Effects of local oscillator phase noise on interference rejection capability of CDMA receivers using adaptive antenna arrays

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***Abstract* - It has been determined that the receiver local oscillator noise (or sampling timing jitter) sets a fundamental limit on the ability of the adaptive antenna array to reject strong in-band interferers. This work briefly describes the theoretical background of the problem and provides some bounds on interference rejection as a function of local oscillator phase noise power in adaptive antenna arrays. With the insight gained from the theoretical exploration, an example numerical simulation of the problem is presented where a null is steered in the direction of the interferer and the resulting degradation in the desired signal is presented as a result of the "smearing" of the array null because of the noisy local oscillator.**

I. INTRODUCTION

If one considers a modular CDMA receiver system where separate local oscillators are used in single (or multiple) conversion, operation of the beam-steering can be impaired by the presence of uncorrelated phase noise in the local oscillators (even if they are locked to a common frequency reference). It is desired to quantify this effect by relating the loss of attenuation in a particular antenna array for a given null direction to the levels of LO phase noise power.

In a multicarrier CDMA environment, it is well known that the receiver local oscillator phase noise level determines, in a large part, the ability of the receiver to reject interference in adjacent frequency bands. Reciprocal mixing causes unwanted power from adjacent bands to leak into the desired band [1],[2]. Mixer nonlinearities (particularly in the presence of strong signals) compound the problem by the presence of third-order products [3] which also allow adjacent channel power to leak into the desired signal band.

These impairments affect the single receiver as well as multiple receivers by increasing the apparent noise floor and reducing the receiver dynamic range. When considering a system with multiple receivers (downconverters) in an adaptive antenna array, two questions which arise are: how do nonlinearities affect the performance of an adaptive antenna (see [4]) and how does the phase uncertainty in receiver local oscillators (or timing jitter in bandpass/lowpass sampling) affect the ability of a software reconfigurable antenna array to steer nulls toward strong interferers? To work toward an answer to the second question, some theoretical background needs to be established such that the behaviour of the antenna pattern can be related to some usual descriptive quantities (e.g. noise power, signal levels, attenuation). A time domain numerical model of an adaptive antenna receiver is used in the analysis presented here.

II. THEORY

In order to understand how phase uncertainties in local oscillators affect the antenna pattern, a four element linear antenna array is used as an example architecture. This system is shown in schematic form in Figure 1. One can see that each receiver has inputs for the complex weighting factor W_i, which defines the antenna pattern. The output data streams for each receiver are present at I and Q. It is important to note that each receiver has its own local oscillator which is phase-locked to a common frequency reference (a rubidium standard, for example). Each of the local oscillators will generate a sinusoidal signal contaminated with phase noise which is (mostly) statistically independent of the noise in any other local oscillator.

The block diagram does not distinguish between analog and digital signal processing operations. De-

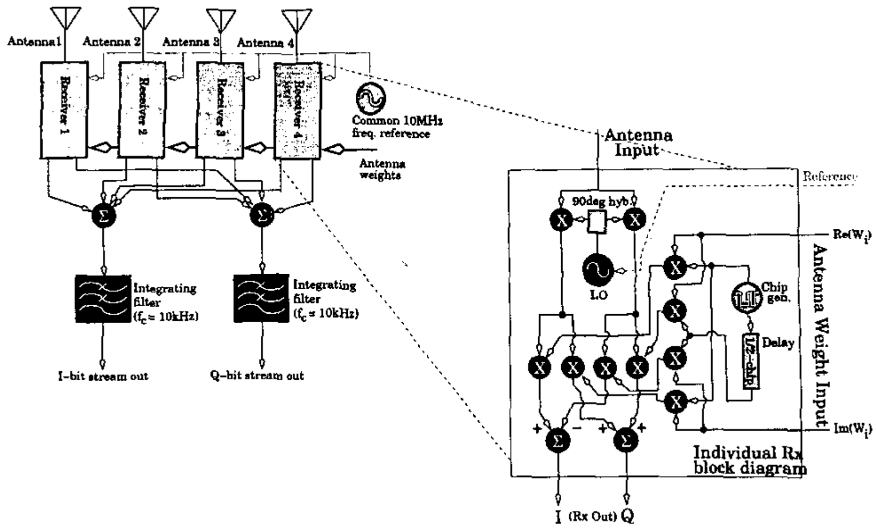

Figure 1: The four-element antenna architecture showing the detailed block diagram of the individual receivers.

modulation and despreading are likely to be performed in the digital domain. This should not detract from the phenomenon described here because it should be remembered that the sampling and analog to digital conversion is essentially a downconversion operation which is subject to subtle loss of coherence due to phase jitter in the sampling timing. Digital downconversion is therefore subject to the same phase noise constraints as analog conversion.

A. The antenna pattern -

Without reducing the generality of the phenomenon, a uniform four-element linear receiving array is assumed. The desired signal comes from the broadside direction (90°) while a strong interferer is positioned over the null that appears 30° off broadside. Figure 2 shows this positioning of the transmitters with respect to the receiving array.

It can be shown that if the beamforming takes place after downconversion (or down-sampling), the amount of power that leaks through the null can be quantified in terms of the phase errors between the local oscillators. The expected value of the leakage power is given by

$$\langle V_{int}^2 \rangle = \alpha A_{int}^2 \frac{1}{16} \sum_{m=1}^{4} \sum_{n=1}^{4} (-1)^{m+n} \langle \phi_n \phi_m \rangle, \quad (1)$$

where V_{int}^2 is the output interference signal (either I, Q or a composite) assuming an interferer strength of A_{int}, α represents a weighting factor derived from the desired/undesired spreading code cross-correlation and system gain, and the ϕ_n represent the phase random variables. The angle brackets $\langle \cdot \rangle$ indicate the computation of a moment (correlation). The expression in (1) therefore is a function which relates the degradation of the pattern null to the expected value

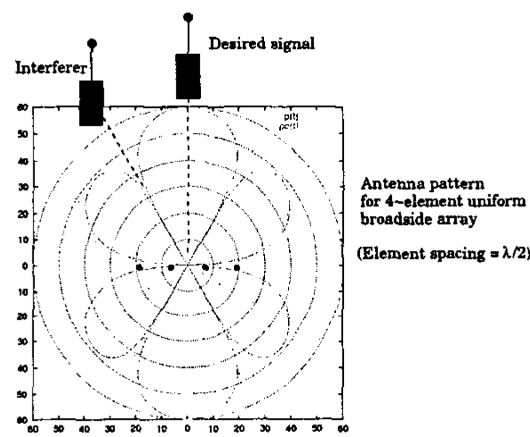

Figure 2: Illustration of the transmitter positioning with respect to the example receiver array. The ideal antenna pattern exhibits deep nulls while the degraded pattern (corresponding to about -77dBc/Hz phase noise in the LOs) shows finite dips instead of nulls.

of the local oscillator phase errors. If each oscillator generates noise which is uncorrelated to any other oscillator, the cross terms $\langle \phi_n \phi_m \rangle \to 0$, and (1) reduces to

$$\langle V_{int}^2 \rangle = \alpha \frac{1}{16} A_{int}^2 \sum_{m=1}^{4} \langle \phi_m^2 \rangle. \quad (2)$$

It is worth noting that the array proportionality factor of 1/16 appears because the first null of a uniform array was chosen. A Chebyschev array, for example, or another null would generate other weights. This indicates that the susceptibility of arrays to phase-noise induced degradation is somewhat dependent on the desired array pattern function, but for the sake of brevity, will not be discussed here. It is also worth pointing out that the degradation of interference rejection is proportional to the sum of the expected mean square error in the local oscillator phase, which can be shown to be proportional to the fraction of power existing in the noise sidebands of each LO carrier, viz.

$$\frac{P_{noise}}{P_{carrier}} \approx \langle \phi^2 \rangle, \quad (3)$$

if the phase error is "small" (RMS phase error << $\pi/2$ - DSB phase noise of around -10dBc represents a typical upper limit).

Where the noise powers increase linearly with the number of elements N, the signal levels add coherently, i.e. the received signal powers add vectorially as N^2. As a consequence of this, it can be shown that the null leakage will decrease by 3 dB when the number of antenna elements is doubled. Figure 3 shows the fraction of unwanted signal leakage as a function of individual LO phase error for four and eight-element arrays. The eight-element array suffers one-half the leakage through the null that the four-element array has. As is expected, desired signal-to-interference-and-noise ratio doubles as the number of antenna elements doubles (as long as the interfering signal does not saturate the receiver front-end).

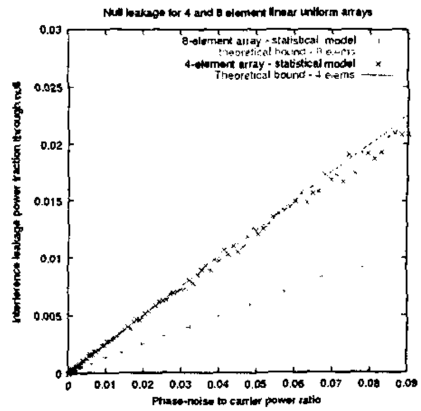

Figure 3: Illustration of leakage fraction as a function of LO phase error and number of antenna elements in the array. Solid lines indicate approximate model and scattered points indicate the results of a statistical phase model.

III. NUMERICAL EXPERIMENT: 4-ELEMENT ARRAY

Referring to the transmitter placement in Figure 2, it can be readily found that one needs weighting factors all equal to unity $(1, 1, 1, 1)$ to receive the desired transmitter at the maximum level. The undesired signal would require antenna weights equal to $(1, j, -1, -j)$ for perfect reception. Using the weights for the desired signal, the undesired signal should perfectly cancel out, since it sits in a null position. However, if the down-converted signals contain phase errors produced by the local oscillators, the unwanted signal will not cancel out and will degrade the SINR of the receiver array.

The numerical model is reasonably straightforward. Two "perfect" transmitters, each transmitting a single PN sequence at a defined power level (desired signal: 0dBm and undesired signal: 20, 26dBm) are located at the broadside maximum and the first null (at 30° off broadside), respectively. The DSB phase noise power fraction of the individual receiver local oscillators is varied. Please note that the choice of absolute signal levels is arbitrary. It is the S/I ratio that is of interest. The units of dBm are used here only to maintain clarity of the exposition.

The noisy local oscillators are modeled using sinusoidal generators which are phase modulated with band-limited Gaussian time-domain noise sources. The noise bandwidth is 10 kHz and the modulation index is adjusted to give the required noise power fraction. While it is recognised that the spectral properties of the noise may differ from "real" oscillators (particularly phase-locked oscillators), the effect described here can exist regardless of the spectral or statistical nature of the noise.

The transmitters emit a 5 MHz wide signal centered about a 10 MHz carrier (for ease of numerical calculation). Each transmitter uses a 255+1 PN spreading sequence stepped at 3.84 MChips/sec (correlation properties in Table 1). The spreading sequence is used to modulate the carrier into a QPSK wave. The data is a 1 ms snapshot of a 12.2 kb/s message. The channel, to avoid confounding the results, was taken to be noiseless and non-fading. There existed only a 360ns delay, which was the group delay of the band-limiting filter model. Coherent detection as well as perfect PN sequence lock was assumed in the receiver. Sequence acquisition was not modeled.

Table 1: Table of simulated non-ideal PN sequence correlations. PN1 = desired code, PN2 = undesired code, PN2D = Undesired code delayed 1/2 chip.

	PN1	PN2	PN2D
PN1	0.9336	-6.663×10^{-2}	5.904×10^{-3}
PN2	-6.663×10^{-2}	0.9336	0.4381
PN2D	5.904×10^{-3}	0.4381	0.9336

To illustrate the effect of null power leakage, consider the results in Table 2. Here, the signal to interference ratios are listed as a function of phase noise and interference power. The desired signal level is always 0 dBm. Theoretical values are also given, which were derived from the results in Figure 3. Note that the SIR was computed over a 10 kHz wide despread baseband channel.

Table 2: Table of S/I ratios versus local oscillator phase noise and interferer strength. Desired signal is 0 dBm in all cases. All numerical quantities in dB.

P_{int} (dBm)	ϕ-noise (dBc)	S/I (comp) (dB)	S/I (theory) (dB)
none	-10.4	29.5	∞
20.0	none	∞	∞
20.0	-10.4	19.8	20.7
26.0	-10.4	14.2	14.7
26.0	-16.0	19.8	20.3

From Table 2, one sees good agreement between the theoretical approximations (from (2)) and the system numerical model results. To remove the effect of spreading gain, subtract 25 dB from the S/I ratios to get raw S/I ratios. The first two rows in the table establish the baseline interference. Note that in-channel reciprocal mixing generates a finite interference level without an interferer actually being present (as expected).

IV. SUMMARY AND CONCLUSIONS

Perhaps the most important conclusion which can be drawn from this work is that the interference power which leaks through a steered null is directly dependent on the total amount of phase noise power present in the down-converting system. Proportionality constants which fix the actual power levels depend on the type of array factor as well as which null one is attempting to steer. At this point, it does not appear that the interference levels are affected by the distribution of the noise spectral density, only the noise power level, which is directly related to the RMS phase error in the oscillators.

Three methods of avoiding this type of interference: (best) use a single common LO synthesizer, reduce individual synthesizer noise or use a larger antenna array. In the first option, the nearly perfect correlation of the phase noise in this case means that (1) is essentially zero. However, this may not be convenient for modularized systems (or systems located some distance from one another) which need only be synchronised to a common reference timebase. In this case, each receiver has its own LO, locked to the common reference. Noise outside of the PLL loop bandwidth is likely to be uncorrelated, giving rise to the phenomenon described in this paper. Here, the method of reducing the interference requires the use of high quality VCOs. Low power levels in the oscillator noise sidebands guarantee that the phenomenon described in this paper will be small. Furthermore, the calculations here demonstrate that the larger the antenna array is, the less sensitive the receiver array is to phase noise in the local oscillators.

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