HYBRID INTERFERENCE SUBSPACE REJECTION FOR MULTI-RATE CDMA WITH IMPROVED PERFORMANCE/COMPLEXITY TRADEOFF

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ABSTRACT

Interference subspace rejection (ISR) offers a wide range of canonic suppression modes that range in performance and complexity between interference cancellers and linear receivers. In this paper, we propose a hybrid ISR scheme that, instead of suppressing all users with the same canonic ISR mode, splits them into several groups based on their data-rates before applying different canonic ISR modes for their nulling. The resulting receiver provides a much better performance/complexity tradeoff. Simulations suggest that a hybrid of the two simplest canonic ISR modes performs almost as well as the more complex mode with 30 to 60% less complexity, while it outperforms the simpler of the two by several dB gains with minimal increase in complexity.

1. INTRODUCTION

In order to support the simultaneous transmission of diverse information sources such as voice, video or data in future cellular communication systems, several multi-rate access schemes have been proposed such as multi-code, variable spreading factor or different modulation format. In such mixed-rate traffic scenarios, the conventional receiver fails to demodulate transmissions from the weak low-rate users. It is therefore desirable to use more sophisticated multi-user receivers with better near/far resistance.

So far, several multi-user receivers originally proposed for single-rate transmission have been investigated for multi-rate CDMA systems, including the linear and non-linear multi-user detectors [1]-[7]. Most of these receivers assume multi-code and/or variable spreading factor multi-rate schemes. Only the work on successive interference cancellation (SIC) [4] and more recently the partial PIC receiver in [8] consider the multi-modulation scheme. An alternative multiuser detection technique, denoted interference subspace rejection (ISR), has been proposed for single-rate DS-CDMA [9]. This technique offers different detection modes (referred to as canonic in the following) that range in performance and complexity between IC detectors and linear receivers. Each canonic mode characterizes the interference vector by a different set of null constraints - their number increasing for modes with higher performance and complexity - and accordingly suppresses it. For example, the TR (total realizations) mode nulls the total interference vector and hence requires accurate estimation of all the channel and data parameters of the *NI* interferers. The R (realizations) mode nulls the signal vector of each interferer and hence becomes robust to power estimation errors. The H (hypotheses) mode nulls the signal vector from each interfering symbol of each interferer and hence introduces robustness to symbol data estimation errors.

In multi-rate transmissions, low-rate users require increased protection from the strong interference of high-rate users. Unfortunately the simplest canonic mode is unable to provide adequate protection and a potential upgrade to more robust modes will note only increase the complexity but also results in more severe noise enhancement. Indeed, even though higher complexity modes are able to effectively suppress interference despite the estimation errors, their performance suffers from a problem known as noise enhancement. By exploiting, the performance-complexity tradeoffs between the different ISR canonic modes, we propose a modified ISR scheme, called hybrid ISR for multi-rate transmissions with mixed spreading factors and/or modulations (as well as multi-code). Instead of detecting all active users targeted for suppression with the same canonic ISR mode, hybrid ISR splits them into several groups based on their data rate using the new block data structure, then applies different canonic ISR modes for their nulling, the number of nulling constraints being larger for groups with higher transmission rates. To do so, we derive a data block processing structure well suited to multi-rate data traffic. This data decomposition enables implementation of a new flexible multi-user receiver that simultaneously supports multi-code, variable spreading factor and different modulation format. Note that, in previous work [9], we have proposed a multiuser detection technique for the mixed-rate scenario referred to as Group/Hybrid detection. This technique constructs two interference subspaces (inter-group and intra-

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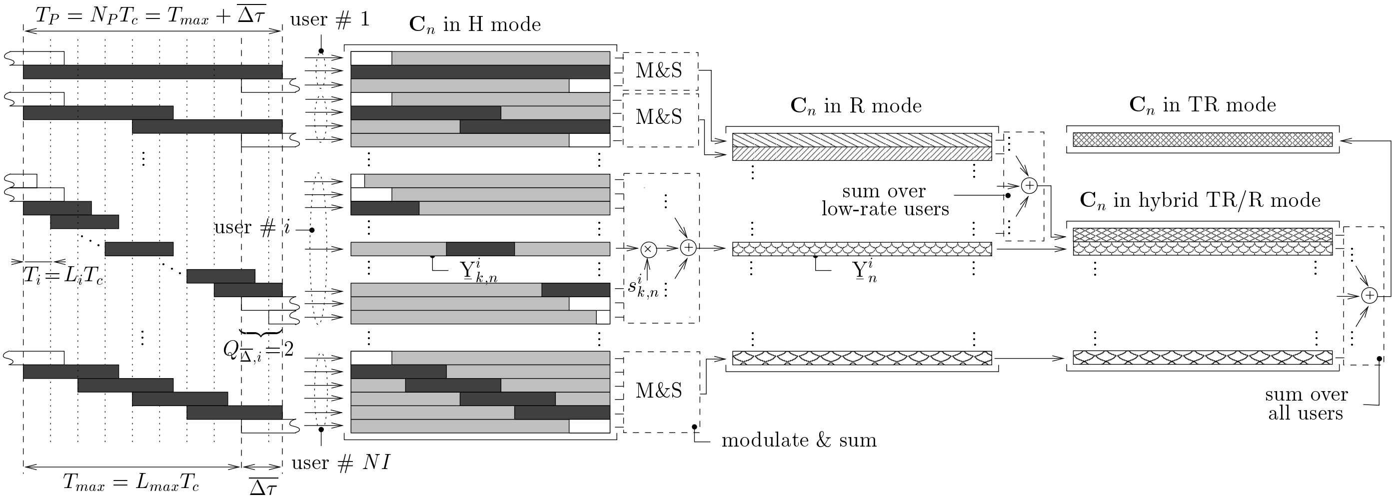

Fig. 1. Signal structure of the data block and construction of the null constraints of $\mathbf{C}_n$ for the canonic ISR modes (H, R and TR) and the hybrid TR/R mode: Desired symbols to be extracted are in dark grey, edge symbols from adjacent frames are in white, zero elements are in light grey. We construct $\mathbf{C}_n^{d,k}$ by excluding $s^d_{k,n}\underline{Y}^d_{k,n}$ from the various summations in the TR, R and TR/R modes.

group) and then successively suppresses the interference generated from each of them. In this paper, in contrast to the former approach, we null a combined and unique interference subspace in a single processing step and hence significantly reduce the computational complexity. We simultaneously reject the interference from the high-rate and low-rate users with different canonic ISR modes. This new approach offers a wider range of hybrid suppression modes with improved complexity/performance tradeoffs.

Simulations of multi-rate transmission with a variable number of BPSK users at 32 Kb/s and 8PSK users at 768 Kb/s suggest that a hybrid of the two simplest canonic ISR modes consistently provides a much better performance and complexity tradeoff. Indeed, it performs almost the same as the more complex mode with 30 to 60% less complexity, while it outperforms the simpler mode by 2 to 5 dB and 1 to 3 dB in required SNR for BPSK and 8PSK users, respectively. Hybrid ISR hence offers a promising path for enabling spectrum-efficient multi-rate transmission with little increase in computational cost.

2. NEW BLOCK DATA MODEL FOR MULTI-RATE CDMA

We consider CDMA uplink transmissions to M receiving antennas at the base station over a multipath Rayleigh-fading channel with number of paths P. The system consists of U active users that transmit data with different spreading factors and different modulation formats (extension to the multi-code scheme is *ad hoc*). The data $b^u_n \in C_{\mathcal{M}_u}$ for user with assigned index u is $\mathcal{M}_u$-PSK modulated at rate $1/T_u$, where T_u is the symbol duration and $C_{\mathcal{M}_u}=\{\ldots, e^{\frac{j2\pi m}{\mathcal{M}_u}}, \ldots\}$, $m \in \{0, \ldots, \mathcal{M}_u - 1\}$. The data sequence is then spread by a long spreading code $c^u(t)$. The spreading factor L_u is defined as the ratio of the symbol duration T_u and the chip duration T_c. We convert the variable spreading factor scenario into a single spreading factor scenario where each high data-rate user is equivalent to Q_u virtual low data-rate users. The spreading sequence for the kth virtual user (kth symbol) of the uth user is

$$c^{u,k}(t) = \begin{cases} c^u(t) & \text{for} \quad (k-1)T_u \le t < kT_u, \\ 0 & \text{else} \quad . \end{cases} \tag{1}$$

We consider a multipath Rayleigh fading channel with P resolvable paths and delay spread $\Delta\tau$. We assume that the channel parameters (*i.e.*, delays, power, fade magnitudes and phases) vary slowly and neglect their variation over the largest symbol duration. This allows for data processing in successive blocks of Q_u symbols.

Regardless of the spreading factor or modulation, the receiver implements down conversion, matched-pulse filtering and chip-rate sampling followed by framing the observation into overlapping blocks of constant length of N_P chips. As shown in Fig. 1, the resulting processing block duration $T_P = N_P T_c$ is equal to $T_{max} + \overline{\Delta\tau}$. The processing period $T_{max} = Q_u T_u$, which is also equal to the maximum spreading factor L_{max} times T_c, contains integer numbers of symbols Q_u targeted for detection in each block for user u. The frame overlap $\overline{\Delta\tau} < T_{max}$, which is larger then the delay spread to allow multipath tracking [10], comprises $Q_{\overline{\Delta},u} = \lceil \overline{\Delta\tau}/T_u \rceil$ symbols for user u. Hence we obtain the $M \times N_P$ matched-filter observation matrix [9]:

$$\mathbf{Y}_n = \sum_{u=1}^{U} \psi^u_n \mathbf{Y}^u_n + \mathbf{N}^{th}_n, \tag{2}$$

where each user u contributes its user-observation matrix $\mathbf{Y}_n^u$ scaled by its total received power $(\psi_n^u)^2$ and where the base-band preprocessed thermal noise contributes $\mathbf{N}_n^{th}$. Note that we consider a closed-loop power controlled system to ensure an equal received power for all users having the same modulation/spreading factor combination. In the following, we assume that the base station targets *NI* interfering users (presumably with high data-rate and/or strong power) for joint suppression among the U active users (*e.g.*, all in-cell users). Using Eq. (2) and defining a vector $\underline{V}$ as matrix $\mathbf{V}$ reshaped columwise, we can rewrite the matched-filtering observation matrix for the desired user assigned index $d \in \{1, \ldots NI\}$ with respect to its kth symbol targeted for detection for $k = 0, \ldots, Q_d - 1$ in the following vector form [9]:

$$\underline{Y}_n = \sum_{i=1}^{NI} \sum_{k=-Q_{\overline{\Delta},i}}^{Q_i+Q_{\overline{\Delta},i}-1} s_n^{i,k} \underline{Y}_{k,n}^i + \underline{N}_n, \quad (3)$$

$$= \underbrace{s_n^{d,k} \underline{Y}_{k,n}^d}_{\text{desired signal}} + \underbrace{\sum_{\substack{i=1 \\ i\neq d}}^{NI} \psi_n^i \underline{Y}_n^i}_{\underline{I}_{\text{MAI},n}^d} + \underbrace{\sum_{\substack{k'=-Q_{\overline{\Delta},d} \\ k'\neq k}}^{Q_d+Q_{\overline{\Delta},d}-1} s_n^{d,k'} \underline{Y}_{k',n}^d}_{\underline{I}_{\text{ISI},n}^{d,k}} + \underline{N}_n, \quad (4)$$

$$= s_n^{d,k} \underline{Y}_{k,n}^d + \underline{I}_n^{d,k} + \underline{N}_n, \quad (5)$$

where $s_n^{d,k} = \psi_n^d b_{k,n}^d$ is the kth signal component and $\underline{Y}_{k,n}^d$ is the canonic user-observation vector due to the k-th symbol. $\underline{I}_{\text{MAI},n}^d$ and $\underline{I}_{\text{ISI},n}^{d,k}$ are the multiple-access interference and the inter-symbol interference to be suppressed with the respect to the kth symbol of user d. The noise vector $\underline{N}_n$ comprises the preprocessed thermal noise and the rest of the active users. Note that in Eq. (3) the summation over the symbol index k ranges from $-Q_{\overline{\Delta},i}$ to $Q_i + Q_{\overline{\Delta},i} - 1$, instead of 1 to Q_i as calculated by the low-rate decorrelator (LDR) [2]. Due asynchronism and multipath propagation, the data block includes all the desired symbols to be extracted and the contribution from adjacent blocks, namely $Q_{\overline{\Delta},i}$ past symbols and $Q_{\overline{\Delta},i}$ future symbols. The resulting decomposition permits the proposed multi-user receiver to combat both ISI and MAI and to efficiently detect multi-rate signals as explained in the next section.

3. HYBRID ISR FOR MULTI-RATE CDMA

In the general case, the total interference $\underline{I}_n^{d,k} = \underline{I}_{\text{MAI},n}^d + \underline{I}_{\text{ISI},n}^{d,k}$ is an unknown random vector which lies in an interference subspace spanned by a user-symbol-specific constraint matrix $\mathbf{C}_n^{d,k}$ with dimension that depends on the number of interference parameters estimated separately [9]. A number of alternative modes are available to construct the constraint matrix $\mathbf{C}_n^{d,k}$ [9].

The canonic implementation modes offered by ISR (TR, R and H) range in performance from that of interference cancelling detectors to that of linear multi-user detectors. Yet the TR mode, which outperforms IC receivers with the same complexity [9], stands out as the least complex and the more practical ISR mode for implementation. Potential upgrade to the R mode can offer a relatively large performance gain (as illustrated later by simulations); however, this also requires a more than twofold increase in complexity. The H mode, which performs the same as linear ZF and MMSE receivers with less complexity, offers even more computationally-expensive performance gains. In Tab. 1, we provide an estimation of the complexity for different items of ISR. The complexity of the ISR technique is mainly determined by the number of users to be cancelled NI, and the total number of constraints N_c imposed by the rejection mode. Hence, for a given multiuser system, reducing N_c will reduce the complexity of the detection technique.

In multi-rate transmissions, however, low-rate users require increased protection from the strong interference of high-rate users. Unfortunately the simplest TR mode (*i.e.*, $N_c = 1$) is unable to provide adequate protection. Hybrid ISR strives to provide a wider range of improved performance/complexity tradeoffs in multi-rate traffic. Instead of detecting all active users targeted for suppression with the same canonic ISR mode, it splits them into several groups based on their data rate, then applies different canonic ISR modes for their nulling, the number of nulling constraints N_c being larger for groups with higher transmission rates.

Consider, for example, the combination of the TR and R modes in hybrid ISR[1]. The NI users targeted for suppression can be split into two groups, a larger number of N_{TR} users with low data rate and a smaller number of N_R users with high data rate. The hybrid TR/R mode will then null the low and high data-rate groups with the canonic TR and R modes, respectively, with only $N_c = N_R + 1 \leq NI = N_R + N_{TR}$ constraints in total. The hybrid constraint matrix $\widehat{\mathbf{C}}_n^{d,k}$ is formed by subtracting the contribution of the k-th symbol of the desired user from the constraint matrix $\widehat{\mathbf{C}}_n$ illustrated in Fig. 1:

$$\widehat{\mathbf{C}}_n = \left[\sum_{\substack{i=1 \\ i\neq d}}^{N_{TR}} \hat{\psi}_n^i \hat{\underline{Y}}_n^i \ , \left\{ \ldots, \hat{\underline{Y}}_n^i, \ldots \right\}_{i=N_{TR}+1}^{NI=N_{TR}+N_R} \right]. \quad (6)$$

Provided that an estimate of the constraint matrix $\widehat{\mathbf{C}}_n^{d,k}$ is made available at the receiver, we can eliminate the total interference and yet achieve distortionless response to the desired signal by imposing the following constraints to the

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[1] Extension of hybrid ISR to more than two transmission rates or groups and to other combinations of the canonic modes is *ad hoc*.

Complexity items for ISR	
Calculation of $\underline{Y}_{k,n}^{d}$	$MN_PL_{\overline{\Delta}}NI$
Reconstruction of $\mathbf{C}_n^{d,k}$	MN_PNI
Projection $\mathbf{\Pi}_n^{d,k}$	$4MN_cN_PNI + \overline{\delta}(N_c)\left[2M(N_c^2/Q_d)N_PNI + (N_c^3/Q_d + N_c^2)NI\right]$
Estimation of $s_n^{d,k}$	$6MN_PNI$
Channel identification and Multipath tracking	negligible

Table 1. Estimated complexity items for ISR. $\overline{\delta}(N_c) = 0$ if $N_c = 1$, and 1 otherwise. $L_{\overline{\Delta}} = \lceil \overline{\Delta\tau}/T_c \rceil$.

combiner:

$$\left\{ \begin{array}{ll} \underline{W}_n^{d,k^H} \underline{\widehat{Y}}_{k,n}^{d} & = 1, \\ \underline{W}_n^{d,k^H} \widehat{\mathbf{C}}_n^{d,k} & = 0. \end{array} \right. \tag{7}$$

The first constraint guarantees a distortionless response to the desired signal while the second directs a null to the total interference realization and thereby cancels it. Exploiting the general framework developed in [9], the solution to the specific optimization problem in Eq. (7) is the hybrid ISR combiner $\underline{W}_n^{d,k}$ given as follows:

$$\mathbf{Q}_n = \left(\widehat{\mathbf{C}}_n^H \widehat{\mathbf{C}}_n\right)^{-1}, \tag{8}$$

$$\mathbf{\Pi}_n^{d,k} = \mathbf{I}_{N_T} - \widehat{\mathbf{C}}_n \mathbf{Q}_n \widehat{\mathbf{C}}_n^{d,kH}, \tag{9}$$

$$\underline{W}_n^{d,k} = \frac{\mathbf{\Pi}_n^{d,k} \underline{\hat{Y}}_{k,n}^{d}}{\underline{\hat{Y}}_{k,n}^{d^H} \mathbf{\Pi}_n^{d,k} \underline{\hat{Y}}_{k,n}^{d}}, \tag{10}$$

where $N_T = M \times N_P$ is the total space dimension and $\mathbf{I}_{N_T}$ denotes an $N_T \times N_T$ identity matrix. We extract the kth signal component of the dth user as:

$$\hat{s}_n^{d,k} = \underline{W}_n^{d,k^H} \underline{Y}_n \,. \tag{11}$$

Such a hybrid multi-user detector adapts efficiently to multi-rate transmissions with mixed spreading factors and/or modulations (as well as multi-code). It offers a wider range of suppression modes with improved complexity/performance tradeoffs, as illustrated by simulations in the next section.

4. LINK-LEVEL PERFORMANCE ANALYSIS

We consider the uplink of a WCDMA base-station with $M = 2$ antennas operating at a chip rate of 3.840 Mcps and a carrier frequency of 1.9 GHz. The Rayleigh fading channel is frequency selective with 3 equal-power paths and a Doppler shift of 8Hz (*i.e.*, speed of 5 Km/h). We assume a frequency offset $\Delta f = 200$Hz (*i.e.*, about 0.1ppm) and a linear delay drift of 0.07 ppm for each path. We implement closed-loop power control operating at 1600 Hz and adjusting the power in steps of ±0.5 dB. An error rate on the power control bit of 5% and a feedback delay of 0.625 ms are simulated. All the channel parameters, varying in time, are estimated by the spatio-temporal array-receiver (STAR) [10]. The multi-rate environment is simulated with N_{TR} BPSK users and N_R 8PSK users with spreading factors of $L = 128$ and $L = 16$, corresponding to transmission rates of 32 Kb/s and 768 Kb/s, respectively. The number of high data-rate users N_R ($N_R < N_{TR}$ practically) is varied while keeping constant the total number of users to $NI = N_R + N_{TR} = 11$.

In Fig. 2-(a)(b) we plot the required SNR[2] of both BPSK and 8PSK users versus N_R for the TR, R and hybrid TR/R modes. Fig. 2-(a)(b) shows that the TR/R hybrid performs better than TR and slightly worse than R in protecting low-rate and high-rate users. As the throughput of the system is increased with N_R, the performance of ISR-TR quickly degrades, whereas the performance of TR/R remains stable and close to that of ISR-R. In Fig. 2-(c), we provide the complexity per user in Mops (Million operation per second) versus N_R of the canonic modes TR and R and the hybrid mode TR/R. Since the complexity is dominated by the number of constraints N_c, the complexity of the TR ($N_c = 1$) and R ($N_c = NI$) remain constant while the complexity of hybrid ISR ($N_c = N_R + 1$) increases with the number of high-rate users.

The hybrid ISR TR/R offers a significantly improved performance/complexity tradeoff. Indeed, with 5 8PSK users and 6 BPSK users in each cell, the hybrid ISR mode outperforms the simplest ISR mode (TR) by about 5 and 3 dB gains for the low and high data-rate users, respectively. In this high throughput system, the hybrid TR/R mode performs almost as well as the R mode but with 30% less complexity than the R mode. As the number of high data-rate users decreases, the orders of complexity of both the TR mode and the hybrid TR/R mode become closer. With 1 8PSK and 10 BPSK users hybrid ISR provides an SNR gain of 2 dB for low-rate users and 1 dB for high-rate users. This gain in performance comes with almost no increase in complexity compared to the TR mode (60% less complexity than the R mode). For the in-between BPSK/8PSK user dis-

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[2] Measured at a BER and an SER of 5 and 7%, respectively, in order to achieve a QoS of 10^{-5} after FEC decoding.

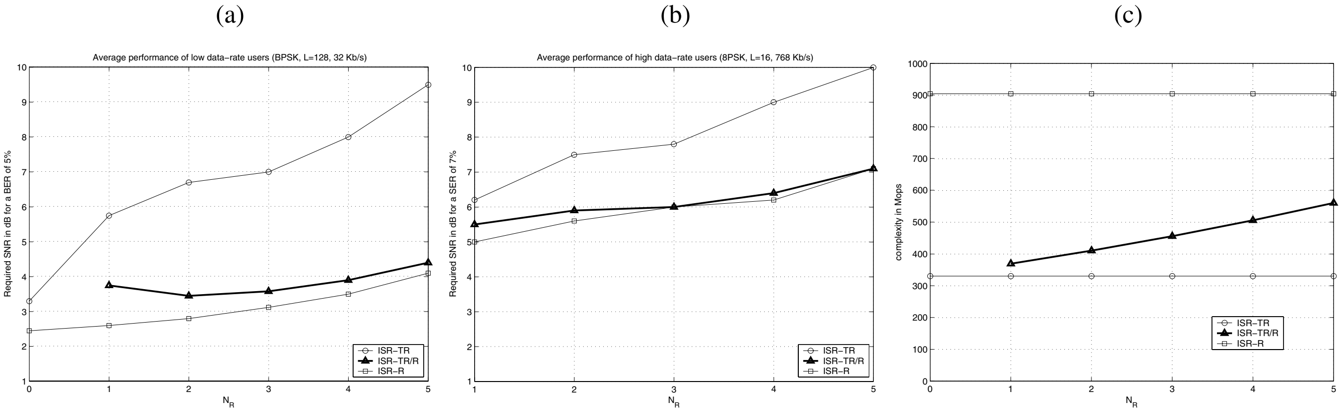

Fig. 2. (a): required SNR in dB for BPSK, (b): required SNR in dB for 8PSK, and (c): required complexity per user, for ISR-TR, ISR-R and hybrid ISR-TR/R versus the number of high data-rate users N_R.

tributions, TR/R performs almost as well as the more complex mode with 30 to 50% less complexity, while it outperforms the least complex of the two by 3 to 4 dB and 1.5 to 2.5 dB in required SNR for BPSK and 8PSK users, respectively.

5. CONCLUSIONS

In this contribution, we proposed a new hybrid ISR scheme that offers a wider range of improved performance/complexity tradeoffs for multi-rate transmissions. Instead of suppressing users with the same canonic ISR mode, the proposed hybrid ISR scheme splits them into several groups based on their data-rates before applying different canonic ISR modes for their nulling, the number of nulling constraints being larger for groups with higher transmission rates. Simulations suggest that a hybrid of the two simplest canonic ISR modes outperforms the simpler of the two with minimal increase in complexity, while it performs almost as well as the more complex mode with 30 to 60% less complexity.

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