ON JOINT SOURCE-CHANNEL DECODING AND INTERFERENCE CANCELLATION IN CDMA-BASED LARGE-SCALE WIRELESS SENSOR NETWORKS

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ABSTRACT

Motivated by potential applications in wireless sensor networks, we consider the problem of communicating a large number of correlated analog sources over a Gaussian multiple-access channel using non-orthogonal code-division multiple-access (CDMA). We present a joint source-channel decoder which exploits the inter-source correlation for interference reduction in the CDMA channel. This decoder uses a linear minimum mean square error (MMSE) multi-user detector (MUD) in tandem with a MMSE joint source decoder for multiple sources to achieve a computational complexity that scales with the number of sources. However, iterative exchange of extrinsic information between the MUD and the joint source decoder leads to improved interference cancellation. Experimental results obtained with decoding observations from Gaussian random fields show that the proposed iterative decoder can achieve a considerable performance gain compared to a non-iterative decoder. The results also show that the iterative decoder is robust against the performance degradation due to correlated interference in a non-orthogonal CDMA channel.

***Index Terms*—** Multi-terminal source coding, joint source-channel decoding, iterative decoding, CDMA, multi-user detection

1. INTRODUCTION

Multi-terminal (MT) coding of correlated sources, or distributed vector quantization (VQ), has received considerable attention in recent recent research, due to its potential applications in wireless sensor networks (WSNs) [1, 2]. In a WSN based on MT coding, many spatially distributed, possibly a large number of, sensors are used to pickup correlated measurements from a random field. Each sensor quantizes and transmits its measurements over a wireless link to a joint decoder which reconstructs the random field using the quantized measurements received from all the sensors. Most work on MT coding has considered independent channels between the sensors and the joint decoder, assuming the use of an orthogonal multiple-access technique to avoid interference in the wireless channel [3–6]. One of the potential approaches to multiple-access in limited energy wireless sensor networks is CDMA [7]. However, orthogonal CDMA is not practical when the number of sensors can be much greater than the number of *chips* per symbol [8], which is the case in a large-scale WSN. Furthermore, orthogonal CDMA is in general not optimal for transmitting correlated sources over a multiple-access channel [9].

The MMSE joint source-channel decoding of independent sources over non-orthogonal CDMA channels has been previously considered in [10]. However, the complexity of that decoder grows exponentially with the number of sources and hence is impractical in WSNs. Furthermore, such a decoder is not necessarily optimal with correlated sources. This is due to the fact that with correlated sources, the channel interference will also be correlated and hence can potentially lead to destructive interference, depending on the cross-correlation of the CDMA signatures in use. Low complexity joint decoders for large scale WSNs with orthogonal channels have been previously proposed in [5, 6]. Such decoders can clearly be used on a non-orthogonal CDMA channel as well, if used in tandem with a MUD. However, that approach amounts to separate source-channel decoding and renders it impossible to exploit the inter-source correlation in interference cancellation.

In contrast to previous work, in this paper we present and investigate a low complexity iterative joint source-channel (JSC) decoder for correlated sources and a CDMA channel, in which inter-source correlation can be exploited for improved interference cancellation. More specifically, we extend the joint VQ decoder presented in [6], to obtain a low complexity JSC decoder wherein the key idea is to perform iterative decoding, by using the joint VQ decoder in tandem with a soft-input soft-output MUD. The overall computational complexity of the resulting JSC decoder is $O(K^2)$ for $K >> 1$, making it feasible to use it in large-scale WSNs. We present simulation results obtained with 4 Gaussian sources, for which it is also feasible to implement the MMSE decoder, as well as those obtained with 16 sources modeled by a Gaussian random field (for which MMSE decoder is too complex to implement). While the proposed decoder is not necessarily optimal for the problem at hand, we demonstrate that, due to the use of interleaving between the MUD and the joint VQ decoder, it is robust against destructive interference in the channel caused by the correlation between the sources, and hence can in some cases outperform the non-iterative MMSE joint decoder, such as that considered in [10].

2. PROBLEM DESCRIPTION

Consider a WSN with K sensors, observing a correlated random field $(X_1, \ldots, X_K)$. Suppose that sensor k encodes a vector $\mathbf{X}_k$ of d samples at the rate R bits/sample VQ [11] and transmits the quantization index I_k over a symbol synchronous CDMA channel [12], $k = 1, \ldots, K$. We assume that the channel input vector representing I_k to be of the form $\mathbf{U}_k = (U_{k,0}, \ldots, U_{k,L-1})^T$, where $U_{k,n} \in \{-1, +1\}$ for $n = 0, \ldots, L-1$ and $L = dR$, *i.e.*, baseband equivalent of binary phase-shift keying (BPSK) modulated bits. The channel (matched filter) output vector at time n, $\mathbf{Y}^{(n)} = (Y_{1,n}, \ldots, Y_{K,n})^T$ is given by [12, Sec. 2.9.1]

$$\mathbf{Y}^{(n)} = \mathbf{RWU}^{(n)} + \mathbf{Q}^{(n)}, \tag{1}$$

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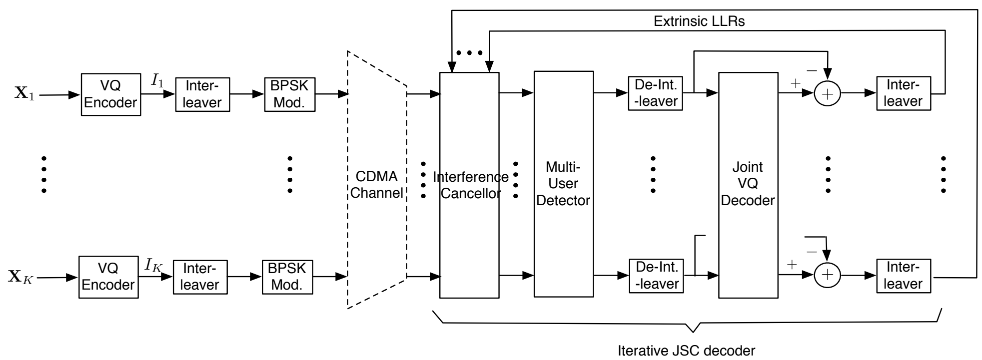

Fig. 1. *Block diagram of the proposed iterative JSC decoder for correlated sources.*

$\mathbf{R}$ is the $K \times K$ matrix of cross-correlations between the spreading waveforms of different sensors, $\mathbf{W}$ is the $K \times K$ diagonal matrix of the amplitudes of the signals received from different sensors, and $\mathbf{Q}^{(n)}$ is the zero-mean Gaussian channel noise vector with covariance matrix $\sigma^2\mathbf{R}$ [12, Eq. 2.79]. Let $\hat{\mathbf{X}}_k \in \mathbb{R}^d$ be the reconstructed value of $\mathbf{X}_k$ using some decoder. Then, the average distortion of the system is measured by the mean square error (MSE) $D = \sum_{k=1}^{K} E\|\mathbf{X}_k - \hat{\mathbf{X}}_k\|^2$. The problem considered in this paper is joint decoding of $(\hat{\mathbf{X}}_1, \ldots, \hat{\mathbf{X}}_K)$, based on the observed channel outputs $\mathbf{Y}^{(n)}$, $n = 0, \ldots, L-1$. This system does not use channel coding and hence we use a JSC decoder which exploits the inter-source correlation to mitigate channel noise and CDMA interference. The MMSE decoder is given by [10, 11]

$$\hat{\mathbf{X}}_k = E\{\mathbf{X}_k|\underline{\mathbf{Y}} = \underline{\mathbf{y}}\} \approx \sum_{i=0}^{2^L-1} \mathbf{c}_{i,k} P(I_k = i|\underline{\mathbf{Y}} = \mathbf{y}), \quad (2)$$

where $\mathbf{c}_{i,k} = E\{\mathbf{X}_k|I_k = i\}$ are the centroids of VQ encoder partition, $k = 1, \ldots, K$, and $\underline{\mathbf{Y}} = (\mathbf{Y}^{(0)T}, \ldots, \mathbf{Y}^{(L-1)T})^T$. The evaluation of $P(I_k = i|\underline{\mathbf{Y}} = \mathbf{y})$ in (2) requires a computational complexity which grows exponential with K [10]. If $\mathbf{R}$ is the identity matrix, then we have orthogonal CDMA. While this does not reduce the complexity, in this case the correlation between the channel outputs for different sensors is only due to the inter-source correlation. As a result, provided the quantized outputs of the encoders can be modeled by a Markov random field (MRF), it is then possible to evaluate $P(I_k = i|\underline{\mathbf{Y}} = \mathbf{y})$ with a computational complexity that grows only linearly with K, see [6]. In the following, we propose an extension of the joint VQ decoder in [6] to realize a low-complexity iterative JSC decoder for a non-orthogonal CDMA channel.

3. AN ITERATIVE JSC DECODER

The proposed decoder is shown in Fig. 1. The key idea is to reduce the computational complexity by performing multi-user detection and VQ decoding in tandem, so that the MUD does not directly account for the inter-source correlation, but only the correlation among the users at the channel output due to CDMA . *i.e.,* channel input bits at time t, $V_{1,t}, \ldots, V_{K,t}$ are assumed independent. The latter condition is ensured by the use of a bit-interleaver in each sensor. However, in order to reduce multi-user interference compared to the CDMA channel with independent sources, the MUD in the proposed decoder is allowed to exploit the inter-source correlation by using the *extrinsic* log likelihood ratios (LLRs) of the transmitted bits obtained from the joint VQ (JVQ) decoder. The MUD and the JVQ decoder iteratively exchange extrinsic-LLRs between each other to achieve JSC decoding. Note that in this decoder, the MUD operates at bit-level while the JVQ decoder operates at VQ-index level. It should also be emphasized that in terms of optimal achievable performance, the two stage decoder in Fig. 1 is fundamentally different from the MMSE JSC decoder given by (2). In the former, the CDMA channel inputs are independent (due to interleaving), whereas in the latter, the channel inputs are dependent (due to inter-source correlation). We discuss the implications in Sec. 4.

3.1. MUD with Extrinsic Interference Cancellation

The optimal [maximum likelihood (ML)] MUD also has a computational complexity that grows exponentially with K [12]. Therefore, we here adopt the soft-input soft-output MMSE MUD presented in [13], whose computational complexity is only $O(K^2)$. Suppose that a sequence of ML bits $\mathbf{U}_{k,1}, \ldots \mathbf{U}_{k,M}$ obtained by quantizing M input vectors in the sensor k are interleaved to generate a sequence of CDMA-channel input bits $V_{k,t}$, $t = 0, \ldots, ML-1$. If extrinsic estimates for bits transmitted by other sensors at time t, $\{\tilde{V}_{l,t}, l = 1, \ldots, K, l \neq k\}$ are available, then these estimate can be used to cancel the interference in the CDMA-channel output $\mathbf{y}^{(t)}$ of the sensor k at time t as

$$\tilde{\mathbf{y}}_k^{(t)} = \mathbf{y}^{(t)} - \mathbf{RW}\tilde{\mathbf{v}}_k^{(t)}, \quad (3)$$

where $\tilde{\mathbf{V}}_k^{(t)} = (\tilde{V}_{1,t}, \ldots \tilde{V}_{k-1,t}, 0, \ldots \tilde{V}_{k+1,t}, \ldots, V_{K,t})^T$. We can then obtain an equivalent additive white Gaussian noise (AWGN) channel for each sensor $k = 1, \ldots, K$, by using a linear MMSE estimator as considered in [13, Sec. IV-B]. Let $z_{k,t} = \mathbf{a}_k^{(t)}\tilde{\mathbf{y}}_k^{(t)}$, where $\mathbf{a}_k^{(t)}$, be the linear MMSE estimate of $V_{k,t}$ based on $\tilde{\mathbf{y}}_k^{(t)}$. Then, the equivalent AWGN channel output for the sensor k at time t is given by

$$z_{k,t} = \mu_{k,t} v_{k,t} + \eta_{k,t}, \quad (4)$$

where the channel gain $\mu_{k,t}$ and the variance $\sigma^2_{\eta_{k,t}}$ of noise $\eta_{k,t}$ can be computed by using [13, (48), (49)]. Note that $z_{k,t}$ ideally contains only the extrinsic information regarding the bit $v_{k,n}$ (channel output LLRs and LLRs of other bits provided by the JVQ decoder).

3.2. LLR-based Optimal JVQ Decoder

The sequence of outputs $z_{k,0}, \ldots, z_{k,LM-1}$ from the aforementioned equivalent AWGN channel for each sensor $k = 1, \ldots, K$ is de-interleaved to form the input to the JVQ decoder. Thus, for the VQ index I_k transmitted by the sensor k, the JVQ decoder receives the vector $\mathbf{Y}'_k = (Y'_{k,0}, \ldots, Y'_{k,L-1})^T \in \mathbb{R}^L$. The MMSE

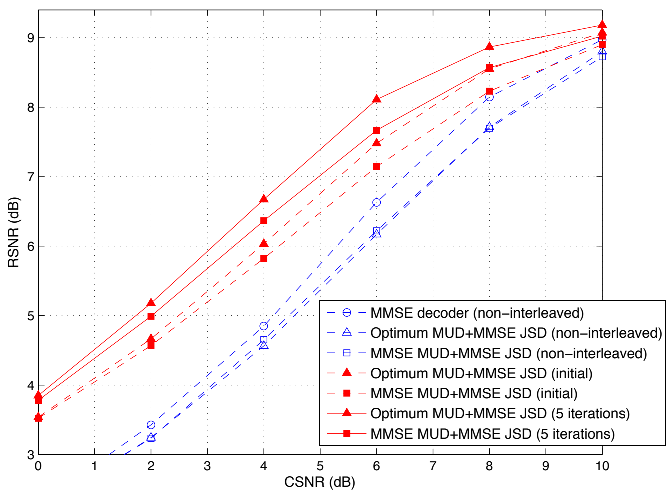

Fig. 2. *Performance comparison of JSC decoding with and without interleaving of 4 correlated Gaussian sources over a CDMA channel with destructive interference. Quantization rate is 2 bits/sample.*

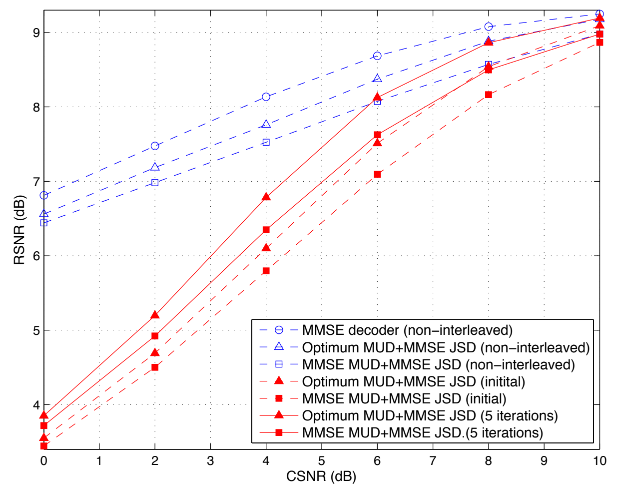

Fig. 3. *Performance comparison of JSC decoding with and without interleaving of 4 correlated Gaussian sources over a CDMA channel with constructive interference.*

optimal VQ decoder output, given the AWGN channel outputs, can thus be given by (2), but with $\underline{\mathbf{Y}}$ replaced by the vector $\underline{\mathbf{Y}}' = \left(\mathbf{Y}_1'^T, \ldots, \mathbf{Y}_K'^T\right)^T$. Now consider

$$P(I_k = i|\underline{\mathbf{Y}}' = \mathbf{y}') = \frac{\sum_{\mathbf{I}:I_k=i} P(\mathbf{I}, \mathbf{y}')}{\sum_{\mathbf{I}} P(\mathbf{I}, \mathbf{y}')}, \tag{5}$$

where $\mathbf{I} = (I_1, \ldots, I_K)^T$, $P(\mathbf{I}, \mathbf{y}') = \prod_{k=1}^K f(\mathbf{y}_k'|I_k)P(\mathbf{I})$ and $f(\mathbf{y}_k'|I_k)$ is the conditional pdf of the AWGN channel output of the sensor k, given by [$f(\cdot)$ denotes the pdf of Gaussian noise]

$$f(\mathbf{y}_k'|I_k = i) = \prod_{n=0}^{L-1} g_{k,n} \exp\left(\frac{\mu_{k,n} y_{k,n}' u_{k,n}(i)}{\sigma^2_{\eta_{k,n}}}\right), \tag{6}$$

$U_{k,n}(i) \in \{-1, +1\}$ is the BPSK modulated value of the n-th bit of $I_k = i$ and $g_{k,n} = (1/\sqrt{2\pi}\sigma_{\eta_{k,n}}) \exp[-(y'^2_{k,n} + \mu^2_{k,n})/(2\sigma^2_{\eta_{k,n}})]$. Now using the facts that $\exp(u\theta) = \cosh\theta(1 + u\tanh(\theta))$ for $u \in \{-1, +1\}$, and that the LLR of the AWGN channel output $y_{k,n}'$ is given by [14]

$$\lambda^{(c)}_{k,n} = \ln\left[\frac{f(y_{k,n}'|U_{k,n} = +1)}{f(y_{k,n}'|U_{k,n} = -1)}\right] = \frac{2\mu_{k,n} y_{k,n}'}{\sigma^2_{\eta_{k,n}}}, \tag{7}$$

we can express (5) as

$$P(I_k = i|\underline{\mathbf{Y}}' = \mathbf{y}') = \frac{\sum_{\mathbf{I}:I_k=i} \prod_{k=1}^K \prod_{n=0}^{L-1} \phi_{k,n} P(\mathbf{I})}{\sum_{\mathbf{I}} \prod_{k=1}^K \prod_{n=0}^{L-1} \phi_{k,n} P(\mathbf{I})}, \tag{8}$$

where $\phi_{k,n}(i) = [1 + U_{k,n}(i)\tanh(\lambda^{(c)}_{k,n}/2)]$. The joint pmf $P(\mathbf{I})$ can also be expressed as a product of simple factors, each involving only a small bounded subset of VQ indexes, if we assume that $(I_1, \ldots, I_K)$ is an MRF [6]. Then, by representing (8) in the form of a factor-graph, these posterior probabilities can be computed using the sum-product algorithm, with $O(K)$ computational complexity, see [6] for details. Thus the overall complexity of the JSC decoder is $O(K^2 + K) \approx O(K^2)$ for $K >> 1$.

The posterior LLR of the bit $U_{k,n}$ of VQ index I_k, at source-decoder output is given by $\lambda^{(s)}_{k,n} = \ln\left[\frac{P(U_{k,n}=+1|\mathbf{y}')}{P(U_{k,n}=-1|\mathbf{y}')}\right]$, where the bit posterior probabilities $P(U_{k,n}|\mathbf{y}')$ can be computed by marginalizing the index probabilities in (8), $P(I_k = i|\mathbf{y}') = P(U_{k,0}, \ldots, U_{k,L-1}|\mathbf{y}')$. It follows that

$$\lambda^{(s)}_{k,n} = \underbrace{\ln\left[\frac{f(y_{k,n}'|U_{k,n} = +1)}{f(y_{k,n}'|U_{k,n} = -1)}\right]}_{\lambda^{(c)}_{k,n}} + \underbrace{\ln\left[\frac{P(U_{k,n} = +1|\bar{\mathbf{y}}_k')}{P(U_{k,n} = -1|\bar{\mathbf{y}}_k')}\right]}_{\lambda^{(se)}_{k,n}},$$

where the vector $\bar{\mathbf{y}}_k'$ contains $y_{l,n}'$ for $l = 1, \ldots, K$ but $l \neq k$ and $n = 0, \ldots, L-1$. Thus, the *extrinsic* LLR of the bit $U_{k,n}$ (which contains the information revealed by corresponding bits in other VQ indexes only) can be computed from the JVQ decoder output as $\lambda^{(se)}_{k,n} = \lambda^{(s)}_{k,n} - \lambda^{(c)}_{k,n}$, which is fed-back to the MUD (after interleaving) for interference cancellation in bits other than $U_{k,n}$ in (3), see Fig. 1.

4. SIMULATION RESULTS AND DISCUSSION

We now present and discuss simulation results obtained by applying the proposed iterative JSC decoder. All the results presented here have been obtained with 2 bits/sample Lloyd-Max scalar quantization [11] of mean-zero, unit-variance correlated Gaussian sources. First, we consider an example with $K = 4$ sources, for which case it is feasible to compute the performance of the MMSE decoder given by (2). Furthermore, it is also possible to implement the MMSE joint source decoder (JSD) without the MRF source-model assumption. The source covariance matrix in this example is given by $[\mathbf{C}]_{k,l} = 0.9^{|k-l|}$ for $k, l = 1, \ldots, 4$. In all simulations, a training set of 10^5 source samples have been used.

We first consider a CDMA channel with the cross-correlation matrix $[\mathbf{R}]_{k,k} = 1$ and $[\mathbf{R}]_{k,l} = 0.7(-1)^{|k-l|}$, $k \neq l$ for $k, l = 1, \ldots, 4$. Note that, since the sources are positively correlated, the sensor-pairs which use CDMA signatures with a negative cross-correlation can interfere destructively in the channel. On the other hand source-pairs with $\mathbf{R}_{k,l} > 0$ can interfere constructively. Fig. 2 shows the average reconstruction signal-to-noise ratio (RSNR) of the 4 sources as function of the channel signal-to-noise ratio (CSNR), where all sensors have equal transmitter powers (*i.e.*, $[\mathbf{W}]_{k,k} = 1$). Except the MMSE decoder [see (2)], all systems shown in Fig. 2 use interleaving (interleaver depth is 1000 bits). The plots labeled "initial" refer to the performance of JSC decoders without any iterations. The *optimal MUD* refers to the maximum-likelihood MUD (see [13, (23)]) which gives an upper-bound to the performance of the linear MMSE-MUD described in Sec. 3.1. MMSE-JSD refers to the JVQ decoder described in Sec. 3.2. The fact that the performance of the optimal (MMSE) JSC decoder for non-interleaved transmission is poor compared to iterative JSC decoders for interleaved transmission is due to the aforementioned destructive interference between highly correlated sources in this particular CDMA channel. As can be seen, the iterations between the joint source decoder and the MUD improves interference cancellation in interleaved (and hence independent) channel inputs, and hence the RSNR of the sources.

We next use a CDMA channel with $[\mathbf{R}]_{k,l} = 0.7$, $k \neq l$ for $k, l = 1, \ldots, 4$. For positively correlated sources in our example, this choice of CDMA signatures can expect to give rise to constructive interference. This is confirmed by the simulation results shown in Fig. 3 which show that in this case the transmission without interleaving actually outperforms the interleaving-based iterative decoding. The choice of CDMA signatures, and hence the cross-correlation matrix in this case is better "matched" to the inter-source correlation structure. The superior performance of direct transmission of sources is a manifestation of the fact that, the optimal channel inputs required for transmitting correlated sources over a multiple-access channel must also be correlated, see [9]. While we do not address the problem of optimizing the channel inputs to achieve MMSE source reconstruction, this shows that the optimization of CDMA signatures for correlated sources in conjunction with JSC decoding may offer significant performance gains in multiple-access channels. However, notice that the performance of iterative decoding shown in Figs. 2 and 3 are actually very close despite the differences in the CDMA cross-correlations. This shows that, by rendering the channel inputs independent and then by using the inter-source correlation for interference mitigation in the receiver, we obtain iterative JSC decoders which are robust against the effects, destructive or constructive, of particular CDMA signature set in use, compared to non-interleaved transmission.

Next, we consider an example in which the proposed iterative decoder is applied to a system with $K = 16$ sensors. In this case, neither the optimal (non-interleaved) MMSE decoder nor the optimal MUD is computationally tractable. The sensors are assumed to be arranged in a 4×4 array, observing a mean zero, unit-variance Gaussian random field in which the correlation between any pair of senor observations X_k and X_l is given by the power exponential model $E\{X_k X_l\} = \sigma_x^2 e^{-(\Delta d_{k,l})^2}$ [15], where $d_{k,l}$ is the distance between the two sensors and Δ is a constant. In the simulations we have used a sensor array placed on square grid of spacing 1.0, $\sigma_x^2 = 1.0$, and $\Delta = 0.325$ so that the correlation between two closest sensors is 0.9. Again, we have considered two CDMA cross-correlation matrices, $\mathbf{R}_1$ and $\mathbf{R}_2$. In the former case, $[\mathbf{R}_1]_{k,l} = 0.7(-1)^{|k-l|}$, $k \neq l$ for $k, l = 1, \ldots, 16$. Fig. 4 shows the performance of the MMSE-MUD+MMSE-JSD decoder for both non-interleaved (with non-iterative decoding) and interleaved transmission. The results with $\mathbf{R}_1$ indicates that the use of interleaving and iterative decoding outperform the system with no interleaving. This is again due to fact that $\mathbf{R}_1$ produces destructive interference. In order to further demonstrate this issue, we have chosen $\mathbf{R}_2$ such that the cross-correlation between the CDMA signatures used by any two sensors decays with the distance between the sensors and thus matches the source correlation- $[\mathbf{R}_2]_{k,l} = e^{-0.3 d_{k,l}^2}$, $k \neq l$ for $k, l = 1, \ldots, 16$. This is also an example in which CDMA signatures are chosen (though in a heuristic manner) to exploit the inter-source correlation in the multiple-access channel. The results in Fig. 4 shows that, when the CDMA channel corresponds to $\mathbf{R}_2$, decoding with no-interleaving outperforms decoding with interleaving. While the performance of the latter significantly improves with iterations, the direct transmission of the sources remains superior at low CSNRs. This is because, the CDMA channel matrix $\mathbf{R}_2$ produces constructive interference between highly correlated (closely located) sources. These results show that the direct transmission of correlated sources over a multiple-access channel requires careful optimization of the CDMA signatures to prevent performance degradation. On the other hand the proposed iterative decoding is more robust against the effects of the CDMA cross-correlation matrix.

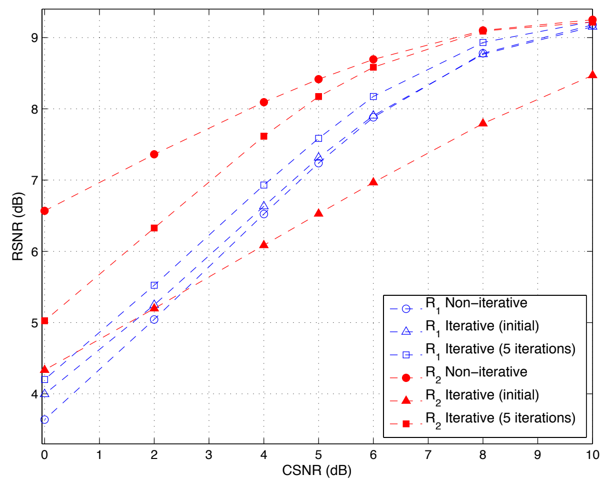

Fig. 4. *Performance of iterative JSC decoding of 16 sensors placed in a Gaussian random field.* $\mathbf{R}_1$ *and* $\mathbf{R}_2$ *correspond to two different CDMA channels.*

5. RELATION TO PRIOR WORK

Compared to the optimal (MMSE) JSC decoder for independent sources over CDMA channels considered in [10], the iterative JSC decoder proposed in this paper not only has a much lower computational complexity for $K >> 1$, but as demonstrated in this paper, also achieves performance gains in some cases of CDMA, due to the use of interleaving. A low complexity approximation to the MMSE decoder is presented in [16], but it is based on separate decoding of independent sources and hence cannot exploit the inter-source correlation in either source decoding or interference cancellation. On the other hand, even though near optimal joint source decoders for correlated sources presented in [5, 6] have low complexity, they assume an independent (orthogonal) channel between each source and the joint decoder and hence cannot handle multiple-access interference. In this paper, we present an extension of our previous work in [6] to obtain a low-complexity JSC decoder for a large number of correlated sources transmitted over a non-orthogonal CDMA channel. Related work on iterative multi-user detection in channel coded CDMA systems with independent sources appears in [13, 14, 17]. In this paper, we have adopted the linear MMSE MUD presented in [13]. Compared to iterative JSC decoding of a single source over an AWGN channel as in [18, 19], we consider here multiple correlated sources and a multiple-access channel with interference.

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