators (low power dissipation) coupled with the use of digital correction. The output of the ADC will be digital IFs. This will be further down converted to baseband using digital LO (NCO), digital mixers, and decimation filters.

This process, referred as Quadrature sampling. converts the input signal into a complex, I and Q, baseband representation. These signals are then digitally filtered to pass the desired channel.

These bands have centre frequencies at 890.90 MHz and 909.9 MHz for GSM and 829.625 MHz and 835.875 MHz for the CDMA bands.

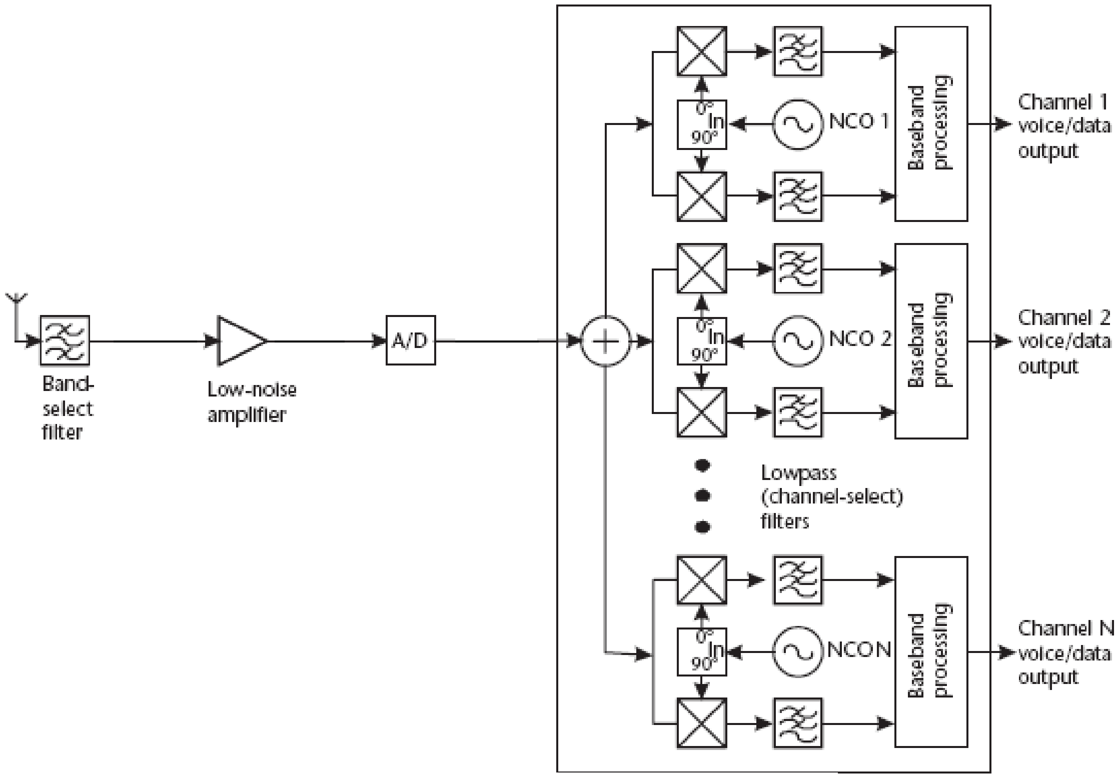

Fig.4 SDR Receiver Architecture

Here, multiple quadrature down conversions are performed in the digital domain using separate NCOs. Channel selectivity is provided using digital lowpass filtering on the resulting I and Q baseband signals; as a consequence, the selectivity achieved can be very good. This has the significant advantage of a considerable saving in RF hardware over an approach involving a number of separate receivers.

We consider the case of BTS containing 4 channels, two for GSM and CDMA. For simulation we considered, Gaussian noise and band limited them by filters to obtain the appropriate bands. The number of channels considered here are four in number. Two GSM channels and two CDMA channels are considered. The 5^{th} and 100^{th} channels are considered in GSM case while the 5^{th} and 10^{th} channels are considered in the case of CDMA. These channel numbers correspond to 890.8 - 891 MHz and 909.8 - 910 MHz for GSM and 829 - 830.25 MHz and 835.25 - 836.5 MHz for CDMA.

The sum of the four bands is considered to be the received signal for the BTS which is represented as in Fig. 5.

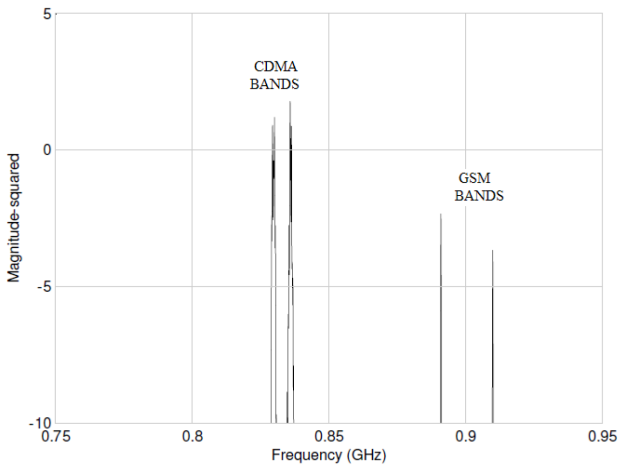

Fig.5 Spectrum of simulated GSM and CDMA bands

This signal sampled by ADC whose sampling frequency is determined by the algorithm. Here there are many possible sampling frequencies; one of them ranges from 17.6699 MHz and 17.816 MHz. Choosing 17.6699 MHz as the sampling frequency of ADC, the incoming signal is digitized and down converted to IF.

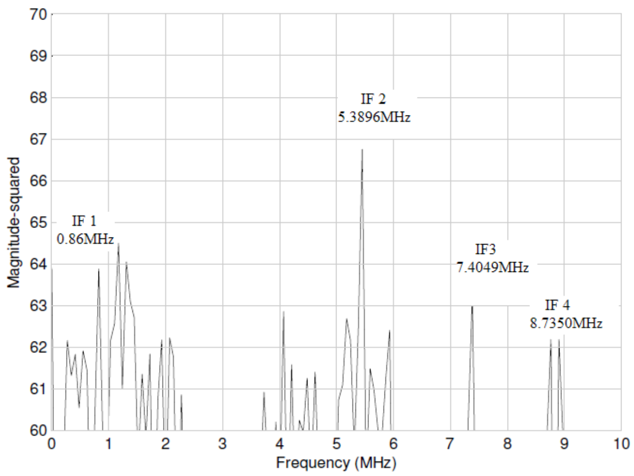

Fig.6 The sampled spectrum of the four bands

Using the above value of sampling frequency, the IFs are obtained by eqn.1. The down converted IFs thus obtained are 0.8604 MHz and 5.3896 MHz for CDMA and 7.4049 MHz and 8.7350 MHz for GSM.The sampled spectrum is shown in Fig. 6.

This sampled signal is then downconverted to baseband with NCOs. This signal will be further taken in to the processing of baseband processors where the original data is recovered. As the proof of our concept, one GSM band and one CDMA band are shown below in Fig. 7 and Fig. 8.

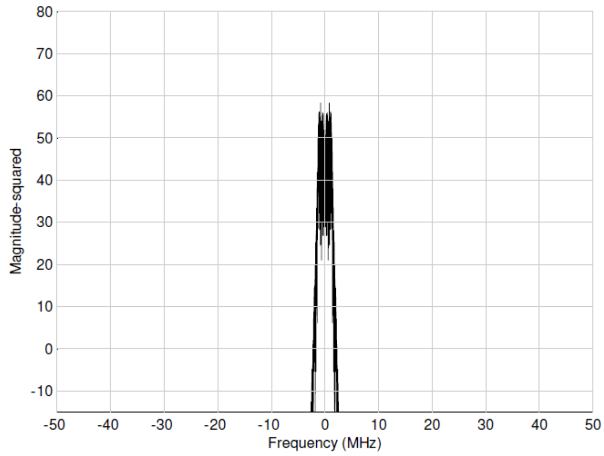

Fig.7 Spectrum of CDMA at baseband

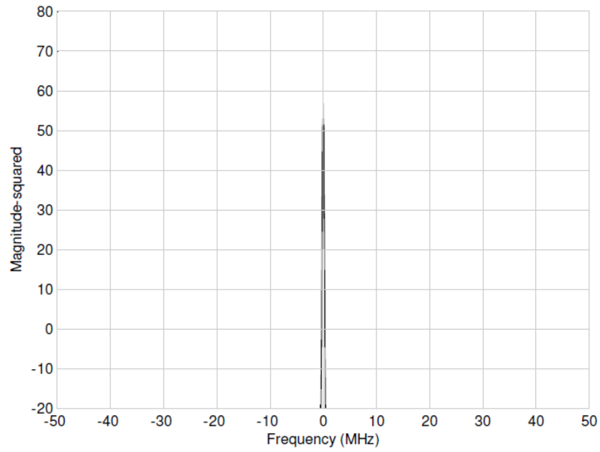

Fig.8 Spectrum of GSM at baseband

3 SDR Transmitter Architecture

The most important element of any software defined radio system, whether in a base station or handset, is the linearised transmitter.

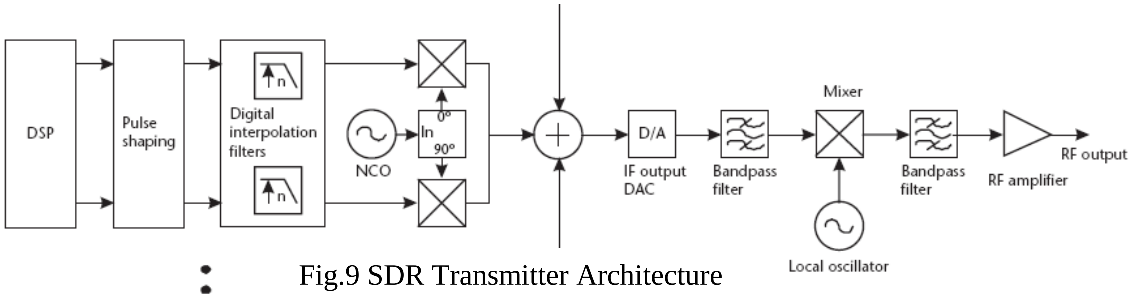

Fig.9 SDR Transmitter Architecture

Receiver systems have always required a high degree of linearity, as they must possess a good strong signal handling capability, in addition to good low-noise performance.

In the case of transmitters, however, a high degree of linearity is a relatively recent requirement, arising predominantly from the widespread adoption of cellular networks. The basic architecture of a software defined radio transmitter revolves around the creation of a baseband version of the desired RF spectrum, followed by a linear path translating that spectrum to a high-power RF signal. The frequency translation (upconversion) and power amplification processes involves creating the high power RF signal.Basically the same choice applies to transmitter architectures as applies to receiver architectures. The advantages and disadvantages associated with receiver architectures more or less translate to transmitters.

While the SDR concept heavily focuses on ADC performance, transmit path requirements are data Conversion in software defined radios usually given less attention, although the problem is of comparable complexity. More of the signal processing in these new generations of communication equipment is being performed in the digital domain for multiple reasons (i.e. higher spectral efficiency thus higher capacity, improved quality, added services, software programmable, lower power, etc.). Furthermore, many of these DSP functions are being integrated with the DAC itself to enhance its performance and to enable new transmitter architectures. These DSP functions may range from digital interpolation filters, which reduce the complexity and cost of the required analog reconstruction filter, to complete application specific digital modulators for quadrature or spread spectrum modulation schemes. Synthesizing communication signals in the digital domain typically allows the characteristics of a signal to be precisely controlled. However, in the reconstruction process of a digitally synthesized signal, it is the DAC and its no ideal characteristics which often yield unpredictable results.

In some cases, it is the performance of the DAC which actually determines whether particular modulation scheme or system architecture can meet the specification. Selecting the optimum DAC for a given wireless system requires an understanding of how to interpret various specifications and an appreciation of their effects on system performance. Achieving the optimum performance while realizing other system objectives demands careful attention to various analog interface issues. Much design effort has gone into improving the frequency domain and static performance of these devices while meeting other system objectives such as single supply operation, lower power consumption, lower costs, and ease of digital integration.

Our SDR transmitter architecture as shown in Fig. 9 consists of DSPs where the baseband processing is done and the processed signal is upconverted to an intermediate frequency by NCOs. The up converted signals from NCOs are combined together and passed onto a DAC, where it is converted to an Analog signal. This signal is band pass filtered and beaten up to the required frequency with the help of mixer circuit. The output of receiver architecture, which is the band pass version all signals is considered as the input to the transmitter architecture.The baseband signals are first up converted to an intermediate frequency. This up conversion is done by NCOs. The up converted spectrum of signals is shown below.

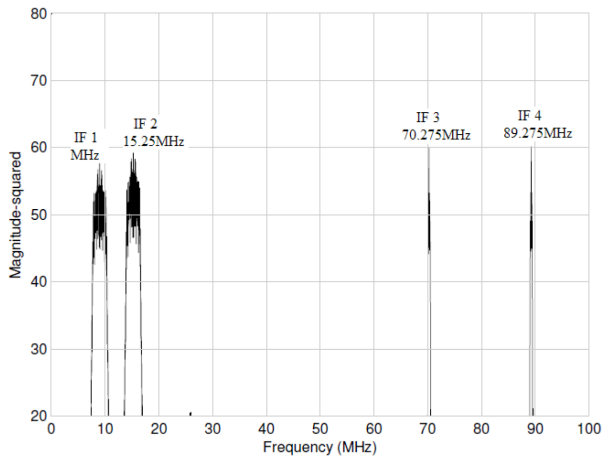

Fig.10 The combined up converted spectrum at IF

This signal forms the input to the DAC. The analog output of the DAC is then upconverted to the desired transmitting bands with the help of a mixer. Using the frequency generated by the VCO, the bands are converted to transmitting bands centred at 874.625 MHz, 880.875 MHz, 935.9 MHz and 954.9 MHz. Hence the transmitting bands are 935.8MHz - 936 MHz, 954.8 MHz - 955 MHz, 874 MHz - 875.25 MHz, 880.25 MHz - 881.5 MHz. The transmitted bands are illustrated in Fig. 10 and Fig. 11.

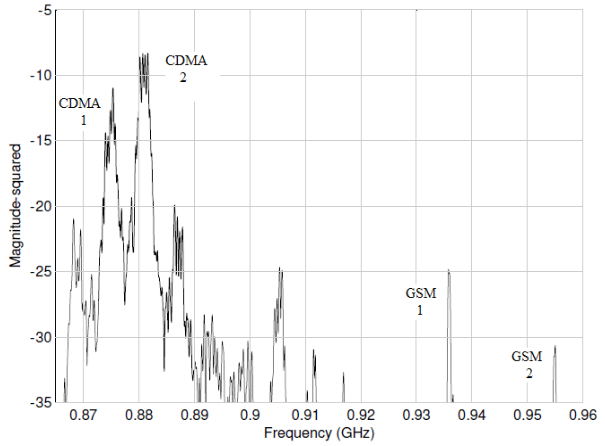

Fig.11The up converted bands

4 Conclusion

The software simulation of the complete software defined BTS has been performed in MATLAB. This architecture is set to interoperate between the cellular standards namely GSM and IS 95. Though this architecture deals with the interoperability between GSM and IS 95, it can be configured to operate between any given standards. The number of standards that can be interoperated can also be more than two thus providing greater flexibility.

For the software simulation of the transceiver architecture, a four channel case is considered. Among these four channels, either of the two channels can be chosen arbitrarily. This can be extended to any number of channels.

The band pass sampling algorithm determines the sampling frequency of the ADC which is an integral part of the receiver architecture. This BPS algorithm has been optimally formulated to determine the valid sampling frequency for any number of input bands, thus providing robustness to the receiver architecture. The aim of an ideal SDR receiver is to place the ADC as close to the antenna as possible. This critical criterion is carefully implemented in the receiver architecture thus making it closer to the ideal architecture.

The ADC and DAC structure that incorporated are also designed in such a way that they provide ease of implementation in hardware. The transmitter has been designed to operate dynamically at appropriate transmitting bands depending upon the standards used. Here appropriate bands refer to the duplex counterpart of the receiving bands.

The entire transceiver architecture has been simulated and the BTS architecture that is proposed has been substantiated with the simulation results.

5 References

1. Paul Burns, *Software Defined Radio for 3G*, Artech house, 2003.
2. http://www.sdrforum.org
3. Erik L. Org, John A. Kilpatrick, Russell J. Cyr and Geoffrey Dawe, “New SDR Architecture enables ubiquitous connectivity”, *Proceedings of SDR Forum Technical Conference 2007*, pp. 56-62.
4. Walter Tuttlebee, *Software Defined Radio Enabling Technologies*, John Wiley & Sons, 2002.
5. Jeffery A. Wepman, “Analog-to-digital converters and their applications in radio receivers”, *IEEE Communication Magazine*, vol. 33, no. 5, pp. 39-45, May 1995.
6. Simon Haykin, *Communication Systems*, 4th edition, John Wiley & Sons, 2001.
7. R. G. Vaughan, N. L. Scott, and D. R. White, “The theory of band pass sampling”, *IEEE Transactions on Signal Processing*, vol. 39, no. 9, pp.1973- 1984, Sep 1991.
8. Peter B.Kenington, *RF and Baseband Techniques for Software Defined Radio*, Artech house, 2005.
9. C.H.Tseng and S.C.Chou, “Direct Downconversion of Multiple RF Signals Using Band pass Sampling”, in *Proceedings of IEEE International Conference on Communications, 2003*, vol. 3, May 2003, pp. 2003-2007.
10. Jie-Cherng Liu, “Band pass Sampling of Multiple Single Sideband RF Signals”, *ISCCSP 2008*, Malta, 12-14 March 2008.
11. SrikathyayaniSrikanteswara, Jeffrey Reed, Peter Athanas and Robert Boyle, “A Soft Radio Architecture for Reconfigurable Platforms”, *IEEE Communications Magazine*, vol. 38, no 2, pp 140-147, February 2000.
12. Prasanna C, Subramanian R, Manikandan K, Saranesh S, Prithiviraj V, “Interoperability of GSM and CDMA using Software Defined Base Transceiver Station”, *Proceedings of International Conference on Advanced Communication and Informatics 2009*, Vellore, pp 32-34, January 2009.
13. Prithiviraj V, Manikandan K, Prasanna C, Saranesh S, Subramanian R, “Front End Design of Software Defined BTS for Interoperability between GSM and CDMA *Proceedings of IEEE Wireless VITAE 2009*, Alborg, Denmark, May 2009.