Performance Analysis of Hybrid Interference Subspace Rejection in Multi-Rate CDMA

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Abstract—An efficient multiuser detection technique, denoted hybrid interference subspace rejection (ISR), has been recently developed for multi-rate CDMA transmissions with mixed spreading factors and/or modulations (as well as multi-code). In this paper, we derive a link/system-level performance analysis of hybrid ISR based on the Gaussian assumption (GA) and validate it by simulations. In addition, we design an efficient strategy for hybrid ISR, well adapted to multi-rate CDMA transmission, that strives to maximize throughput while containing the extra computational cost.

I. INTRODUCTION

The “third-generation and beyond” wireless communication systems must be able to offer wireless transport for a variety of information sources with inherently different data rates, including data, image, and voice. In such mixed-rate traffic scenarios, the conventional receiver fails to demodulate transmissions from the weak low-rate users. It is therefore imperative to develop effective multi-rate code division multiple access (CDMA) multiuser detectors.

An efficient multiuser detection technique, denoted hybrid interference subspace rejection (ISR), first proposed for single-rate DS-CDMA [1], has been recently developed for multi-rate transmissions with mixed spreading factors and/or modulations (as well as multi-code) [2]. Indeed, single-rate ISR offers different modes (referred to as canonic in the following). Each canonic mode characterizes the interference vector in a different way and accordingly suppresses it. 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 is not sensitive to power estimation errors. The D (diversities) mode nulls the signal vector from each interfering finger and hence gains additional robustness to channel estimation errors. The H (hypothesizes) 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, however, 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. Hybrid ISR exploits the performance-complexity tradeoffs between the different ISR canonic modes. 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, then applies different canonic ISR modes for their nulling, the number of nulling constraints being larger for groups with higher transmission rates. The performance of hybrid ISR was evaluated through simulations using very realistic link-level simulation setups [2]. Simulation results confirm the improved complexity/performance tradeoffs provided by hybrid ISR.

In this paper, we develop a theoretical link/system-level performance analysis of hybrid ISR based on the Gaussian assumption (GA), under the condition of realistic wireless transmission that takes into account frequency mismatch, imperfect power control and channel identification errors. We validate the Gaussian approximation (GA) of the interference by comparison with simulation results. In addition, we design an efficient strategy for hybrid ISR, well adapted to multi-rate CDMA transmission, that strives to maximize throughput while containing the extra computational cost.

II. MULTI-RATE CDMA DATA MODEL

We consider the uplink of an asynchronous multi-cellular multi-rate CDMA system where each base station is equipped with M receiving antennas. The system consists of U in-cell active users that transmit data with different spreading factors and different modulation formats (extension to the multi-code scheme is ad hoc). The data \\( u^m \in C_{M_u} \) for a user assigned the index \( u \) is \( M_u \)-PSK modulated and differentially encoded at rate \( 1/T_u \), where \( T_u \) is the symbol duration and \( C_{M_u} = \{ \ldots , e^{\frac{2\pi i}{M_u}}, \ldots \}, m \in \{0, \ldots, M_u - 1\} \). 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. Regardless of the data-rate, 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. The resulting processing block duration \( T_P = N_P T_c \) is equal to \( T_{max} + \Delta \tau \). 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 \( \Delta \tau \) is larger than the delay spread to allow multipath tracking [5], comprises \( Q_u \Delta \tau = \left[ \frac{\Delta \tau}{T_u} \right] \) symbols for user \( u \). Hence we obtain the \( M \times N_P \) matched-filter observation matrix [1]:

\[
Y_n = \sum_{u=1}^{U} \psi^n_u Y_n^u + N_n^{h},
\]

where each user \( u \) contributes its user-observation matrix \( Y_n^u \) scaled by its total received power \( (\psi^n_u)^2 \) and where the base-band preprocessed thermal noise contributes \( N_n^{h} \). In the following, we assume that the base station targets NI

\[^1\text{We can also use pilot symbols for coherent modulation and detection [6], but that is beyond the scope of this paper.}\]
interfering users (presumably with high data-rate and/or strong power) for joint suppression among the $U$ active users (e.g., all incell users). Using Eq. (1) and defining a vector $\mathbf{\gamma}$ as matrix $\mathbf{V}$ reshaped columnwise, we can rewrite the matched-filtering observation matrix for the desired user assigned index $d \in \{1, \ldots, N\}$ with respect to its $k$th symbol targeted for detection for $k = 0, \ldots, Q - 1$ in the following vector form [1]:

$$
\mathbf{y}_d = \mathbf{s}^d_k \mathbf{I}^d_k + \sum_{i \neq d}^{N} \mathbf{h}_{d,i}^\top \mathbf{\psi}^i + \sum_{i \neq d}^{N} \sum_{k' \neq k}^{Q} \mathbf{s}^d_{k'} \mathbf{I}^d_{k',n} + \mathbf{n}_d \quad (2)
$$

where $s^d_{k} = \mathbf{h}_{d,k}$ is the $k$th signal component and $\mathbf{I}^d_{k',n}$ is the canonical user-observation due to the $k'$-th symbol. $\mathbf{I}^d_{k,i,n}$ and $\mathbf{I}^d_{k,i,n}$ are the multiple access interference and the inter-symbol interference to be suppressed with the respect to the $k$th symbol of user $d$. The noise vector $\mathbf{n}_d$ comprises the preprocessed thermal noise and the rest of the active users.

### III. HYBRID ISR PERFORMANCE EVALUATION

This section is dedicated to the performance analysis of hybrid ISR. We exploit the analysis results of ISR recently developed in [3] at the link-level and extend them to hybrid ISR. Additionally, we broaden the scope of the analysis to include frequency mismatch, channel identification errors and imperfect power control [4]. We also provide a simple procedure to evaluate the capacity in terms of number of users per cell and the total system throughput.

#### A. LINK-LEVEL PERFORMANCE ANALYSIS

The signal after hybrid ISR combining is:

$$
\hat{s}_n^d = \frac{\mathbf{w}_d^H \mathbf{y}_d}{\|\mathbf{w}_d\|^2} = \frac{\mathbf{s}^d_k + \delta_{MAI,k,n} + \delta_{ISI,k,n} + \mathbf{w}_d^H \mathbf{n}_d}{\|\mathbf{w}_d\|^2},
$$

where $\delta_{MAI,k,n}^d$ is the residual MAI and $\delta_{ISI,k,n}^d$ is the residual ISI. The hybrid ISR combiner $\mathbf{w}_d^H$ satisfies:

$$
\begin{align*}
\mathbf{w}_d^H \mathbf{s}^d = 1, \\
\mathbf{w}_d^H \mathbf{s}^d = 0.
\end{align*}
$$

These constraints allow to derive the variance of the interference rejection residuals. The residual interferences are approximated as a Gaussian distributed random variable with zero mean. Only their variance needs to be evaluated. We define $E[||\mathbf{w}_d^H\mathbf{y}_d||^2] = \pi$ as a measure of the enhancement of the white noise compared to MRC ($\pi = 1$ for MRC) [3]. We exploit the expression of the variance of the channel identification error in [6] and the variance of the power control error in [4]. Let $\bar{\mathbf{s}}_d^2 = E[\mathbf{y}_d^2]$ be the average power of the desired user and $\bar{\mathbf{\psi}}_i^2$ be the average interference power of user $i$ which varies with the spreading factor and modulation format. The variances of the residual MAI interferences can be written as:

$$
\text{Var} [\delta_{MAI,k,n}^d] = \frac{1}{L_d} \sum_{i \neq d}^{N} I(\psi_i^2, m_i).
$$

The interference term $I(\psi_i^2, m_i)$ from user $i$ depends on the power of the interferer as well as the canonical suppression mode $m_i$ applied to this user:

$$
\begin{align*}
\psi_i^2, m_i \quad &\psi_i^2, m_i \quad (1 + \rho_d(f_d + \Delta f))(1 + \rho_s(f_d + \Delta f)) \\
&- \psi_i^2, m_i \quad (f_d + \Delta f), \\
&\psi_i^2, m_i \quad (1 + \rho_d(f_d) - \rho_d(f_d))^2, \\
&\psi_i^2, m_i \quad (1 + \rho_d(f_d) - 1), \\
&0
\end{align*}
$$

where $f_D$ and $\Delta f$ are the maximum Doppler frequency and the carrier frequency offset, respectively. The detailed expressions of $\rho_d(f)$, $\rho_s$, $\rho_R^M(f)$, $\rho_R^I(f)$ and $\rho_D$ are derived for a Rayleigh fading channel with $P$ equal-power paths to yield:

$$
\begin{align*}
\rho_d(f) &= \frac{P_d(\pi \bar{\mathbf{s}}^d_\text{MAI} + \text{Var}\mathbf{\psi}_i^d + \text{Var}\mathbf{\psi}_i^d)}{2(1 - \cos(2\pi f_\text{d} T))}, \\
\rho_s(f) &= \frac{4\pi^2 P_d \mathbf{n}_d^2}{f_\text{d}^2}, \\
\rho_R^M(f) &= \rho_R^M(f) + \rho_R^I(f) = \frac{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f))(1 + \rho_d(f)(1 + \rho_d(f))))}{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f))(1 + \rho_d(f)))}, \\
\rho_R^I(f) &= \rho_R^I(f) + \rho_R^I(f) = \frac{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f)(1 + \rho_d(f))))}{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f)(1 + \rho_d(f)))}, \\
\rho_D &= \frac{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f)(1 + \rho_d(f))))}{\mathbf{N}_\text{MP}(1 + \rho_d(f)(1 + \rho_d(f)(1 + \rho_d(f)))},
\end{align*}
$$

where $\rho_d$, $\rho_s$, $\rho_R^M$, $\rho_R^I$ and $\rho_D$ are the channel identification, channel identification, power control, power control and power control error rates, respectively. The channel identification error variance is derivable from the analysis in which we have $\text{Var} \mathbf{s}_n^d + \text{Var} \mathbf{s}_n^d = \pi \mathbf{N}_\text{MP} + \pi \mathbf{N}_\text{MP}$. This is the same as assuming that all the users are detected by simple MRC, and hence the gains due to interference rejection are not taken into account when evaluating the channel identification error. The variances of the residual ISI interferences can be written as:

$$
\text{Var} [\delta_{ISI,k,n}^d] = I(\psi_i^2, m_d)(\pi - 1 + \delta_s)/\pi,
$$

where $\delta_s$ is a measure of the relative impact of the interference generated by the other paths on a given path of the desired user [3]. The SNR of the desired user can be estimated as:

$$
\text{SNR}_\text{ISR} = \frac{\mathbf{M} \bar{\mathbf{s}}^d_d}{\text{Var} \mathbf{s}_n^d + \text{Var} \mathbf{s}_n^d + \pi \mathbf{N}_\text{MP}}
$$
The BER performance of the d-th user’s hybrid ISR receiver is then given as follows:

\[ P_e^d = \Omega(\text{SNR}_{ISR}^d), \]  

where \( \Omega \) represents the single-user bound (SUB), which is classically defined as a conditional Gaussian Q-function over \( \psi_d \) and \( \psi_1 \). When using this classical representation, the average BER is derived by first finding the pdfs of \( \psi_d \) and \( \psi_1 \) and then averaging over those pdfs. Since it is difficult to find a simple expression for the pdfs of \( \psi_d \) and \( \psi_1 \), we may consider an approximative pdf. In this analysis, we choose to simulate \( \Omega \) without imposing any pdf approximation.

The link-level performance analysis leads to a fundamental insight into the hybrid ISR mechanisms. It shows that hybrid ISR performance varies from user to user and depends on a wide variety of factors such as the detection mode, the propagation environment (data, channel, and power control estimation errors), and the strength of the background noise. It also confirms that the number of nulling constraints should be larger for the groups of users that generate higher transmission powers in order to improve the overall performance of the multi-rate system.

### B. System-Level Performance Analysis

Using the link-level performance analysis established earlier, we propose a simple computation procedure to evaluate the capacity in terms of number of users per cell for a specific operating condition and mode assignment. The capacity evaluation procedure provides a classification of the different mode assignments at specific operating conditions. We translate the link-level results into system-level results in terms of total throughput (or spectrum efficiency) under the following four assumptions: 1) All the cells have the same average load of \( C \) users per cell. 2) All the cells have the same multi-rate distribution: The \( C \) users are divided into \( G \) groups, the proportion of users in the group \( g \) is denoted \( r_g \) (i.e. \( \sum_{g=1}^{G} r_g = 1 \)). 3) Within each group \( g \), all users are received with equal power denoted \( \psi_g^0 \) (i.e., perfect PC). 4) The out-cell to in-cell interference ratio \( f \) is set to 0.3 [7]. Given these assumptions in an interference-limited system (noise is low compared to interference), the link-level SNR of the users in the \( g \)-th group (ignoring ISI for simplicity) is:

\[ \text{SNR}_{ISR}^g = \frac{M \psi_g^0}{\sum_{i=1}^{G} Cr_i \psi_i^0} \]

The maximum number of users that can access the system can be hence calculated by the simple procedure illustrated in Tab. I. For a specific operating condition and mode assignment, the capacity evaluation procedure computes the link-level SNR for all groups of users. In a multi-rate system, each group of users has its own required SNR. The quality of service (QoS) constraints on the capacity become:

\[ \forall g \in \{1, \ldots, G\}, \quad \text{SNR}_{ISR}^g \geq \text{SNR}_{req}^g, \]

where \( \text{SNR}_{req}^g \) is the required SNR derived from link-level simulations to meet a BER of 5\% in order to achieve a QoS of 10^{-6} after channel decoding. After initialization, this procedure increments the capacity \( C \), until the \( \text{SNR}_{ISR}^g \) given by Eq. (14) no longer exceeds the required \( \text{SNR}_{req}^g \). C is then reduced to the largest value for which \( \forall g \in \{1, \ldots, G\}, \text{SNR}_{ISR}^g \geq \text{SNR}_{req}^g \). In step 2.2.1, we use the fact that in each group \( g \), all users are received with equal power denoted \( \psi_g^0 \). Hence, the in-cell interference powers before despreading resulting from the C - 1 in-cell users are \( \sum_{i \neq g} Cr_i \psi_i^0 + (Cr_g - 1)\psi_g^0 \). Assuming that the out-cell to in-cell interference ratio is \( f \), the total received interference before despreading is \( \sum_{i \neq g} Cr_i \psi_i^0 + (Cr_g - 1)\psi_g^0 + f \sum_{i=1}^{G} Cr_i \psi_i^0 \). The total interference power is then reduced by the processing gain \( L_g \). In step 2.2.2, we evaluate the symbol error rate \( S_{MRC}^g \) after the MRC stage as follows:

\[ S_{MRC}^g = \Omega(\text{SNR}_{MRC}^g), \]
ISR. We also assume a frequency offset \( \Delta f = 200 \) Hz (i.e., about 0.1 ppm). All users targeted for suppression are split into two groups, a larger number of \( N_1 \) users with low data-rate and a smaller number of \( N_2 \) users with high data-rate. The hybrid TR/R, TR/D, and TR/H modes null the low data-rate groups with the canonic TR mode. The hybrid TR/R, TR/D and TR/H null the high data-rate users with the canonic R, D and H modes, respectively. The multi-rate environment is simulated with \( N_1 = 10 \) BPSK users and \( N_2 = 5 \) 8PSK users with spreading factors of \( L = 128 \) and \( L = 32 \), corresponding to transmission rates of 30 Kb/s and 360 Kb/s, respectively. In Fig. 1-(a)(b), we plot the link-level performance of both BPSK and 8PSK users with the hybrid TR/R, TR/D, and TR/H modes. It is seen that there is in general a good match between analytical (plotted with solid line) and simulation (plotted with circles) results. We notice, however, that the analytical evaluation is less accurate for BPSK users with the TR/H mode because we overestimate the effect of the residual interference on the channel identification error. This approximation is even less accurate with low background noise and high residual interference.

In the following, we compare the performance of the different mode assignments. First, we select the operating conditions (i.e., speed= 100 Km/h, \( \Delta f = 0 \) Hz and data-rate distribution: \( 80\% \) BPSK users and \( 20\% \) 8PSK users with spreading factors of \( L = 128 \) and \( L = 32 \)). Then, we derive the \( SNR_{req} \) from link-level simulations. After that, we translate the link-level results into system-level results using the capacity evaluation procedure introduced in section III-B. Finally, we calculate the number of constraints required by each detection mode. In Fig. 2, we provide the total throughput versus the number of constraints for the different mode assignments. It is seen that some detection modes, plotted with circles, perform worst than less complex modes. Indeed, even though the TR/D, R/D, D and H modes are able to effectively suppress 8PSK interference despite the channel estimation errors, their performance suffers from noise enhancement. The reason is that the noise and residual interference components\(^2\) in the received signal are also being scaled by the combiner. This has been shown to result in greater noise and residual interference power. It is therefore inefficient to apply TR/D, R/D, D or D/H (complex modes) in an environment with accurate channel estimation where they do not significantly outperform modes with lower complexity. However, the R/H and H modes are more robust to the data estimation error, which is larger with high-order modulation (8PSK). Therefore, they outperform TR, TR/R and R despite noise enhancement. Fig. 2 also confirms that hybrid ISR provides a wider range of performance/complexity tradeoffs. Indeed, we can select one of the five detection modes plotted with squares: TR, TR/R, R, R/H and H compared to only three canonic detection modes TR, R and H. In wireless communication systems, there is a practical limit to the number of processing operations that can physically be supported. Taking into consideration the complexity limit, we choose the multi-user detection mode that maximizes the total throughput of the system. This work hence provides an analytical tool for a reliable, quick and efficient design of hybrid multi-user detection strategy in multi-rate CDMA transmission.

REFERENCES


\(^2\)The residual interference is due to wrong tentative data decisions, channel estimation errors and power control errors.