Impact of the Undesired RF-IF Chain Effects on the LS-CMA based Beamformer in CDMA Mobile Communications

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Abstract- **In mobile communications, nonideal operation of the RF-IF chain has significant effects on the signal received by the BS. Since most beamforming algorithms use the received signal parameters to steer suitable beam, any error or uncertainty cause significant degradation in beamforming performance.**

In this paper, effects of some of the most important RF-IF chain errors occurred in down conversion process are investigated theoretically as well as by simulation. Our investigations show that the error caused by the difference between down converters, has a significant effect on the beamformer performance. It is shown that the RF-IF chain phase and amplitude errors have a more significant effect on the beamformer performance than the other errors. Because of the higher sensitivity of the phase of the received signal, phase error has the most significant effect.

I. INTRODUCTION

In mobile communications, adaptive beamforming is one of the most efficient techniques to increase the mobile network capacity. This technique decreases the necessary power for data transmission; besides, it also decreases the power of undesired signals (interference and noise) received by each user and by the BS. Since in CDMA mobile communications, capacity is mostly limited by interference power, adaptive beamforming can efficiently increase the capacity of the mobile network by increasing the carrier to interference ratio.

In mobile communications, beamformer gets its necessary information from the received signal by the BS array antenna. So, any error or distortion in this signal will severely degrade the beamformer performance. Therefore, nonideal operation of the transmission channel and any subsystem of the BS through which the received signal passes can severely degrade the beamformer performance.

In mobile environment, signal of mobile users are transmitted omnidirectionally in a nonideal transmission channel. This causes the reception of the signals in several paths with different phase, amplitude, Time of Arrival (TOA) and Angle of Arrival (AOA);(multipath effect). Beamformer uses these signals plus noise to extract the transmitted data from the desired user. [1]

To take the transmission channel effect into account, different channel models discussed in [1-8] can be

implemented. In this paper we use a signal model as established in [9] which is based on Gaussian Wide Sense Stationary Uncorrelated Scatterers (GWSSUS) [4]. Based on this model, the signal received by the BS is

$$\mathbf{x} = \sum_{i=1}^{U} \mathbf{x}_i + \mathbf{n} \tag{1}$$

where $\mathbf{n}$ is the impinging AWGN noise vector and $\mathbf{x}_i$ is the received signal from the i-th user given by

$$\mathbf{x}_i = \sum_{t=1}^{N} e_{i,t}(t) \operatorname{Re}\left[s_i\left(t - \tau_{i,t}(t)\right) e^{j\omega_{RF}\left(t - \tau_{i,t}(t)\right)} \mathbf{a}\left(\theta_{i,t}\right) \right] \tag{2}$$

U is the number of users. $s_i(t)$ is the signal received from the i-th user, θ_i is the AOA of the LOS ray of the i-th user, $\tau_{i,t}(t)$ is the time delay, $e_{i,t}(t)$ represents the transmission channel effect on the phase and amplitude of the t-th path of the i-th user, ω_{RF} is the angular frequency of the received signal and $\mathbf{a}(\theta)$ is the steering vector for θ direction. When the uniform linear array is used, this vector can be written as

$$\mathbf{a}(\theta) = \left[1 \quad e^{j\frac{2\pi d}{\lambda}Sin\theta} \quad \cdots \quad e^{j\frac{2\pi d}{\lambda}(M-1)Sin\theta} \right]^T \tag{3}$$

where d is the interelement spacing of the antenna array and λ is the wavelength. In [9] undesired effects of the transmission channel on the beamformer are investigated in detail. Thereby, in our paper, we focus on the effects of the RF-IF chain nonidealities on the beamformer performance.

The RF-IF chain whose effects are more significant than the transmission channel, is used to down convert the received RF signal into baseband or IF. Several methods have been proposed to analyze the RF-IF chain effects on the received signal [10-16]. Roome [10] assumed a general RF-IF chain model in order to analyze the nonidealities effects. Gerlach [12] analyzed these effects in the frequency domain. In another work, Green [13] established a nonlinear regression technique to estimate the gain and phase mismatches between the in-phase and quadrature branches of a quadrature receiver.

In the past works, mostly a special mixer was investigated or only some of the RF-IF chain errors were considered. On the other hand, the signal model of those works was based on an ideal transmission channel. In this paper, undesired effects of the RF-IF chain on the Least Squares Constant Modulus Algorithm (LS-CMA) [17-19] are investigated both

theoretically and using simulations. Results of the general RF-IF chain model of this paper, can be applied to a wide variety of mixers. Moreover, taking the nonideal transmission channel effects into account causes different results.

In section 2, the RF-IF chain and its effects on the signal model are investigated. Section 3 represents a theoretical analysis of the RF-IF chain effects on the LS-CMA based beamformer. Finally simulation results are given in section 4.

II. RF-IF CHAIN

A simple RF-IF chain consists of a Low Noise Amplifier (LNA), a multiplier and an IF filter. Since it is impossible to preserve all information stored in the phase and amplitude of the received signal by using a simple down converter, quadrature detection technique is usually used for down conversion [11]. Fig. 1 shows a simple quadrature detector block diagram.

There are some methods to generate the local oscillator signal for I and Q branches. One of the mostly used methods is represented in Fig. 1. In this method, the same oscillator signal is used for I and Q branches. Obviously, the oscillator signal in the Q branch passes through a 90° phase shifter to generate quadrature oscillator signals. Some other methods use two separate oscillators for I and Q branches to reach higher local oscillator power.

Nonideal operation of the phase shifter is one of the keen sources of phase and amplitude errors. Another considerable source of such errors is the tolerance occurred in the implementation of the RF-IF chain. These tolerances affect the phase and amplitude of the signal passing through the RF-IF chain.

Due to the small wavelength of the received signal, its phase is more sensitive than other properties. Therefore, phase error is usually the most important undesired effect of the RF-IF chain nonidealities.

In order to take the errors into account, the following models are stablished for the LO signal of the in-phase and quadrature branches

$$S'_I(t) = \alpha_{1,m}\left[e^{j(\omega_{LO}t+\varphi_{1,m})} + e^{-j(\omega_{LO}t+\varphi_{1,m})}\right] \quad (4)$$

and

$$S'_Q(t) = \frac{\alpha_{2,m}}{j}\left[e^{j(\omega_{LO}t+\varphi_{1,m}+\varphi_{2,m})} - e^{-j(\omega_{LO}t+\varphi_{1,m}+\varphi_{2,m})}\right]. \quad (5)$$

where $\varphi_{1,m}$, $\varphi_{2,m}$, $\alpha_{1,m}$ and $\alpha_{2,m}$ are the I and Q phase and amplitude errors in the RF-IF chain of the m-th error respectively and ω_{LO} is the LO angular frequency.

Leaked signals from the I and Q oscillators to the corresponding RF inputs, interfering signals and different harmonics of the desired signal generated in the mixer are another source of RF-IF chain errors whose effects on beamformer will be examined in the next section.
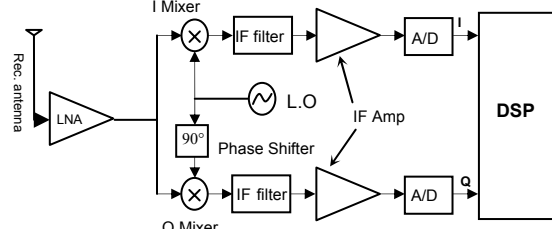

Fig. 1. A simple view of the quadrature detection

To analyze the effect of these errors on the beamformer performance, the RF signal vectors input to the I and Q branches are modified as

$$\mathbf{x}'_I = \mathbf{x} + \boldsymbol{\beta}_I \otimes \mathbf{s}_I + \mathbf{r}_{rnd} \quad (6)$$

$$\mathbf{x}'_Q = \mathbf{x} + \boldsymbol{\beta}_Q \otimes \mathbf{s}_Q + \mathbf{r}_{rnd} \quad (7)$$

where $\boldsymbol{\beta}_I$ and $\boldsymbol{\beta}_Q$ are $M \times 1$ vectors whose elements show the eakage factor of the corresponding RF-IF chain, $\otimes$ represents the element by element multiplication and $\mathbf{r}_{rnd}$ is the random signal vector which contains all the undesired harmonics, interference and noise.

III. THEORETICAL ANALYSIS

In LS-CMA algorithm, beamforming weights are calculated as

$$\mathbf{w} = \mathbf{R}_{xx}^{-1}\mathbf{r}_{xd} \quad (8)$$

where $\mathbf{R}_{xx}$ and $\mathbf{r}_{xd}$; the autocorrelation matrix and cross correlation vector, can be written as

$$\mathbf{R}_{xx} = E\left[\mathbf{x}(n)\mathbf{x}^H(n)\right] \quad (9)$$

and

$$\mathbf{r}_{xd} = E\left[\mathbf{x}(n)\hat{d}^*(n)\right] \quad (10)$$

where $\mathbf{x}(n)$ and $\hat{d}(n)$ are the input vector and the training signal, respectively. The latter is correlated with the signal of the desired user.

In order to converge the beamformer to the proper weights, a known signal is transmitted at the beginning of the transmission. After convergence is achieved, the training signal is constructed by using the beamformer output.

By using the signal model established in 1and 2, 9and 10 change into

$$\mathbf{R}'_{xx} = \sigma_s^2 \sum_{i=1}^{U} \sum_{p=1}^{P} \rho_i^2(\theta_{ip}) \sigma_{e,ip}^2 \mathbf{R}(\theta_{ip}) + \mathbf{R}_n \quad (11)$$

and

$$\mathbf{r}_{xd} = \sigma_s^2 \sum_{p \in S} \rho_1(\theta_{1p}) \mathbf{a}(\theta_{1p}) \quad (12)$$

where $\rho_i(\theta)$ is the PDF describing the angular distribution of the i-th signal paths, θ_{ip} is the angle of arrival of the p-th path of the i-th user, $\mathbf{R}(\theta)$ is the correlation matrix corresponding to $\mathbf{a}(\theta)$, and S is the set of paths of the desired signal which is correlated with the training signal because of its small time delays.

As explained in the past section, in a nonideal RF-IF chain, the phase and amplitude errors are represented in I and Q local oscillators while the leakage error and the random signals are dealt with in the input signals to the I and Q branches. In this case, the input signal vector to the beamformer is

$$\mathbf{y}' = \mathbf{y}'_I - j\mathbf{y}'_Q \tag{13}$$

where $\mathbf{y}'_I$ and $\mathbf{y}'_Q$ are

$$\mathbf{y}'_I = \sum_{i=1}^{U} \sum_{t=1}^{N} \mathrm{Re}\left[e_{i,t}\hat{s}_i\left(n - k_{i,t}(n)\right)\mathbf{a}(\theta_{i,t}) \otimes \mathbf{e}_I\right] + \mathbf{e}_{DC,I} + \mathbf{e}_{rnd,I} \tag{14}$$

and

$$\mathbf{y}'_Q = -\sum_{i=1}^{U} \sum_{t=1}^{N} \mathrm{Im}\left[e_{i,t}\hat{s}_i\left(n - k_{i,t}(n)\right)\mathbf{a}(\theta_{i,t}) \otimes \mathbf{e}_Q\right] + \mathbf{e}_{DC,Q} + \mathbf{e}_{rnd,Q} \tag{15}$$

In the above, $\mathbf{e}_I$ and $\mathbf{e}_Q$ represent the phase and amplitude error in different elements of the I and Q branches, $\mathbf{e}_{DC,I}$ and, $\mathbf{e}_{DC,Q}$ are the leakage error and finally $\mathbf{e}_{rnd,I}$ and $\mathbf{e}_{rnd,Q}$ are the random signal vectors of the I and Q branches.

Accordingly, the autocorrelation matrix is in the form of

$$\mathbf{R}'_{yy} = \sum_{i=1}^{U} \mathbf{R}'_{yy,i} + \mathbf{R}_{yy,e} \tag{16}$$

with

$$\mathbf{R}'_{yy,i} = \sum_{t=1}^{N} \sigma_{i,t}^2 \rho_i(\theta_{i,t})\mathbf{R}(\theta_{i,t}) \tag{17}$$

which is the autocorrelation matrix for the of i-th user signal in case of an ideal RF-IF chain and

$$\mathbf{R}_{yy,e} = \sum_{i=1}^{U} \sum_{t=1}^{N} \bar{e}_{i,t}\sigma_{s,1}^2 \mathbf{R}(\theta_{i,t}) \otimes \left(\mathbf{R}_{e,I} + \mathbf{R}_{e,Q} - 2\right) + \mathbf{R}_{DC} + \mathbf{R}_{rnd} \tag{18}$$

is the error term in the autocorrelation matrix caused by the RF-IF chain errors, $\mathbf{R}(\theta)$ is the autocorrelation matrix of the steering vector and $\mathbf{R}_{e,I}$, $\mathbf{R}_{e,Q}$, $\mathbf{R}_{DC}$ and $\mathbf{R}_{rnd}$ are the autocorrelation matrices which correspond to $\mathbf{e}_I$, $\mathbf{e}_Q$ $\mathbf{e}_{DC} = \mathbf{e}_{DC,I} - j\mathbf{e}_{DC,Q}$, and $\mathbf{e}_{rnd} = \mathbf{e}_{rnd,I} - j\mathbf{e}_{rnd,Q}$.

The cross correlation vector also changes to

$$\mathbf{r}'_{yd} = \sigma_{s,1}^2 \sum_{t \in S} \mathbf{a}(\theta_{1,t}) \cdot \tag{19}$$

In [8] it is shown that the beamforming weights are calculated by multiplication of the inverse of the autocorrelation matrix to the cross correlation vector. But these parameters are so complex that it is very difficult to calculate the effects of the RF-IF chain on the beamforming weights; therefore we focus on the effects of the RF-IF chain on the autocorrelation matrix and cross correlation vector.

As is seen in [18, 19], the amplitude error affects the autocorrelation matrix by multiplication of the error terms into its all elements and so it has significant effect on this matrix.

But since $\mathbf{R}_{e,I}$ and $\mathbf{R}_{e,Q}$ are achieved by multiplication of the I and Q phase and amplitude error vectors to their conjugate transpose, phase error has no effect on the autocorrelation matrix. The independent amplitude error of each pair of RF-IF chain causes $\mathbf{R}_{e,I}$ and $\mathbf{R}_{e,Q}$ to be diagonal matrices with real positive elements.

$\mathbf{R}_{DC}$ and $\mathbf{R}_{rnd}$ are two diagonal matrices which affect the diagonal elements of the autocorrelation matrix. Since these errors are uncorrelated with the desired signal, they have no severe effect on the autocorrelation matrix.

In the above calculations the statistical properties of the signal and RF-IF chain errors are used and they indicate that RF-IF chain nonidealities have no significant effect on the cross correlation vector.

About the autocorrelation matrix, its diagonal elements are just affected by amplitude error. Theoretically, this error can be efficiently mitigated by diagonal loading which adds proper loads to the diagonal elements of the autocorrelation matrix.

IV. SIMULATION RESULTS

The receiver is assumed to use
uniform linear array antenna with nine omnidirectional elements
one desired signal from 0°
two interfering signal from ± 30°
random binary data sequences with the length of 200 bit spreaded by 32 chips Walsh codes
Phase Shift Keying modulation of order 8
15 non LOS multipath signal for each user
Rician distribution for the amplitude error and uniform distribution in the interval of $[0 \quad 2\pi)$ for the phase error of the transmission channel
Gaussian distributions for TOA and AOA

To examine the beamformer performance, the following parameters are investigated: Signal to Interference and Noise Ratio (SINR), Bit Error Rate (BER) calculated after despreading, and the Sample Error Rate (SER) calculated after beamforming and before despreading. Since SER is calculated before despreading, it only represents the improvements caused by the beamformer.

Since calculation of the statistical parameters of the signal is impossible, assuming the stationary and ergodic signals, the autocorrelation matrix and cross correlation vector can be replaced by their estimates obtained from a single realization of the input signal. One of the most efficient techniques for obtaining these estimates is the Sample Matrix Inversion (SMI) method [20], which uses temporal averaging instead of statistical expectation

$$E(\cdot) \approx \frac{1}{K}\sum_{k=1}^{K}(\cdot) \tag{20}$$

where K is the signal sequence length. If K is increased to infinity, the temporal averaging will approach its corresponding expected value. But since the stationary assumption is not valid for long time intervals, very large values of K can not be implemented. Furthermore, this helps avoiding increased computational complexity.

Limited length of K in the SMI method causes errors in the calculation of the autocorrelation matrix and the cross correlation vector. So, the RF-IF chain errors affect all the
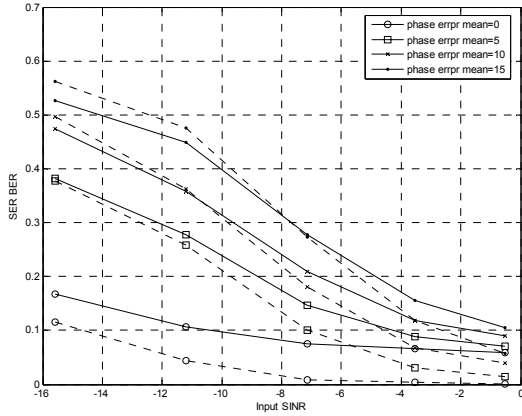
Fig. 2.   Effect of changing the phase error variation on the output BER
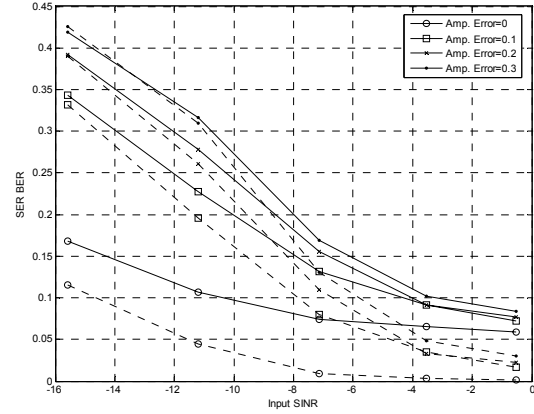(dashed curves) and SER (solid curves)

Fig. 3.   Effect of changing the amplitude error variation on the BER
(dashed) and SER (solid)

elements of the autocorrelation matrix and the cross correlation vector. Since the cross correlation vector plays a key role in determining the direction of the constructed beam, its error degrades the beamformer performance significantly.

Fig. 2 represents the effect of the RF-IF chain phase error on the SER and BER output. Phase error is a zero mean uniform random variable. The maximum phase error variation for each curve is also mentioned in the figure. As shown in the figure, increasing the variance of the phase error causes significant effects on the beamformer performance. Also the difference between the curves decreases when the input SINR increases. Moreover, the beamformer can moderately overcome the phase error in high SINR.

The smaller difference between the SER and BER curves in low SINR shows a decrease in CDMA efficiency caused by RF-IF chain errors. It is because of the decreased correlation between the received signal from the desired user and the corresponding Walsh code.

The effect of the RF-IF chain amplitude error on the beamformer performance is sketched in Fig. 3. As mentioned before, the amplitude of the signal is less sensitive than its phase. Thus, as expected, the amplitude error has a smaller effect on the output SER or BER. As shown in this figure, the difference between SER and BER curves is larger compared to fig. 2, i.e. the amplitude error degrades the CDMA efficiency more than the phase error. The reason is that the Walsh code is a real signal and is not affected by the phase error.
In Fig. 4 the effect of the LO leakage to the RF port is represented. It shows that the beamformer can overcome this error properly. The effect of random input signals to the beamformer on the output SER is demonstrated in fig. 5. Since these signals are uncorrelated with the desired signal, they have no severe effect on the output SER. Therefore in the last two figures the output BER is equal to zero for all SINR.

V.   CONCLUSION

The effects of nonideal behavior of the RF-IF chain on the performance of the LS-CMA based beamformer is investigated both theoretically and by simulation. Theoretical analysis

shows that the amplitude error has a more significant effect on the beamformer performance than other RF-IF chain errors.

These results are achieved based on the statistical properties of the signal and the RF-IF chain errors.
Similar to the practical case, the use of SMI method instead of statistical properties yields different results. Simulation results show that the RF-IF chain phase and amplitude errors have the most significant effects on the beamformer performance. Of course, because of the higher sensitivity of the `phase of the received signal, phase error has a more significant effect. Since the leaked and random signals are uncorrelated with the desired signal, their effects on the beamformer can be neglected.

The BER and SER curves show that the amplitude error has a more significant effect on the CDMA signals compared to the phase error. Moreover, SER and BER are uniformly increased by phase and amplitude error variations.

REFERENCES

[1]   R. B. Ertal, P. Cardier, K. W. Sowerby, T. S. Rappaport and J. H. Reed, "Overview of Spatial Channel Model for Antenna Array Communication System,' *IEEE Personal Communication*, pp. 10 – 22 Feb. 1998.

[2]   W. C. Y. Lee, Mobile *Communications Engineering*, New York: McGraw Hill,1982.

[3]   P. Petrus, J. H. Reed and T. S. Rappaport, "Geometrical-Based Statistical Macrocell Channel Model for Mobile Environments," *IEEE Trans. On Comm.*, Vol. 50, No. 3, pp. 495 – 50, Mar. 2002

[4]   U. Martin and M. Gerigat, "A Statistical Simulation Model for Directional Mobile Radio Channel and its Configuration," International Symposiem on Spread Spectrum Techniques and applications proceedings, vol.1, pp. 86 – 90, Sep. 1996.

[5]   J. S. Sadowsky and V. Kafadziski, "On the Correlation and Scattering Functions of the WSSUS Channel for Mobile Communications," IEEE Trans. Vehicular Technology, vol. 47, Issue 1, pp. 270 - 282, Feb, 1998.

[6]   W. C. Jakes, *Microwave Mobile Communications*, IEEE Press, New Jersey, 1994.

[7]   A. A. M. Saleh and R. A. Valen zuela, "A Statistical Model for Indoor Multipath Propagation," IEEE   Journal of Selected Area in Communications, vol. 5, no. 2, pp. 128 – 137, Feb. 1987.

[8]   B. Banitalebi, M. Kamarei, M. Karimi, and G. R. Dadashzadeh, "Effects of the Transmission Channel on the LS-CMA Based Beamformer in Mobile Communications," *to be accepted in Antem 2005.*
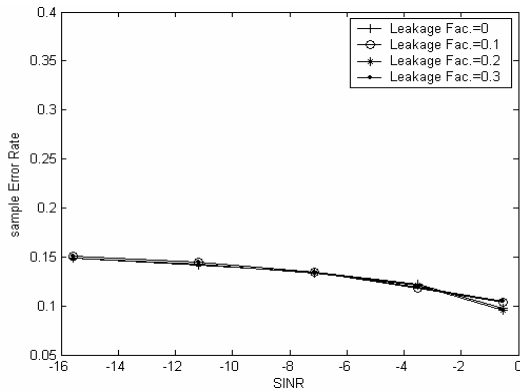
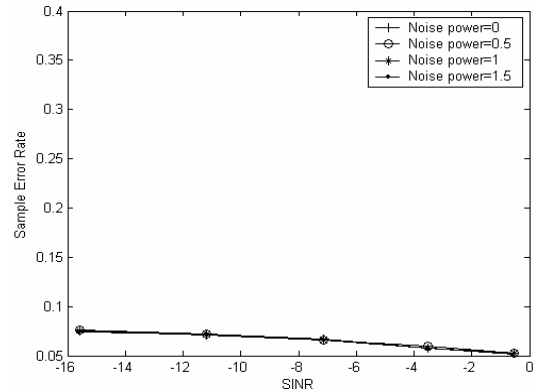Fig. 4. Effect of changing the leakage error variation on the output BER and SER

Fig. 5. Effect of changing the power of random signals on the output BER and SER

[9]   S. J. Roome, "Analysis of Quadrature Detectors Using Complex Envelope Notation," *IEE Proceeding*, vol. 136, Pt. F, no. 2, pp. 95 – 100, Apr. 1989.

[10] S. L. Loyka, "The Influence of Electro-magnetic Environment on Operation of Active Array Antennas: Analysis and Simulation Techniques," *IEEE Antenna and Propagation Magazine*, vol. 41, no. 6, pp. 23 – 39, Dec. 1999.

[11] K. Garlach, "The effect of I,Q mismatch errors on adaptive cancellation," *IEEE Trans. Aerosp. Electron. Sys.*, vol. 28, no. 3, pp. 729 – 740, Jul. 1992.

[12] R. A. Green, R. Aanerson-Sprecher, and J. W. Pierre, "Quadrature Receiver Mismatch Calibration," IEEE Trans. Signal Processing, vol. 47, no. 11, pp. 3130 – 3133, Nov. 1999.

[13] L. Yu and W. M. Snelgrove, "A Novel Adaptive Mismatch Cancellation System for Quadrature IF Radio Receivers," *IEEE Trans. Circuits and Systems II: Analog and Digital Signal Processing*, vol.46, Issue. 6, pp. 789 – 801, Jun. 1999.

[14] K. Pun, J. E. Franca, and C. Azeredo-Leme, "Wideband digital correction of I and Q mismatch in quadrature radio receivers," ISCAS 2000, vol. 5, pp. 661 - 664, 2000.

[15] S. A. Maas, *Microwave Mixers*, Dedham, MA, Artech House,1986.

[16] D. Godard, "Self-Recovering Equalization and Carrier Tracking in Two-Dimensional Data Communication Systems," *IEEE Trans. Communications*, vol. 28, Issue 11, pp. 1867 – 1875, Nov. 1980.

[17] J. Treichler and B. G. Agee, "A new approach to multipath correction of constant modulus signals," *IEEE Trans. Acoustics, Speech, Signal Processing,* vol. 31, Issue 2, pp. 459 - 472, Apr. 1983.

[18] B. Agee, "The Least Squares CMA: A New Technique for Rapid Correction of Constant Modulus Signals," *Acoustics, Speech, and Signal Processing, IEEE Conferences on ICASSP '86, vol.11, Apr. 1986.*

[19] K. L. Bell, Y. Ephraim, and H. L. Van Trees, "A bayesian approach to robust adaptive beamforming," *IEEE Trans. Signal Processing*, vol. 48, no. 2, Feb. 2000.