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Pilot-Assisted STAR for Increased Capacity and Coverage on the Downlink of Wideband CDMA Networks [1]

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Abstract — **We previously reported on a new uplink array-receiver, referred to as pilot-sign STAR (spatio-temporal array-receiver). This receiver combines an earlier blind version of STAR with use of a very weak pilot (~ 1% power/overhead fraction) to resolve the sign ambiguity of the blindly identified channel. In this contribution, we update and exploit the advantages of this receiver on the downlink. Simulations indicate SNR advantages for the new pilot-sign STAR over the conventional pilot-channel version at relatively weak received pilot powers on the downlink. Hence, use of pilot-assisted STAR in both directions increases capacity by reducing the interference power of the pilot and/or improves coverage by maintaining more robust links in the presence of strong near-far ratios.**

I. Introduction

To increase the downlink capacity of wideband wireless CDMA networks, various works recently investigated the implementation of transmit diversity or beamforming at the base-station, as well as receive beamforming at the mobile-station [1]-[6]. Many of the assessed solutions are now part of the 3G standard recommendations. In this contribution, we adopt both transmit diversity and receive beamforming, but focus on a more efficient exploitation of the base-station pilot on the downlink.

Use of a pilot on the downlink was already included in the early IS-95 CDMA standard and has been recently included in 3G standards for coherent detection on the uplink. Several studies allowed optimization of performance by specifying an optimal pilot-to-data power ratio (*e.g.*, [7],[8]). These works mainly focused on the uplink.

In the same framework, we previously reported on a new version, referred to as pilot-sign STAR (spatio-temporal array-receiver) [9]. This technique combines an earlier blind version of STAR [10] with use of a very weak pilot (~ 1% power/overhead fraction) to resolve the sign ambiguity of blind channel identification [9]. We adapt this receiver to the downlink and extend its advantages to increase capacity and coverage there.

II. Assumptions and Data Model

We denote by M_{Tx} and M_{Rx} the number of the downlink transmitting and receiving antennas at the base and mobile-station, respectively, and consider a multipath Rayleigh fading environment with number of paths P. The data destined for a given mobile is BPSK modulated at the rate $1/T_s$ where T_s is the symbol duration, then spread with a processing gain L. A constant unmodulated pilot signal, specific to the serving base-station and common to all mobiles, is spread with a pilot code and transmitted without power control.

After despreading of the data channel, we obtain the post-correlation model (PCM) of the received signals over the $M_{Tx} \times M_{Rx} \times P$ spatio-temporal diversity branches in the data observation vector [9]:

$$\underline{Z}_n^\delta = \underline{H}_n s_n^\delta + \underline{N}_n^\delta = \underline{H}_n \psi_n^\delta b_n + \underline{N}_n^\delta \;, \tag{1}$$

where $s_n^\delta = \psi_n^\delta b_n$ is the data signal component, b_n is the BPSK data sequence and $\left(\psi_n^\delta\right)^2$ is the total received power of the data signal. $\underline{H}_n$ is the $M_{Tx} \times M_{Rx} \times P$ spatio-temporal Rayleigh fading channel vector normalized to $\sqrt{M_{Rx}}$. $\underline{N}_n^\delta$ is a spatially-uncorrelated Gaussian interference vector with mean zero and variance σ_N^2 after despreading of the data channel. The resulting input SNR after despreading, SNR_{in} equals $\left(\psi^\delta\right)^2/\sigma_N^2$ per antenna element.

Using the above PCM model for the pilot channel after despreading, we obtain the following pilot observation vector [9],[10]:

$$\underline{Z}_n^\pi = \underline{H}_n s_n^\pi + \underline{N}_n^\pi = \underline{H}_n \psi_n^\pi + \underline{N}_n^\pi \;, \tag{2}$$

where $s_n^\pi = \psi_n^\pi$ is the pilot signal component and $(\psi_n^\pi)^2$ denotes the total received power of the pilot signal and $\underline{N}_n^\pi$ is a zero-mean spatially-uncorrelated Gaussian interference vector with the same variance as $\underline{N}_n^\delta$ (*i.e.*, σ_N^2).

III. Assessed Downlink Versions of STAR

Using the channel estimate $\hat{\underline{H}}_n$ at iteration n, STAR first performs a simple extraction of the data signal component by spatio-temporal maximum ratio-combining (MRC) [9],[10]:

$$\hat{s}_n^\delta = \text{Re}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\delta}{M_{Rx}}\right\} \tag{3}$$

STAR could extract the pilot signal component by the same MRC rule:

$$\hat{s}_n^\pi = \text{Re}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\pi}{M_{Rx}}\right\} \tag{4}$$

The data sequence b_n is then estimated as:

$$\hat{b}_n = \text{Sign}\left\{\hat{s}_n^\delta\right\} \tag{5}$$

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The data and pilot power estimates $\left(\hat{\psi}_n^\delta\right)^2$ and $\left(\hat{\psi}_n^\pi\right)^2$ are calculated by simple smoothing of the corresponding beamforming output of Eq. (3) or (4):

$$\left(\hat{\psi}_n^\delta\right)^2 = (1-\alpha)\left(\hat{\psi}_{n-1}^\delta\right)^2 + \alpha \max\left\{\left|\hat{s}_n^\delta\right|^2 - \hat{\sigma}_{\text{res}}^2, 0\right\}, \tag{6}$$

$$\left(\hat{\psi}_n^\pi\right)^2 = (1-\alpha)\left(\hat{\psi}_{n-1}^\pi\right)^2 + \alpha \max\left\{\left|\hat{s}_n^\pi\right|^2 - \hat{\sigma}_{\text{res}}^2, 0\right\}, \tag{7}$$

$$\hat{\sigma}_{\text{res}}^2 = (1-\alpha)\,\hat{\sigma}_{\text{res}}^2 + \frac{\alpha}{2}\left(\text{Im}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\delta}{M_{Rx}}\right\}^2 + \text{Im}\left\{\frac{\hat{\underline{H}}_n^H \underline{Z}_n^\pi}{M_{Rx}}\right\}^2\right), \tag{8}$$

where α is a smoothing factor and where $\hat{\sigma}_{\text{res}}^2$ is a smoothed estimate that approximates the variance of the residual interference in $\hat{s}_n^\delta$ or $\hat{s}_n^\pi$ after MRC combining (*i.e.*, $\sigma_{\text{res}}^2 = \sigma_N^2/2M_{Rx}$).

In a second step, STAR feeds back the estimate of the data signal component $\hat{s}_n^\delta$ (or $\hat{\psi}_n^\delta \hat{b}_n$) in a decision feedback identification (DFI) scheme to update the channel estimate using a blind channel identification procedure [9]:

$$\hat{\underline{H}}_{n+1} = \hat{\underline{H}}_n + \mu\left(\underline{Z}_n^\delta - \hat{\underline{H}}_n \hat{s}_n^\delta\right)\hat{s}_n^\delta\,, \tag{9}$$

where $\hat{\underline{H}}_n$ is the adaptive channel estimate and μ is the adaptation step-size. The simple DFI scheme of Eqs. (3) and (9) allows coherent detection of the signal component within a sign ambiguity, say $a = \pm 1$, thereby giving[2]:

$$\hat{s}_n^\delta \simeq a\,\psi_n^\delta\, b_n\,, \tag{10}$$

$$\hat{b}_n \simeq a\, b_n\,, \tag{11}$$

$$\hat{\underline{H}}_n \simeq a\,\underline{H}_n\,. \tag{12}$$

Without additional processing before binary decision, the resulting **blind version of STAR** requires differential decoding of DBPSK modulated data to remove the sign ambiguity a. If $\underline{b}_n$ denotes the original information bit sequence before differential coding, then we have:

$$\text{differential modulation} \Rightarrow b_n = \underline{b}_n b_{n-1}, \tag{13}$$

$$\text{coherent detection} \Rightarrow \hat{b}_n = \text{Sign}\left\{\hat{s}_n^\delta\right\} \simeq a b_n, \tag{14}$$

$$\text{differential decoding} \Rightarrow \hat{\underline{b}}_n = \hat{b}_n \hat{b}_{n-1}. \tag{15}$$

If we use the pilot amplitude estimate $\hat{\psi}_n^\pi$ for decision feedback identification from the pilot channel observation vector:

$$\hat{\underline{H}}_{n+1} = \hat{\underline{H}}_n + \frac{\mu}{\left(\hat{\psi}_n^\pi\right)^2}\left(\underline{Z}_n^\pi - \hat{\underline{H}}_n \hat{\psi}_n^\pi\right)\hat{\psi}_n^\pi\,, \tag{16}$$

we obtain the **pilot-channel assisted version of STAR** where coherent detection of BPSK modulated data can be achieved without a sign ambiguity (*i.e.*, $a = 1$). In contrast to the corresponding uplink version [9], note that we normalize the step-size μ by the time-varying pilot-power $\left(\hat{\psi}_n^\pi\right)^2$.

On one hand, pilot-channel STAR allows coherent modulation and detection. However, it requires a minimum level of received pilot-power to maintain reliable identification. Hence, coverage[3] and/or capacity are limited by a strong near-far ratio at the cell boundary and/or by an excess interference from a relatively strong pilot power, respectively. On the other hand, blind STAR does not require a pilot and hence may increase coverage and capacity due to its reliability on the power-controlled data signals for identification and to a possible pilot-power reduction. However, it requires differential decoding of the data, therefore it performs worse than coherent pilot-channel STAR close to the base-station.

A hybrid version suggested for the uplink in [9] - which retains channel identification from the data and uses the pilot to resolve the sign ambiguity - results in the best structure for intermediate near-far ratios on the downlink. Using the fact that the pilot signal component estimate resolves the sign ambiguity a:

$$\hat{s}_n^\pi \simeq a\psi_n^\pi\,, \tag{17}$$

the hybrid version provides an estimate for it $\hat{a}$ by taking the sign of the average of the pilot signal components over consecutive blocks of A samples weighted by the corresponding time-varying pilot-amplitude estimates:

$$\bar{s}_n^\pi = \sum_{i=0}^{A-1} \hat{\psi}^\pi_{(\lfloor n/A\rfloor-1)A+i}\; \hat{s}^\pi_{(\lfloor n/A\rfloor-1)A+i}\,, \tag{18}$$

$$\hat{a}_n = \text{Sign}\left\{\bar{s}_n^\pi\right\}. \tag{19}$$

In contrast to the above downlink implementation, note that the pilot amplitude is a fraction of the data amplitude on the uplink and almost constant due to power control, hence the possible suppression of weighting as in [9]. Coherent demodulation is achieved by eliminating the estimated sign ambiguity from the estimated sequence in Eq. (5), leaving the final bit estimate as:

$$\tilde{b}_n = \hat{a}_n \hat{b}_n\,. \tag{20}$$

We hence obtain the **pilot-sign assisted version of STAR**.

In the following, we study and compare the above three downlink versions of STAR (*i.e.*, pilot-channel, pilot-signal, and blind).

IV. Evaluation Results

Use of simple antenna transmit diversity at the base-station amounts to multiplying the number of natural paths P by the number of transmit antennas M_{Tx} to yield the total number of diversity paths per receive antenna $\bar{P} = P \times M_{Tx}$. We fix $\bar{P}$ here to 1 or 3 (*e.g.*, nonselective 1.25 MHz bandwidth with 1 path and 1 or 3 Tx antennas; or selective 5 MHz with 3 paths and 1 Tx antenna). We also fix the number of Rx antennas to 1 or 2 and limit the number of (Tx/Rx) antenna configurations to (3,1), (1,2), and (3,2).

We consider a carrier frequency of 1.9 GHz and a voice-rate mobile of 9.6 Kbps with a speed of 1 Kmph (processing gain L could be 128 or 512). We use FER channel coding with rate 1/2 over data blocks of 192 bits (*i.e.*, frame length of 20 ms). We also update power control every 1.25 ms to instruct to the mobile to either increase or decrease its power by a constant step-size of 0.5 dB. This binary command experiences 10 % BER and a delay of 1.25 ms. Finally, for simplification we model both incell and outcell interference by spatially-uncorrelated white noise at a given SNR level (more elaborate models will be addressed in the future).

Results in Fig. 1 suggest the following:

- In all tested configurations [Figs. 1-(a),(c),(e)], we identify three SNR operating zones over the received pilot power where one of the three STAR versions performs best: 1) pilot-channel for relatively strong powers, 2) new pilot-sign for relatively weak powers, and 3) blind for relatively very weak powers[4].

[2] A "sign hopping" in the DFI scheme may occur, but the sign ambiguity a is in most cases stable and constant in time.

[3] We mean coverage in terms of both area extent and quality in reduced call drops.

[4] We still require that the blind version maintain other control links between the base and the mobile-station.

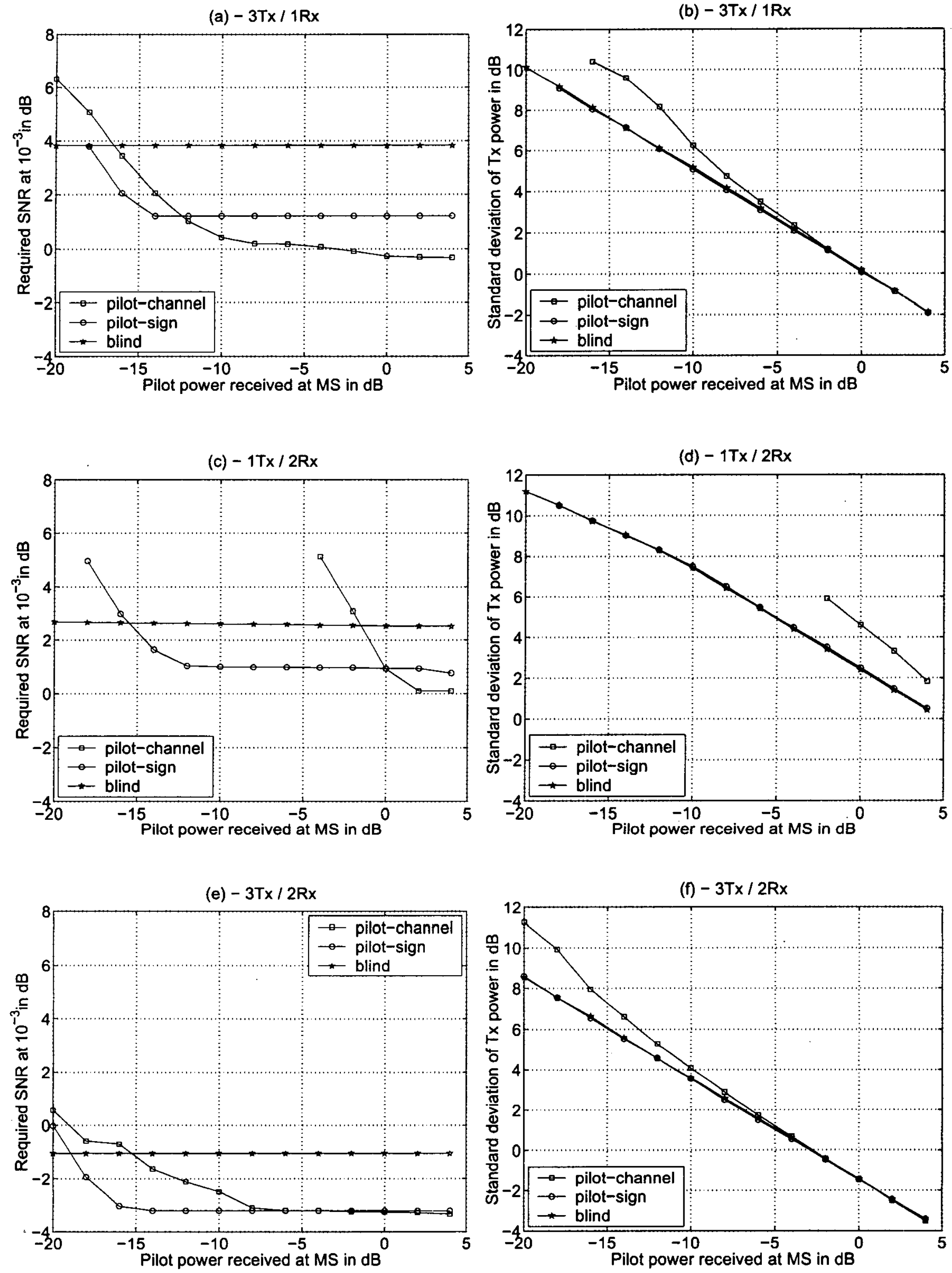

Figure 1: Downlink results in the three selected (Tx/Rx) antenna configurations - (a),(c),(e): Required SNR at a BER of 10^{-3} after FEC decoding, and (b),(d),(f): the corresponding standard deviation of the data transmitted power, both versus the average received pilot power, for the three STAR versions.

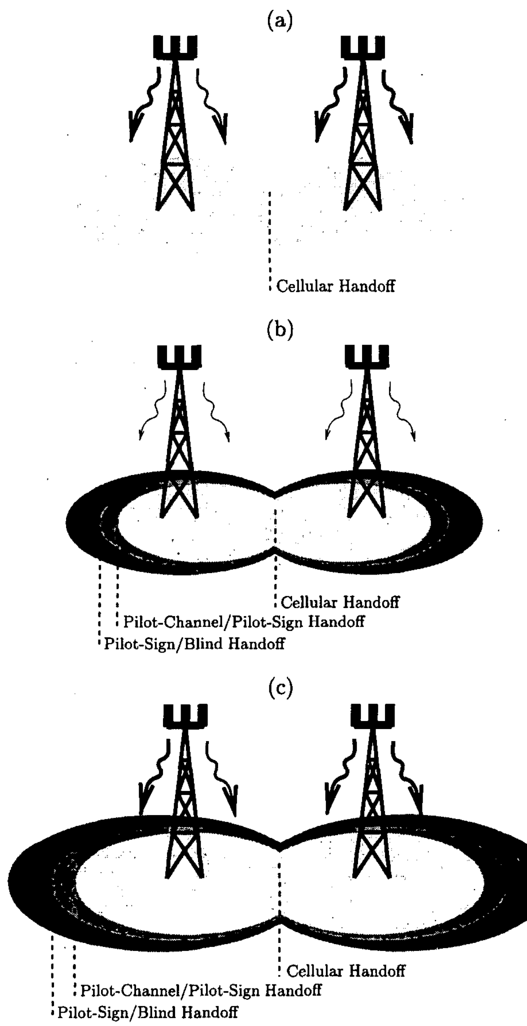

Figure 2: Benefits of modulation&identification "handoff" between STAR versions. (a) to (b): Increased capacity with reduced pilot-power transmission. (a) to (c): Increased coverage and reduced call drops.

• Poorer diversity increases pilot power variations and tends to favor the new pilot-sign over the pilot-channel version, and to a lesser extent the blind over the pilot-sign version. In general, benefits due to an increase in number of diversity paths tend to saturate while more transmit antennas (limited here to 2 for practical reasons) further increase the antenna gain.

• The standard deviation of transmitted data power impacts assignment of power resources at the base-station as well as interference statistics, the outage probability and hence capacity. It increases the operating margin of the new pilot-sign STAR against the pilot-channel version.

• Provided that modulation can be switched smoothly between BPSK and DBPSK in response to requests by the mobile, the three versions of STAR can coexist in the same cell and provide the following benefits (see Fig. 2): 1) increased capacity or spectrum efficiency by allowing weaker pilot-power transmission and generating less interference, 2) increased coverage and reduced call drops by maintaining links at stronger near-far ratios.

V. Conclusions

We proposed a modulation&identification "handoff" scheme between three downlink versions of STAR. Pilot-channel STAR performs best close to the base station. Blind STAR favors near-far situations close to cell boundary. On the other hand, the new semi-blind hybrid version of STAR, named pilot-sign, stands out as the best compromise for intermediate near-far ratios.

The new scheme increases cell capacity and coverage on the downlink as compared to conventional pilot-channel assisted reception. System level capacity evaluation is envisaged in the future. We also plan to combine the proposed scheme of modulation/identification "handoff" between STAR versions with transmit antenna selection and joint power control [5],[6]. Additionally, we plan to incorporate it into a new multi-user version of STAR [11].

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