Addressing Challenges of Software Radio

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Abstract: - True Software Radio (TSR^{TM}) products are at the verge of revolutionizing the communication industry as we know it. It bears a promise of seamless operation of different systems in multiterminal/multifrequency communications environments by automatically downloading software corresponding to the specifics of the communicating terminals. However, the road to these remarkable benefits is laid with thorns asking to be properly addressed. This paper describes the main challenges in building software radios and suggests the ways to effectively deal with them. The simulation results show efficiency of proposed solutions.

Keywords: Software radio, Frequency agility, Standard independence, Outband Interference, Channel Imbalance Compensation, Simulation

1 Introduction

Software definable radio (SDR) products are at the verge of revolutionizing the communication industry as we know it. It bears a promise of seamless operation of different systems in multiterminal/multifrequency communications environments by automatically downloading software corresponding to the specifics of the communicating terminals. It is especially indicative for the True Software Radio (TSR^{TM}) systems, the most suitable ones for realization of ideal SDRs. Its main feature is providing all signal processing in software by converting the received signal immediately after an antenna into digital form; and dynamically downloading software corresponding to specifics of the received signal. However, there is a price to pay for frequency agility and protocol independence. Design of direct downconversion receivers, the heart of the TSR systems, poses its own challenge.

To be frequency agile while being operational in the wide range of frequencies the front end receiver of such software radio has to be broadband. The challenge stems from the necessity of maintaining linearity in broadband receivers in light of potentially unpredictable levels of outband interference. Any signals within a broad bandwidth of such receivers represent interference to a specific signal of interest that may be a few orders of magnitude have less spectrum width compared to the bandwidth of such receivers. Fig. 1, showing typical spectral distribution statistics for PCS bands in New York City, illustrates the potentially expected level of interference for the PCS systems [1]. It is necessary to emphasize that since interference is not predictable its cancelling has to be done by the adaptive means [2]-[3].

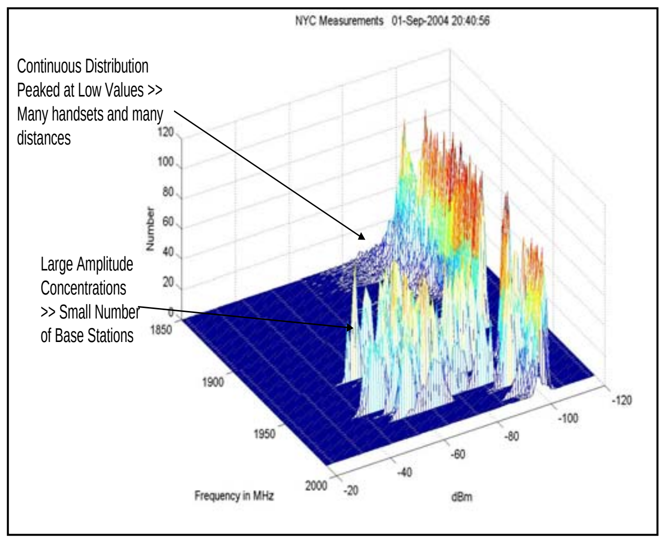

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Fig. 1 Amplitude histogram of the PCS band

Another important feature of software radios is its ability to respond to changes in operating conditions by, for example, changing their modulation schemes. Rather than having a circuit that generates a particular fixed waveform, a more flexible radio could synthesize the waveform required for a particular set of conditions. A radio that generates and detects many types of waveforms could operate in a much broader range of locales and environmental conditions. While serious efforts have been used in developing highly integrated solutions for digital basebands covering multiple standards, the vast majority of these efforts ended up using stacked transceivers [4] – [7], [11]. Each analog transceiver in such stack is used for operating in its own frequency band. The offered direct conversion software radio systems described in this paper will make analog based communication obsolete for many practical applications. It opens a new page in communication industry as we know it.

However to realize full potential of direct conversion software radio some challenges typical for that sort of communication systems have to be addressed. The most important among them are the in-phase and quadrature phase channel imbalances as well as powerful outband interference. Since SDR based systems will operate in different environments particularly the ones characterized by using sophisticated modulation techniques such as 64 or higher QAM type the bit error rate for such operations will be highly sensitive to amplitude or phase mismatch in the quadrature I-Q channels. Taken into account the mismatch time varying nature the channel imbalance compensation to be successful has to be done through adaptive means (similar in spirit to the case of interference cancellation but different in realization).

A good overview of IQ problems impact can be found in Razavi [8] and Liu [9]. Tarighat and Sayed in [10] propose a technique for compensation schemes and performance analysis of IQ imbalances in OFDM receivers using training sequences.

This paper extends the previous results by developing a simplified solution for addressing IQ imbalances in direct conversion software radio receivers. It is based on using correlation analysis between I and Q channels taking into account that ideally orthogonal signals have zero correlation. So, correlation analysis of I and Q signals is used for identifying IQ channels mismatch and generating adaptive imbalance compensation.

2 Proposed solutions to interference cancellation

To cancel interference the proposed adaptive interference canceller has to create the accurate replica of interfering signal(s), and subtract it from the original interference signal(s). **That approach allows solving the problem of how to cancel the interference without impairing the useful signal at the same time.** Narrow band interference signals have substantially larger correlation time compared to the desirable broadband signals. By delaying signals in the auxiliary channel by the time larger than a correlation time of desirable signals these signals in the main and auxiliary channels become practically uncorrelated while still maintaining high correlation for interfering signals. Correspondingly, the main principle of interference cancellation in our case is based on creating an additional auxiliary channel having interference signal equal in amplitude and in a counter phase to the interference signal in the main channel and adding them up. That additional auxiliary channel is created by using a delay line having an adjustable delay T larger than chip duration for desirable signals ($T \geq 1\mu$sec for IS95 and CDMA2000 systems and $T \geq 0.3\mu$sec for WCDMA systems). Operation in the WiFi or WiMAX environments will require delays corresponding to correlation properties of their signals. Since signal bandwidths for these standards are wider than for the CDMA standards there is broader difference in correlation properties between interference and signals corresponding to these standards. Correspondingly better interference suppression may be expected in operation with these signals.

The block diagram of adaptive interference canceller is shown on Fig. 2. The operation of the

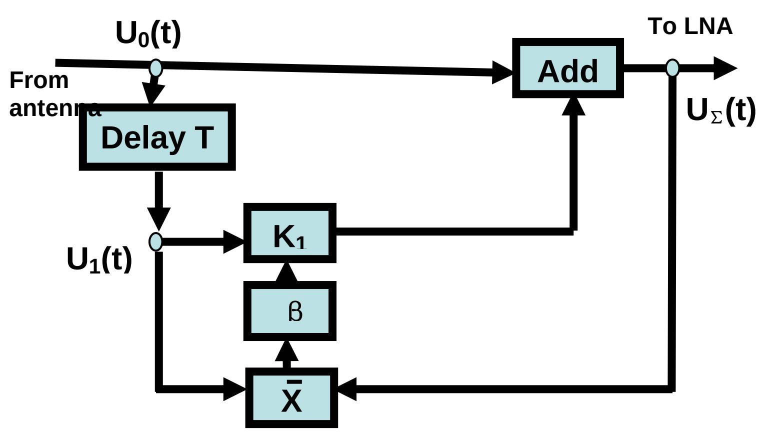

Fig. 2 Adaptive narrow band interference canceller

adaptive narrow band interference canceller will be considered for the case of one interferer. To cancel interference from multiple sources the number of quadrature auxiliary channels has to be equal to the number of interference sources. Here a signal from an antenna $\mathring{U}_0(t)$ is split between a main channel and an auxiliary one. The auxiliary channel is formed by using a delay line providing delay T. Selection of the value of delay T was described above. After forming the correlation function between auxiliary and adder

output signals in $\overline{X}$ and amplifying the signal proportional to that function with the amplification coefficient β a resultant voltage sets a coefficient of amplification of a controlled amplifier to the value K_1 sufficient for interference cancellation. Summing up interference signals of the main and auxiliary channels cancels interference leaving intact of the desirable signal. Below we will derive operation of the narrowband interference canceller shown in Fig. 2.
The signal in the main channel is the combination of signals from the desirable source $U_{0s}(t)$ and interference $U_{0i}(t)$

$$U_o(t) = U_{os}(t) + U_{oi}(t) \quad (1)$$

The signal in the auxiliary channel $U_1(t)$ is

$$U_1(t) = U_0(t-T) \quad (2)$$

The delay time T has to be selected in a way to prevent correlation of desirable signal components from different channels, i.e. it has to satisfy condition

$$\overline{U_{os}(t) \cdot U_{os}(t-T)} = 0 \quad , \quad (3)$$

where a bar over the function means operation of averaging.
The amplification coefficient of controllable amplifier K_1 will be

$$K_1 = \beta \overline{U_1(t) U_\Sigma(t)} \quad (4)$$

where the signal at the adder output

$$U_\Sigma(t) = U_0(t) + K_1 U_1(t) \quad (5)$$

Substituting (5), (1)-(3) into (4) yields

$$K_1 = \beta \frac{\overline{U_{oi}(t) \cdot U_{1i}(t-T)}}{1 - \beta \overline{U_{1i}^2(t)}} \quad (6)$$

Selecting the control signal amplification β such that even for the smallest power of interfering signal the condition $\beta \overline{U_{1i\,min}^2(t)} >> 1$ holds true, Eq (6) could be simplified as

$$K_1 = \frac{\overline{U_{oi}(t) \cdot U_{1i}(t-T)}}{-\overline{U_{1i}^2(t)}} \quad (7)$$

Substituting (7) into (5) the average power of interference at the output of adder will be

$$\overline{U_{\Sigma i}^2(t)} = \overline{U_{0i}^2(t)}(1-\rho^2) \quad (10)$$

where the square of correlation coefficient between interference signals in the main and auxiliary channels is equal to

$$\rho^2 = \frac{\overline{U_{oi}(t) \cdot U_{1i}(t)}}{\overline{U_{0i}^2(t)} \cdot \overline{U_{1i}^2(t)}} \quad (11)$$

The coefficient of interference suppression K_s can be defined as the ratio of interference power in the main channel to the interference power at the output of that channel (adder). It can be easily found from (10)

$$K_s = \frac{1}{1-\rho^2} \quad (12)$$

Described adaptive interference cancellation provides efficient means in dealing with interference. Fig. 3 shows simulation results of a CDMA/WCDMA receiver operation in the presence of a powerful narrowband signal. The total time scale here is about 6 ms. It is clear from the upper plot of Fig. 3 that after about 5.5 ms the interference is reduced by about 20 times (K_s = 20). That especially well may be seen from comparing the interference power at the input (middle plot) and output (bottom plot).

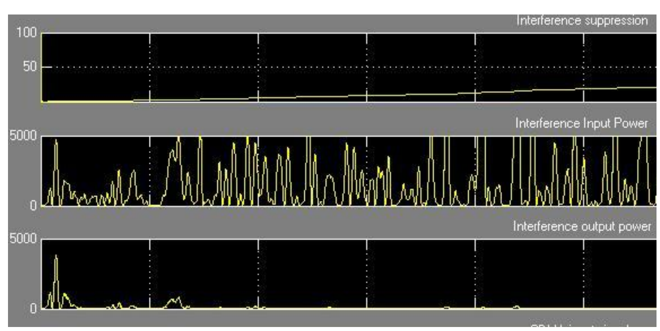

Fig.3 Adaptive compensation of a powerful interferer

3. Cancelling I and Q channel imbalances

Phase mismatch occurs when phase difference between local oscillator signal for the In-phase and Quadrature (I and Q) channels is different from 90^0. Gain mismatch between I and Q channels results from channel components gain A and B mismatch (see Fig. 4). Without a loss of generality we will assume that a phase imbalance is due to an additional phase shift φ in the in-phase (I) channel while both channel have different amplitude gains (A and B correspondingly).

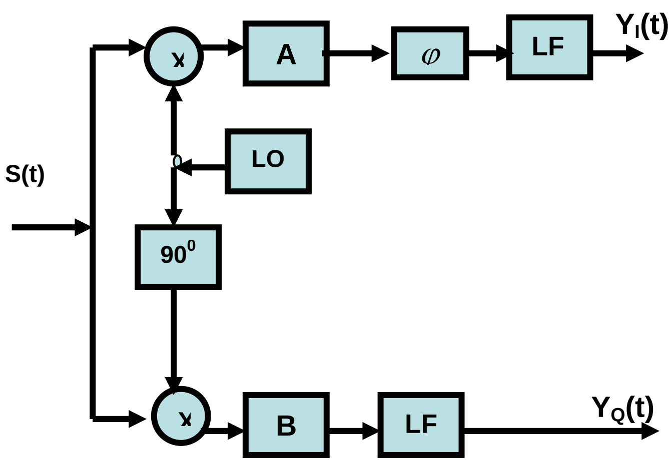

Fig. 4 Model of the I and Q channels gain and phase mismatch

The end result of IQ imbalance in a quadrature receiver is the frequency interference aliasing into the desired signal band which reduces the dynamic range and degrades the receiver performance. It can be viewed as quizistationary over time [9], [10]. When the channel imbalance corrections are applied to the received signal, the phase and channel amplitude imbalances will require separate compensation as it will be shown later. We will assume for our IQ imbalance analysis that the input signal S(t) in Fig. 4 is the QAM signal having carrier frequency w_0. It can be represented as

$$S(t) = \mathrm{Re}\left\{[I(t) + jQ(t)]e^{jtw_0}\right\} \qquad (13) \qquad \text{or}$$

$$S(t) = I(t)\cos w_0 t - Q(t)\sin w_0 t \qquad (14)$$

After mixing with the signals from a local oscillator LO having w_0 frequency the baseband signals for the in-phase (I) and quadrature phase channels of a quadrature receiver with a low pass filter LF will be

$$Y_I(t) = \frac{A}{2}\left[I(t)\cos\varphi + Q(t)\sin\varphi\right] \qquad (15)$$

$$Y_Q(t) = \frac{B}{2}Q(t) \qquad (16)$$

It is easy to show that the correlation coefficient ρ_{IQ} between $Y_I(t)$ and $Y_Q(t)$ signals is equal to $\sin\varphi$

$$\rho_{IQ} = \sin\varphi \qquad (18)$$

The phase and amplitude imbalance compensation scheme shown on Fig.5 is based on the analysis of correlation properties of signals in I and Q channels.

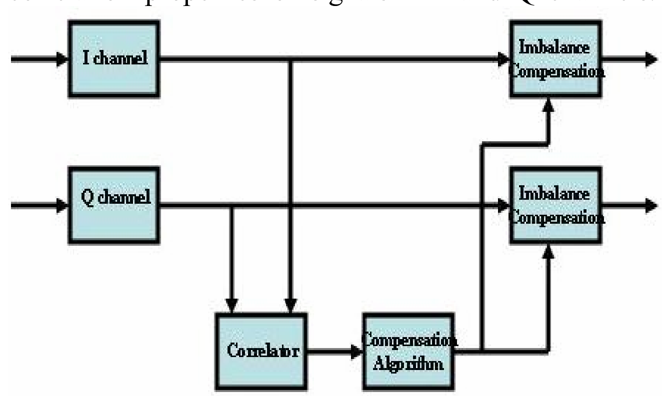

Fig. 5 Block diagram of the phase and amplitude imbalance compensation for I and Q channels

Here the I and Q channel signals are used to separately estimate phase and amplitude imbalance and correct it by multiplying channel signals on the weights proportional to estimated imbalances.

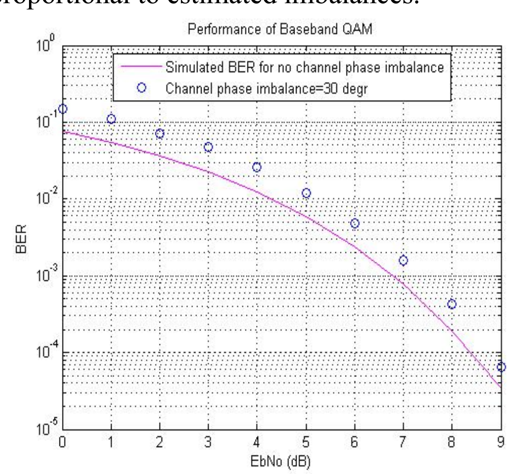

Fig. 6 Bit error rate vs. signal-to-noise ratio for the balanced and 30^0 phase imbalance between I and Q channels

The required corrections for the amplitude and phase imbalance are adaptively estimated after receiving about 1000 samples. Correlation properties of I and Q channel signals are used by a correlation estimator to smooth out potential variations of input signals due to their fluctuations.

The impact of phase imbalance expressed in terms of bit error rates (BER) is shown on Fig.6. It is clear to see that a system has about 5 dB penalties in BER values for the case of 30^0 degrees phase imbalance.

4. Conclusions

The main challenge in building direct conversion software radio comes from outband interference as well as from necessity to maintain amplitude and phase balance in in-phase and quadrature transceiver channels. Analysis of correlation properties of received signals is used to address both problems.

The essence of the proposed solution of narrowband interference cancelling is based on using the differences in correlation time of interference and desirable signals. It is achieved by forming an interference replica in an auxiliary channel and adding it in the counter phase to interference in a receiver channel. The replica of interference is formed by an auxiliary quadrature channels operating on the delayed by T interference signal. Delay T is chosen based on the knowledge of correlation properties of useful signals to decorrelate useful signals in the correlated feedback control loop. For the multiple interferers the number of feedback loops has to be equal to the number of interferers. Coefficients of amplification of controlled amplifiers are automatically selected based on the least mean square error of the interference signals at the output of adder. Correlated feedback control loop(s) implements that procedure. As a result, interference is cancelled and the useful broadband signal remains intact automatically.

The I and Q channels imbalances can be effectively compensated by using adaptive algorithms based on separate estimation of amplitude and phase imbalances. Initial correction of amplitude imbalance may be done through the ratio of average powers of signals in both channels. After that by estimating correlation between I and Q channel signals the proper correction function may be automatically generated.

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