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Near-Far Resistant Single-User Channel Identification by Interference Subspace Rejection in Wideband CDMA [1]

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Abstract — **The single-user CDMA spatio-temporal array receiver (STAR-SU) can be extended to a multi-user version (STAR-MU) by incorporating interference subspace rejection (ISR) using spatio-temporal null-beamforming. We can exploit the data-projection step implemented there to enhance the channel identification for STAR-SU so that it is significantly more robust to near-far power variations than the previous formulation. Our approach effectively decomposes the MU subspace tracking into much simpler single-user 1-D subspace tracking operations. Simulations on the downlink reveal that the performance of the new STAR-SU is close to the single-user bound even for near-far ratios as high as 18 dB.**

I. Introduction

Use of multi-user detection and advanced spatio-temporal array signal processing techniques in wireless communications [1],[2] promises high spectrum efficiency gains in wideband CDMA. Such gains depend strongly on an accurate estimation of all users' channel parameters. Multi-user (MU) channel identification is often addressed as a computationally prohibitive multidimensional optimization problem [3]. However, most recent subspace-tracking approaches reduced its complexity [3]-[5], for instance by decomposing the multidimensional parameter search there into a series of 1-D optimizations [3].

We recently proposed an interference subspace rejection (ISR) technique [6]-[9] which offers advantageous performance/complexity tradeoffs. While ISR implements multi-user detection by nulling interference in the combining step, it still identifies each user-channel using the spatio-temporal array-receiver (STAR) [10] in a single-user (SU) formulation by tracking each channel as the principal eigenvector of the corresponding despread observation. Interference in the despread observation may degrade identification and could prevent full exploitation of the STAR-ISR potential [6]-[9].

We propose here a new scheme which exploits a data-projection step in the ISR combiner to provide almost interference-free despread observations for channel identification. The SU channel identification approach therefore becomes optimal and renders STAR-ISR extremely near-far resistant. In contrast to previous techniques [3]-[5], it decomposes the joint multi-user subspace tracking into much simpler single-user 1-D subspace tracking procedures.

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II. Formulation and Background

We consider an asynchronous cellular CDMA system where each station-terminal is equipped with a receiving antenna-array of M sensors (the model below is for the uplink, but applies to the downlink as well). The modulation is assumed DBPSK. We use long PN codes with a processing gain L and assume a multipath fading environment with P resolvable paths where the delay spread $\Delta\tau$ is small compared to the bit duration T (*i.e.*, $\Delta\tau \ll T$). Finally, we assume the presence of NI high-rate strong-power interfering users with indices $i = 1$ to NI and consider a desired user, assigned the index d.

The preprocessing unit in Fig. 1 successively implements matched-pulse filtering of the observation vector $X(t)$ received by the antenna-array, sampling at the chip rate, framing over $2L-1$ chip samples[2] at the bit rate and vector reshaping, to yield the the $M(2L-1)\times 1$ matched-filtering observation vector [6]-[8]:

$$\begin{aligned} \underline{Y}_n &\simeq \psi_n^d b_n^d \underline{Y}_{0,n}^d + \sum_{i=1}^{NI}\sum_{k=-1}^{+1} \psi_n^i b_{n+k}^i \underline{Y}_{k,n}^i + \underline{N}_n \\ &= \psi_n^d b_n^d \underline{Y}_{0,n}^d + \sum_{i=1}^{NI}\sum_{f=1}^{N_f}\sum_{k=-1}^{+1} \psi_n^i \zeta_{f,n}^i b_{n+k}^i \underline{Y}_{k,n}^{i,f} + \underline{N}_n \\ &= s_n^d \underline{Y}_{0,n}^d + \underline{I}_n + \underline{N}_n \ , \end{aligned} \quad (1)$$

where for a given user assigned the index u, b_n^u is the transmitted DBPSK symbol and $(\psi_n^u)^2$ is the total received power; s_n^u is the signal component and $\underline{Y}_{k,n}^u$ is the spread channel delayed/advanced by kT; $\zeta_{f,n}^u$ is the channel coefficient from the f-th diversity finger for $f = 1,\ldots,N_f = MP$; $\underline{Y}_{k,n}^{u,f}$ is the corresponding spatio-temporal spread sub-channel vector from the f-th finger delayed/advanced by kT; and $\underline{N}_n$ is an uncorrelated additive noise vector due to the other users in the system. Despreading the above vector with the spreading code of user d yields the following $ML\times 1$ post-correlation observation vector:

$$\underline{Z}_n^d \simeq s_n^d \underline{H}_n^d + \underline{I}_{\text{PCM},n}^d + \underline{N}_{\text{PCM},n}^d \ , \quad (2)$$

where $\underline{I}_{\text{PCM},n}^d$ and $\underline{N}_{\text{PCM},n}^d$ are $\underline{I}_n$ and $\underline{N}_n$ despread by the d-th code, respectively, and $\underline{H}_n^d$ is the propagation channel vector (channel coefficients without spreading) normalized to $\sqrt{M}$.

In previous work [10] we assumed that the spatio-temporal noise vector $\underline{I}_n$ is spatially uncorrelated and merged it with $\underline{N}_n$,

[2]The number of chips is fixed here to $2L-1$ to yield despread observation matrices $\mathbf{Z}_n$ with dimension $M\times L$, as initially required for channel identification by STAR [10] (see Fig. 1). This dimension can be reduced, but we omit the discussion for simplicity.

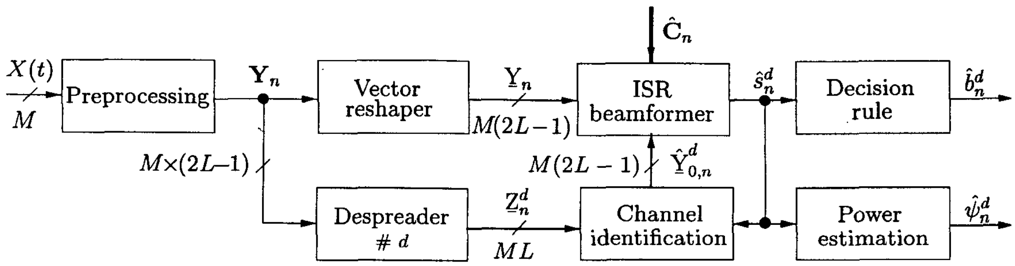

Figure 1: Block diagram of one of the receiver modules (for the desired user) of upgraded multi-user STAR-ISR.

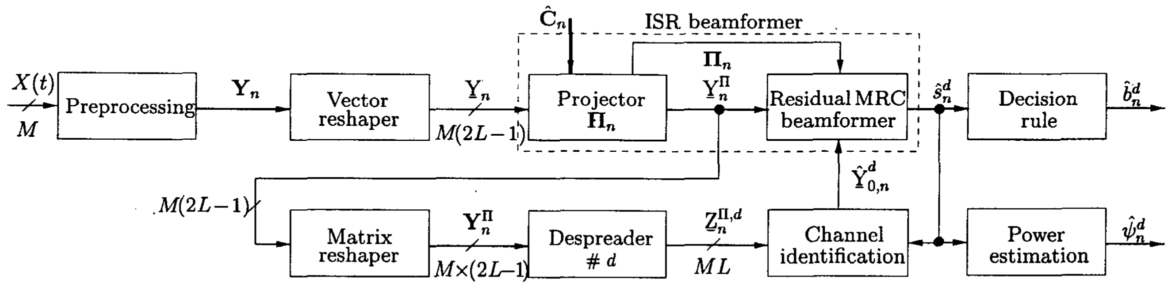

Figure 2: Block diagram of one of the receiver modules (for the desired user) of upgraded multi-user STAR-ISR with the new Π-DFI procedure which incorporates data-projection (Π option) in the decision feedback identification (DFI) process.

and hence suggested the spatio-temporal array-receiver (STAR) [10] as illustrated in Fig. 1. STAR implements coherent MRC combining with the beamformer unit[3]:

$$\hat{s}_n^d = \text{Real}\left\{\mathbf{W}_n^{d^H}\mathbf{Y}_n\right\} = \text{Real}\left\{\frac{\hat{\mathbf{Y}}_{0,n}^{d^H}\mathbf{Y}_n}{\left\|\hat{\mathbf{Y}}_{0,n}^d\right\|^2}\right\}, \qquad (3)$$

and feeds the resulting signal component estimate $\hat{s}_n^d$ to the decision rule unit to compute the bit estimate within a sign ambiguity[4]:

$$\hat{b}_n^d = \text{Sign}\left\{\hat{s}_n^d\right\}. \qquad (4)$$

It also feeds back the signal component estimate $\hat{s}_n^d$ (or $\hat{\psi}_n^d\hat{b}_n^d$) to the channel identification unit to track the channel as follows:

$$\tilde{\mathbf{H}}_{n+1}^d = \hat{\mathbf{H}}_n^d + \mu\left(\mathbf{Z}_n^d - \hat{\mathbf{H}}_n^d\hat{s}_n^d\right)\hat{s}_n^{d^H}. \qquad (5)$$

The above procedure is referred to as decision feedback identification (DFI) [10]. It guarantees channel convergence within a sign ambiguity and hence enables implementation of quasi-coherent detection without a pilot. Note that other operations that estimate the received power $\left(\hat{\psi}_n^d\right)^2$ or estimate the multipath delays from $\tilde{\mathbf{H}}_{n+1}^d$ to reconstruct $\hat{\mathbf{H}}_{n+1}^d$ are detailed in [10].

The high spectrum efficiency of STAR was demonstrated in the single-user (SU) case and proved achievable at a very attractive complexity cost [11]. However, due to near-far situations, the uncorrelated noise assumption there may become untenable and MRC combining may be suboptimal and near-far sensitive. We hence upgraded the above single-user STAR and introduced [6]-[8] a near-far resistant multi-user version referred to as interference subspace rejection (ISR). STAR-ISR constrains the beamformer of the desired user of Eq. (3) to reject the interference subspace estimate $\hat{\mathbf{C}}_n$ in which lies the total interference $\mathbf{I}_n$ in Eq. (1) as follows:

$$\mathbf{\Pi}_n = \mathbf{I}_{M*(2L-1)} - \hat{\mathbf{C}}_n\left(\hat{\mathbf{C}}_n^H\hat{\mathbf{C}}_n\right)^{-1}\hat{\mathbf{C}}_n^H, \qquad (6)$$

$$\mathbf{W}_n^d = \frac{\mathbf{\Pi}_n\hat{\mathbf{Y}}_{0,n}^d}{\hat{\mathbf{Y}}_{0,n}^{d^H}\mathbf{\Pi}_n\hat{\mathbf{Y}}_{0,n}^d}, \qquad (7)$$

where $\mathbf{I}_{M*(2L-1)}$ denotes a $M*(2L-1)\times M*(2L-1)$ identity matrix. In Tab. 1, we show how to form the constraint matrix $\hat{\mathbf{C}}_n$ for different modes, which decompose or regroup interference vectors from different interference subspace characterizations. These modes improve in performance from IC detectors (closer to ISR-TR at the low end) to linear receivers (closer to ISR-H at the high end), and require increasing complexity for implementation (see number of constraints in Tab. 1). For lack of space, a detailed discussion that compares the ISR approach with existing techniques is provided in [6].

Note that the three first of the four decision-feedback (DF) ISR modes (namely TR, R, D and RH) require a delay of a symbol duration to allow estimation of $\hat{b}_{n+1}^i$. Note also that joint (*i.e.*, the desired user is among the interferers) and multi-stage ISR implementations are treated among many other options in [7] while partial ISR is introduced in [9] for enhanced performance.

With the linearly-constrained combing step of Eq. (7), STAR-ISR exploits both space and time diversities as well as the

[3]Note that MRC beamforming in [10] was implemented after despreading (*i.e.*, $\hat{s}_n^d = \text{Real}\{\hat{\mathbf{H}}_n^{d^H}\mathbf{Z}_n^d/M\}$).

[4]The sign ambiguity is simply resolved by differential decoding [10] instead of less efficient differential demodulation.

TR	$\left[\sum_{i=1}^{NI}\hat{\psi}_n^i \sum_{k=-1}^{+1}\sum_{f=1}^{N_f}\hat{b}^i_{n+k}\hat{\zeta}^i_{f,n}\hat{\mathbf{Y}}^{i,f}_{k,n}\right]$ $\Rightarrow N_c = 1$
R	$\left[\ldots,\sum_{k=-1}^{+1}\sum_{f=1}^{N_f}\hat{b}^i_{n+k}\hat{\zeta}^i_{f,n}\hat{\mathbf{Y}}^{i,f}_{k,n},\ldots\right]$ $\Rightarrow N_c = NI$
D	$\left[\ldots,\sum_{k=-1}^{+1}\hat{b}^i_{n+k}\hat{\mathbf{Y}}^{i,1}_{k,n},\ldots,\sum_{k=-1}^{+1}\hat{b}^i_{n+k}\hat{\mathbf{Y}}^{i,N_f}_{k,n},\ldots\right]$ $\Rightarrow N_c = N_f NI$
H	$\left[\ldots,\sum_{f=1}^{N_f}\hat{\zeta}^i_{f,n}\hat{\mathbf{Y}}^{i,f}_{-1,n},\sum_{f=1}^{N_f}\hat{\zeta}^i_{f,n}\hat{\mathbf{Y}}^{i,f}_{0,n},\sum_{f=1}^{N_f}\hat{\zeta}^i_{f,n}\hat{\mathbf{Y}}^{i,f}_{+1,n},\ldots\right]$ $\Rightarrow N_c = 3NI$
RH	$\left[\ldots,\sum_{k=-1}^{0}\hat{b}^i_{n+k}\hat{\mathbf{Y}}^i_{k,n},\hat{\mathbf{Y}}^i_{+1,n},\ldots\right]$ $\Rightarrow N_c = 2NI$

Table 1. Common constraint matrix $\hat{\mathbf{C}}_n$ (the generic columns shown above are actually normalized to 1) and the corresponding number of constraints or columns N_c for each ISR mode (TR: total realization, R: realizations, D: diversities, H: hypotheses, RH: reduced hypotheses).

array-processing capabilities of multiple antennas and carries out simultaneous channel and timing estimation, signal combining and interference rejection. The simplest ISR-TR mode readily outperforms IC methods while it requires the same order of complexity [6]-[8].

III. Single-User Channel Identification

So far, channel identification benefited from ISR only as a result of the feedback of a cleaned signal component estimate $\hat{s}_n^d$ after ISR combining in Eq. (3) using the new combiner of Eq. (7). In this contribution, we also exploit the advantages of ISR in the decision feedback identification (DFI) procedure of Eq. (5) by cleaning as well the despread observation vector $\mathbf{Z}_n^d$ from the perturbing despread interference $\mathbf{I}^d_{\mathrm{PCM},n}$. To do so, we define a new observation vector resulting from the projection of the observation vector $\mathbf{Y}_n$ with $\mathbf{\Pi}_n$ of Eq. (6) as follows:

$$\begin{aligned}\mathbf{Y}_n^{\Pi} &= \mathbf{\Pi}_n\mathbf{Y}_n \\ &\simeq \left(\mathbf{\Pi}_n\mathbf{Y}^d_{0,n}\right)s_n^d + \left(\mathbf{\Pi}_n\mathbf{N}_n\right) \\ &= s_n^d\mathbf{Y}^{\Pi,d}_{0,n} + \mathbf{N}_n^{\Pi,d}\,. \end{aligned} \quad (8)$$

The new observation vector $\mathbf{Y}_n^{\Pi}$ is almost interference-free and contains a projected version of the channel vector (very often we have $\mathbf{Y}^{\Pi,d}_{0,n} \simeq \mathbf{Y}^d_{0,n}$, otherwise we can form an oblique projection which guarantees $\mathbf{Y}^{\Pi,d}_{0,n} = \mathbf{Y}^d_{0,n}$). By despreading $\mathbf{Y}_n^{\Pi}$ with the spreading sequence of the desired user, we obtain an almost interference-free projected despread observation vector:

$$\mathbf{Z}_n^{\Pi,d} \simeq s_n^d\mathbf{H}_n^d + \mathbf{N}^{\Pi,d}_{\mathrm{PCM},n}\,. \quad (9)$$

We hence modify the ISR and DFI steps of Eqs. (7), (3) and (5) as follows (see Fig. 2):

$$\mathbf{W}_n^d = \frac{\hat{\mathbf{Y}}^{\Pi,d}_{0,n}}{\left\|\hat{\mathbf{Y}}^{\Pi,d}_{0,n}\right\|^2} \equiv \frac{\hat{\mathbf{Y}}^{d}_{0,n}}{\hat{\mathbf{Y}}^{d\,H}_{0,n}\mathbf{\Pi}_n\hat{\mathbf{Y}}^{d}_{0,n}}\,, \quad (10)$$

$$\hat{s}_n^d = \mathrm{Real}\left\{\mathbf{W}_n^{d\,H}\mathbf{Y}_n^{\Pi}\right\}\,, \quad (11)$$

$$\hat{\mathbf{H}}^d_{n+1} = \hat{\mathbf{H}}^d_n + \mu\left(\mathbf{Z}_n^{\Pi,d} - \hat{\mathbf{H}}_n^d\hat{s}_n^d\right)\hat{s}_n^d\,. \quad (12)$$

Note the equivalence between the two expressions of the residual MRC beamformer after projection in Eq. (10) due to the nilpotent property of the projection. In more adverse near-far situations, the new scheme, referred to as Π-DFI, allows more reliable channel identification than simple DFI and hence increases the near-far resistance of STAR-ISR.

Likewise in [3]-[5], STAR-ISR identifies the channels using subspace tracking. However, in contrast to these techniques which implement joint estimation of all user-channels, the DFI procedure addresses channel identification with a simple single-user approach and tracks instead the principal eigenvector in each despread observation space. Previously, residual MAI interference could "limit" the near-far resistance of channel identification and STAR-ISR [6,[7]. The new Π-DFI scheme exploits almost interference-free despread vectors and hence renders STAR-ISR extremely near-far resistant.

IV. Simulation Results

We illustrate in Fig. 3 the performance gain of the new Π-DFI procedure with STAR-ISR in the H mode (see Tab. 1) on the downlink (see figure caption). We consider $M = 1$ antenna and $P = 3$ paths with relative powers of (0, -6, -10) dB. The desired data is DBPSK modulated with processing gain L=128 and transmitted in parallel with DBPSK signal with processing gain L=8 which acts as the interferer due to selective fading. The difference in transmission rates[5] results in a power disparity of 12 dB which may be further increased due to the differences in distance of the target and interfering mobiles from the base station. The interfering user actually shows an additional near-far ratio of (a): -∞ dB (*i.e.*, no interference), (b): 0 dB, (c): 3 dB, and (d): 6 dB. Other parameters of the simulation setup (Doppler, delay spread and drift, etc...) can be found in [6]-[8].

Fig. 3-a shows that ISR-H experiences little noise enhancement and hence both DFI/ISR and Π-DFI/ISR perform equally and nearly as well as DFI/MRC in the absence of interference. With a total interference near-far ratio increasing from +12 dB, to +15 dB, then to +18 dB in Figs. 3-b to 3-d, respectively, DFI/ISR shows an increasing SNR gain over simple MRC; however it sees its performance degrade compared to the SU bound (SUB). On the other hand, the new Π-DFI/ISR shows extremely strong near-far resistance and a negligible performance degradation compared to the SUB. Current evaluations suggest similar advantages of the proposed ISR-based SU channel identification approach using other ISR modes. We will report on these results in the near future.

[5]The ISR formulation assumed equal-rate transmission for simplicity. The low-rate user actually nulls the high-rate interference as if coming from 16 users and hence requires $N_c = 16 \times 3$ constraints in a $2L - 1 = 255$ space. Noise enhancement is small in this case [7]. New options [7] keep it small even with additional nulled interferers.

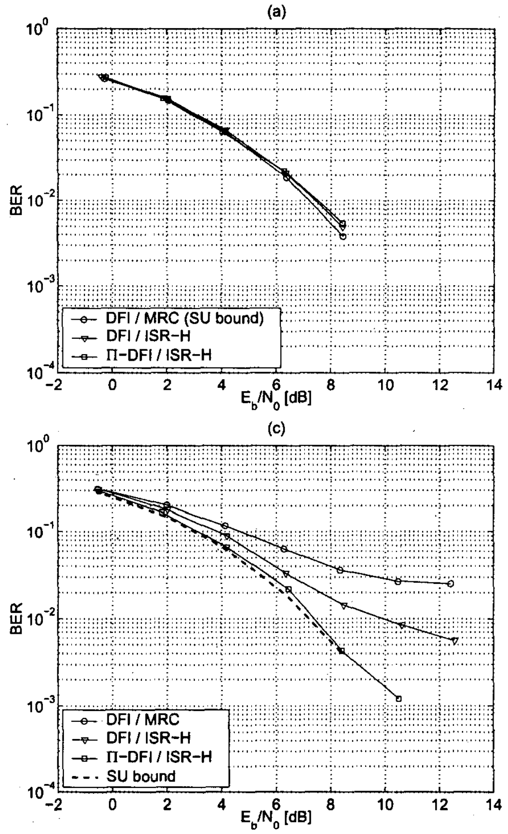

Figure 3: BER vs. E_b/N_0 for STAR with DFI/MRC, DFI/ISR-H, and Π-DFI/ISR-H on the downlink in the presence of an interferer with a total near-far ratio of (a): $-\infty$ dB (*i.e.*, no interference), (b): +12 dB, (c): +15 dB, and (d): +18 dB.

V. Conclusions

In this contribution, we exploited the data-projection step implemented in the multi-user version of STAR, STAR-ISR, to enhance its channel identification. The new version is significantly more robust to near-far power variations than the previous formulation. Its performance is close to the single-user bound even for very high near-far ratios. This improved near-far resistance potentially translates into considerable gains in spectrum efficiency, throughput and peak rate achievable on the downlink of wideband CDMA systems. Similar results are expected on the uplink but have not yet been quantified.

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