Spatial Interference Cancellation Algorithm

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***Abstract*—Future wireless communication systems characterized by tight frequency reuse, adaptive modulation and coding schemes and diversified data services will be interference limited by interfering signals of diverse rates and strengths. We propose in this paper a low complexity algorithm for spatial interference cancellation in the presence of one strong interferer. This algorithm is based on an earlier proposed low complexity max log MAP detector. It encompasses two strategies for interference cancellation which have been termed as partial interference cancellation (PIC) and absolute interference cancellation (AIC). Their corresponding selection in the receiver is dictated by the relative strength and the rate of interfering stream. In the scenario of interfering stream being relatively weak or of higher rate as compared to the desired stream, the mobile station (MS) resorts to PIC while when the interfering stream is relatively stronger or is of lower rate, the MS switches to AIC. Finally we analyze the performance of proposed algorithm by simulations.**

I. Introduction

To cope with the ever-increasing demands on the higher spectral efficiency, a tight frequency reuse will be adopted for the future wireless communication systems as 3GPP LTE [1] and IEEE 802.16m [2]. Adaptive modulation and coding schemes will be supported in the next generation wireless systems which combined with the diversified data services will lead to variable transmission rate streams. These system characteristics will overall lead to an interference-limited system. Most state-of-the-art wireless systems deal with the interference either by orthogonalizing the communication links in time or frequency [3] or allow the communication links to share the same degrees of freedom but model the interference as additive Gaussian random process [4]. Both of these approaches may be suboptimal. First approach entails an *a priori* loss of the degrees of freedom in both links, independenet of the interference strength. The second approach treats the interference as pure noise while it actually carries information and has the structure that can be potentially exploited in mitigating its effect.

3GPP LTE [1] has chosen orthogonal frequency division multiple access (OFDMA) technology for the downlink in order to provide multiple access and eliminate the intracell interference. However frequency reuse factor being 1 will lead to intercell interference impairments among neighboring cells. Intercell interference coordination techniques [3] are studied to minimize the interference level while spatial interference cancellation filters are the focus of attention to cancel the interferers which will be 1 in most cases (near cell boundaries) and 2 in rare cases (near cell corners). Different spatial interference cancellation techniques involving equalization and subtractive cancellation [5] [6] have been proposed in the literature. Amongst them, the MMSE linear detectors are being considered as likely candidates for 3GPP LTE [7]. The suboptimality of MMSE for non Gaussian alphabets in low dimensional systems (less number of interferers) is well known [8] and moreover MMSE detection being based on interference attenuation is void of exploiting the interference structure in mitigating its effect. Though not optimal, but their low complexity still makes them attractive for practical systems.

Optimal strategy for treating the interference in the regime of very strong [9] and very weak interference is well known however if the interference is in the moderate region, no optimal strategy is known but partial decoding of interference can significantly improve performance [10]. We propose a low complexity spatial interference cancellation algorithm for single frequency reuse synchronized cellular networks in the presence of one strong interferer. This algorithm is based on an earlier proposed low complexity version of the max log MAP detector [11] which has complexity analogous to that of MMSE but is based on the match filter outputs. The proposed algorithm encompasses two strategies for interference cancellation which have been termed as partial interference cancellation (PIC) and absolute interference cancellation (AIC) and their selection in the receiver is dictated by the relative strength and the rate of interfering stream. In the scenario of interfering stream being weak or of higher rate relative to the desired stream, thereby making it unfeasible to be decoded, the MS resorts to the strategy of PIC. It can be interpreted as partial decoding of the interference which is the recommended strategy in the regime of moderate interference [10]. When the interfering stream is relatively stronger or is of lower rate thereby making it feasible to be decoded, MS adopts the AIC strategy. It can be interpreted as subtractive cancellation which is the optimal strategy in the case of strong interference [9]. Simulation results demonstrate much improved performance of the proposed algorithm with respect to the other suboptimal linear interference cancellation detectors as MMSE.

Regarding notations, we will use lowercase or uppercase letters for scalars and boldface letters for vectors and matrices. In addition, unless otherwise stated, all logarithms are to the base 2. $\Re(.)$ and $\Im(.)$ indicate real and imaginary parts while $(.)^{\dagger}$ indicates conjugate transpose. $|.|$ and $\|.\|$ indicate norm of scalar and vector respectively. The paper is divided into five sections. In section II we define the system model while section III gives insight into the mutual information analysis of the desired stream in the presence of interfering

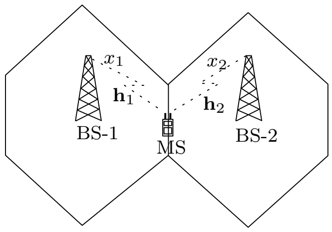

Fig. 1. Interference cancellation in single frequency cellular network. x_1 is the desired signal and x_2 is the interference signal.

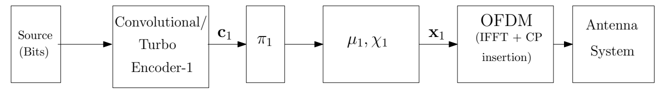

Fig. 2. Block diagram of Transmission chain of BICM OFDM system. π_1 denotes random interleaver, μ_1 labeling map and χ_1 signal set for $\mathbf{x}_1$.

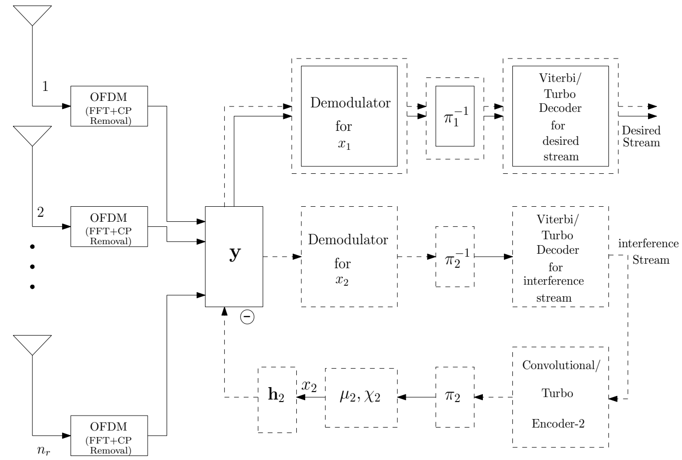

Fig. 3. Block diagram of receiver at MS. Continuous lines indicate PIC approach while dashed lines indicate AIC approach.

stream. Section IV is dedicated to the low complexity version of max log MAP demodulator while section V explains the two interference cancellation strategies which is followed by simulation results and conclusions.

II. System Model

Consider a single frequency reuse cellular network as shown in Fig. 1. Keeping in view the upcoming wireless standards as LTE [1] and 802.16m [2], we assume that both base stations (BSs) use bit interleaved coded modulation (BICM) [12] based OFDM system for the downlink transmission. We further assume antenna cycling at the BS [11]. Block diagram of the transmission chain at the BS and reception chain at the MS are shown in the Figs. 2 and 3 respectively. We assume receive diversity at the MS with n_r receive antennas. Let two spatial streams arriving at the MS be $\mathbf{x}_1$ (desired stream) and $\mathbf{x}_2$ (interference stream). x_1 is the symbol of $\mathbf{x}_1$ over a signal set $\chi_1 \subseteq \mathcal{C}$ of size $|\chi_1| = M_1$ with a Gray labeling map $\mu_1 : \{0,1\}^{\log|M_1|} \rightarrow \chi_1$ and x_2 is the symbol of $\mathbf{x}_2$ over signal set χ_2 of size $|\chi_2| = M_2$ with Gray labeling map μ_2. In the transmission chain, code sequence $\mathbf{c}_1$ is interleaved by π_1 and is then mapped onto the signal sequence $\mathbf{x}_1 \in \chi_1$. The bit interleaver for first stream can be modeled as $\pi_1 : k^{'} \rightarrow (k,i)$ where $k^{'}$ denotes the original ordering of the coded bits $c_{1,k'}$, k denotes the time ordering of the signals $x_{1,k}$ and i indicates the position of the bit $c_{1,k'}$ in the symbol $x_{1,k}$.

We assume that the frequency reuse factor is one and the cyclic prefix (CP) of appropriate length is added to the OFDM symbols at two BSs. We further assume that the BSs are synchronized for the transmission and there is no channel state information (CSI) at the BS while perfect CSI of both the desired and the interference stream is assumed at the MS. We consider the case of one interferer. Cascading IFFT at the BS and FFT at the MS with the CP extension, transmission at the k-th frequency tone can be expressed as:-

$$\mathbf{y}_k = \mathbf{h}_{1,k}x_{1,k} + \mathbf{h}_{2,k}x_{2,k} + \mathbf{z}_k, \qquad k = 1,2,\cdots,K \quad (1)$$

where K is the total number of frequency tones. We assume that the subcarriers are narrowband and model each subcarrier as a frequency flat fading channel so $\mathbf{h}_{1,k} \in \mathbb{C}^{n_r}$ is the vector characterizing flat fading channel response from the first transmitting antenna to n_r receive antennas at the k-th subcarrier. This vector has complex-valued multivariate Gaussian distribution with $E[\mathbf{h}_{1,k}] = \mathbf{0}$ and $E\left[\mathbf{h}_{1,k}\mathbf{h}_{1,k}^{\dagger}\right] = \mathbf{I}$, i.e. each channel between the BS and n_r receive antennas is independent while the channels at different subcarriers are also assumed to be independent. Each subcarrier corresponds to a symbol from a constellation map χ_1 for the first stream and χ_2 for the second stream. $\mathbf{y}_k, \mathbf{z}_k \in \mathbb{C}^{n_r}$ are the vectors of received symbols and circularly symmetric complex white Gaussian noise of double-sided power spectral density $N_0/2$ at the n_r receive antennas at the k-th frequency tone. The complex symbols $x_{1,k}$ and $x_{2,k}$ of the two streams are also assumed to be independent and of variances σ_1^2 and σ_2^2 respectively.

III. An Information-Theoritical View

We focus on the mutual information of the desired stream in the presence of interference stream. We assume perfect CSI at the receiver. Dropping the frequency index, the mutual information of desired stream is given as

$$\begin{aligned} I(\mathbf{Y};X_1) =& \mathcal{H}(X_1) - \mathcal{H}(X_1|\mathbf{Y}) \\ &= \log M_1 - E_{x_1,\mathbf{y}} \log \frac{p(\mathbf{y})}{p(\mathbf{y},x_1)} \\ &= \log M_1 - \frac{1}{M_1}\sum_{x_1}\int_{\mathbf{y}} p(\mathbf{y}|x_1) \log \frac{\sum_{x_1} p(\mathbf{y}|x_1)}{p(\mathbf{y}|x_1)} d\mathbf{y} \end{aligned} \quad (2)$$

where $\mathcal{H}(.) = -E\log p(.)$ is the entropy function and $\mathbf{H} = [\mathbf{h}_1\mathbf{h}_2]$ is the channel matrix. Above quantities can be approximated numerically using sampling (Monte-Carlo) methods with N_z realizations of noise and N_H realizations of the channel.

$$I\left(\mathbf{Y};X_1|\mathbf{H}\right) = \log M_1 - \frac{1}{M_1 M_2 N_z N_H}\left(\sum_{\mathbf{x}}\sum_{\mathbf{H}}^{N_H}\sum_{\mathbf{z}}^{N_z} \log\frac{\sum_{x_1}\sum_{x_2}\exp\left[-\frac{1}{N_0}\left\|\mathbf{y}-\mathbf{H}\mathbf{x}\right\|^2\right]}{\sum_{x_2}\exp\left[-\frac{1}{N_0}\left\|\mathbf{y}-\mathbf{H}\mathbf{x}\right\|^2\right]}\right)$$

where $\mathbf{x} = [x_1 x_2]^T$.

Now we consider the case when the desired stream x_1 belongs to a finite alphabet size ($x_1 \in M_1$) but the interference stream x_2 is Gaussian. The mutual information of the desired stream is given as

$$= \log M_1 - \frac{1}{M_1}\sum_{x_1}\int_{x_2}\int_{\mathbf{y}} p\left(\mathbf{y},x_2|x_1\right)\log\frac{\sum_{x_1} p\left(\mathbf{y}|x_1\right)}{p\left(\mathbf{y}|x_1\right)}d\mathbf{y}$$

Estimation of this quantity using Monte-Carlo simulations with N_{x_2} realizations of x_2, N_z realizations of noise and N_H realizations of the channel is

$$I(\mathbf{Y};X_1|\mathbf{H}) = \log M_1 - \frac{1}{M_1 N_{x_2} N_z N_H}\left(\sum_{x_1}\sum_{x_2}^{N_{x_2}}\sum_{\mathbf{H}}^{N_H}\sum_{\mathbf{z}}^{N_z}\log \frac{\sum_{x_1}\exp\left\{-[\mathbf{y}-\mathbf{h}_1 x_1]^\dagger\left(\sigma_2^2\mathbf{h}_2\mathbf{h}_2^\dagger+N_0\mathbf{I}\right)^{-1}[\mathbf{y}-\mathbf{h}_1 x_1]\right\}}{\exp\left\{-[\mathbf{y}-\mathbf{h}_1 x_1]^\dagger\left(\sigma_2^2\mathbf{h}_2\mathbf{h}_2^\dagger+N_0\mathbf{I}\right)^{-1}[\mathbf{y}-\mathbf{h}_1 x_1]\right\}}\right)$$

Fig. 4 shows the rate of desired stream in the presence of interference stream. The rate of desired stream is a function of the interference stream. An interesting result is the effect of Gaussian alphabets on the rate of desired stream which is more visible in case of QAM 16 and QAM 64 alphabets. There is a significant boost in the rate of desired stream once interference stream is from finite size alphabets as compared to the case when it is Gaussian however the gap shrinks as the rate (constellation size) of the interference stream increases. This diminution of gap may be related to proximity of the behavior of large size constellations to Gaussianity as both are characterized by high peak to average power ratios. This analysis underlines the dependence of the rate of desired stream on the rate (constellation size) of interference stream and in subsequent sections we propose interference cancellation strategies to exploit this dependence.

IV. Detectors for Interference Cancellation

A. MMSE

Frequency domain MMSE filter for $x_{1,k}$ is given as

$$\mathbf{h}_{1,k}^{MMSE} = \left(\mathbf{h}_{1,k}^\dagger\mathbf{R}_{2,k}^{-1}\mathbf{h}_{1,k}+\sigma_1^{-2}\right)^{-1}\mathbf{h}_{1,k}^\dagger\mathbf{R}_{2,k}^{-1} \tag{3}$$

where $\mathbf{R}_{2,k} = \sigma_2^2\mathbf{h}_{2,k}\mathbf{h}_{2,k}^\dagger + N_0\mathbf{I}$. After the application of MMSE filter we get

$$y_k = \alpha_k x_{1,k} + \beta_k x_{2,k} + \mathbf{h}_1^{MMSE}\mathbf{z}_k \tag{4}$$
$$= \alpha_k x_{1,k} + z_k \tag{5}$$

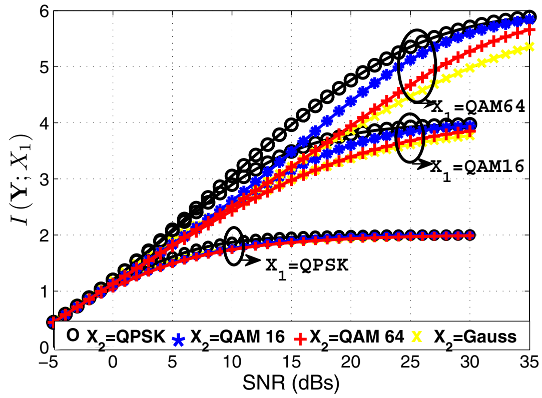

Fig. 4. Mutual information of the desired stream x_1 in the presence of interference stream x_2 for different constellations. SNR is defined as $\mathrm{E}\left\{\left\|\mathbf{h}_1 x_1\right\|^2\right\}/\mathrm{E}\left\{\left\|\mathbf{z}\right\|^2\right\}$. Interference strength is fixed as $\sigma_2^2 = 0.5$

where z_k is assumed to be zero mean complex Gaussian random variable with variance $N_k = \mathbf{h}_{1,k}^{MMSE}\mathbf{R}_{2,k}\mathbf{h}_{1,k}^{MMSE^\dagger}$. Moreover $\alpha_k = \mathbf{h}_1^{MMSE}\mathbf{h}_1$ and $\beta_k = \mathbf{h}_1^{MMSE}\mathbf{h}_2$. From (4) to (5), Gaussianity has been assumed for the post detection interference which increases the suboptimality of MMSE in the case of less number of interferers (central limit theorem). Bit metric for the $c_{k'}$ bit on first stream is given as

$$\lambda_1^i\left(\mathbf{y}_k, c_{k'}\right) \approx \min_{x_1\in\chi_{1,c_{k'}}^i}\left[\frac{1}{N_k}\left|y_k-\alpha_k x_1\right|^2\right] \tag{6}$$

where $\chi_{1,c_{k'}}^i$ denotes the subset of the signal set $x_1 \in \chi_1$ whose labels have the value $c_{k'} \in \{0,1\}$ in the position i. This metric has computational complexity $\mathcal{O}\left(|\chi_1|\right)$.

B. Reduced Complexity Max Log MAP

Considering the system equation (1), the max log MAP bit metric is given as [12]

$$\lambda_1^i\left(\mathbf{y}_k, c_{k'}\right) \approx \min_{x_1\in\chi_{1,c_{k'}}^i, x_2\in\chi_2}\left\|\mathbf{y}_k-\mathbf{h}_{1,k}x_1-\mathbf{h}_{2,k}x_2\right\|^2 \tag{7}$$

which has computational complexity $\mathcal{O}\left(|\chi_1|\,|\chi_2|\right)$. Let

$$y_{1,k} = \frac{\mathbf{h}_{1,k}^\dagger\mathbf{y}_k}{\left\|\mathbf{h}_{1,k}\right\|}, y_{2,k} = \frac{\mathbf{h}_{2,k}^\dagger\mathbf{y}_k}{\left\|\mathbf{h}_{2,k}\right\|}, h_{21,k} = \frac{\mathbf{h}_{2,k}^\dagger\mathbf{h}_{1,k}}{\left\|\mathbf{h}_{2,k}\right\|}, y_{2,k}^{'}\left(x_1\right) = y_{2,k} - h_{21,k}x_1$$

$y_{1,k}$ and $y_{2,k}$ are the match filter outputs for desired stream and interference stream respectively while $h_{21,k}$ is the cross-correlation between $\mathbf{h}_{1,k}$ and $\mathbf{h}_{2,k}$. $y_{2,k}^{'}\left(x_1\right)$ is the match filter output of the interference stream after removing the contribution from desired stream. Ignoring $\left\|\mathbf{y}_k\right\|^2$ and adding $\left|y_{1,k}\right|^2$ in (7)

$$\lambda_1^i\left(\mathbf{y}_k, c_{k'}\right) \approx \min_{x_1\in\chi_{1,c_{k'}}^i}\left[\left\{\left|y_{1,k}-\left\|\mathbf{h}_{1,k}\right\|x_1\right|^2\right\} + \min_{x_2\in\chi_2}\left\{-2\Re\left(x_2^*\left\|\mathbf{h}_{2,k}\right\|y_{2,k}^{'}\left(x_1\right)\right)+\left|\left\|\mathbf{h}_{2,k}\right\|x_2\right|^2\right\}\right]$$

We rewrite above equation as

$$\lambda_1^i(\mathbf{y}_k, c_{k'}) \approx \min_{x_1 \in \chi^i_{1,c_{k'}}} \left[\left\{ \left|y_{1,k} - \|\mathbf{h}_{1,k}\| x_1\right|^2 - \left|y'_{2,k}(x_1)\right|^2 \right\} + \min_{x_2 \in \chi_2} \left\{ \left|y'_{2,k}(x_1) - \|\mathbf{h}_{2,k}\| x_2\right|^2 \right\} \right] \quad (8)$$

To find the minimum value of $x_2 \in \chi_2$ for each value of $x_1 \in \chi^i_{1,c_{k'}}$, we decouple x_2 into its real and imaginary parts i.e.

$$\begin{aligned} |\varphi_{x_2,k}|^2 &= \min_{x_2 \in \chi_2} \left|y'_{2,k}(x_1) - \|\mathbf{h}_{2,k}\| x_2\right|^2 \quad (9) \\ &= \min_{x_2 \in \chi_2} \Re^2\left(y'_{2,k}(x_1) - \|\mathbf{h}_{2,k}\| x_2\right) + \Im^2\left(y'_{2,k}(x_1) - \|\mathbf{h}_{2,k}\| x_2\right) \end{aligned}$$

$\varphi_{x_2,k}$ can be interpreted as the match filter based metric for the interference stream for a particular value of x_1. The decoupling (9) combined with the gray labeling in BICM reduces the search space for $x_2 \in \chi_2$ to $\sqrt{M}/2$ points for M ary QAM [13]. Quantization further reduces this to $1-4$ operations (depending on the constellation size of x_2) by looking for the closest real and imaginary parts of $y'_{2,k}(x_1)$ to those of $\|\mathbf{h}_{2,k}\| x_2$. So the bit metric is written as

$$\lambda_1^i(\mathbf{y}_k, c_{k'}) \approx \min_{x_1 \in \chi^i_{1,c_{k'}}} \left\{ \left|y_{1,k} - \|\mathbf{h}_{1,k}\| x_1\right|^2 + |\varphi_{x_2,k}|^2 - \left|y'_{2,k}(x_1)\right|^2 \right\} \quad (10)$$

where $\left|y_{1,k} - \|\mathbf{h}_{1,k}\| x_1\right|^2$ is the metric for match filter output for desired stream ignoring interference, $|\varphi_{x_2,k}|^2$ is the metric for the match filter output for interference taking into account the contribution from desired stream and $\left|y'_{2,k}(x_1)\right|^2$ can be termed as the correction factor.

This bit metric implies reduction in complexity to $\mathcal{O}(|\chi_1|)$. Additionally this bit metric is based on match filter outputs and does not involve computationally complex operations of matrix inversions as is the case with MMSE detectors. Another point to underline is that the metric (10) necessitates the knowledge of modulation scheme of the interference while MMSE detector only requires the knowledge of interference channel but on the other hand, it needs to estimate the noise variance.

V. Interference Cancellation

Based on the reduced complexity max log MAP detector, we propose an interference cancellation strategy based on the partial decoding of the interference in the regime when interference because of its relative rate or strength is undecodable and subtractive cancellation when the interference is quite strong and is decodable. This strategy is therefore based on exploiting the structure of the interference in mitigating its effect once subtractive cancellation is not possible and resorting to subtractive cancellation otherwise. So in the proposed algorithm, there are two interference canceling options.

1) In the regime when interference has higher rate or is weaker in strength relative to the desired stream thereby rendering the absolute decoding of interference unfeasible, we resort to decode the target stream using the bit metric (10) which takes into account the effect of interference and can be termed as the partial decoding of interference or partial joint decoding. We term this approach as PIC.
2) In the regime when interference has lower rate or is stronger in strength relative to the desired stream thereby rendering the absolute decoding of the interference feasible, we resort to decode the interference stream using the bit metric (10), stripping it off and then decode the desired stream.We term this approach as AIC.

The factors that will decide the strategy to be adopted will be the relative rate and the strength of the interference stream comparative to the desired stream. The requisites for the proposed algorithm are the knowledge of interference channel and the modulation and coding scheme (MCS) of interfering stream. The BSs need to be synchronous with pilot signals from the adjacent BSs to be orhtogonal to meet these requisites.

A. Simulation Results

High SNR regime in the interference-limited scenario demands more attention as when the noise is small, interference will have a significant impact on the performance. Therefore the simulations have been performed in high SNR region while the interference strength is being varied. We consider 2 BSs each using BICM OFDM system for downlink transmission using the *de facto* standard, 64 state $(133, 171)$ rate-$1/2$ convolutional encoder of 802.11n standard and the punctured rate $1/2$ turbo code of 3GPP LTE [1] [1]. The MS has two antennas. We consider an ideal OFDM based system (no ISI and zero correlation between channel responses of different sub carriers) and analyze the system in frequency domain. Due to bit interleaving followed by OFDM, this can be termed as frequency interleaving. Therefore SIMO channel at each sub carrier from BS to MS has iid Gaussian matrix entries with unit variance. Perfect CSI is assumed at the receiver. Furthermore, all mappings of coded bits to QAM symbols use Gray encoding. We consider MMSE approach and the proposed approach.

Figs. 5, 6 and 7 show the frame error rates of the target stream in the presence of one interference stream. These simulation results show that the dependence of the performance for MMSE detection is insignificant on the rate of interference stream but its dependence on interference strength is substantial. This can be interperated as a consequence of the attenuation of interference strength at the output of MMSE filter and the subsequent assumption of Gaussianity for its behavior. For the proposed approach, a significant improvement is observed in the performance as the rate of interference stream decreases which is in conformity with the mutual information results of section III. It is also shown that even if we do not resort to AIC because of the inherent complexity of successive interference cancellation, still the

[1] The LTE turbo decoder design was performed using the coded modulation library www.iterativesolutions.com

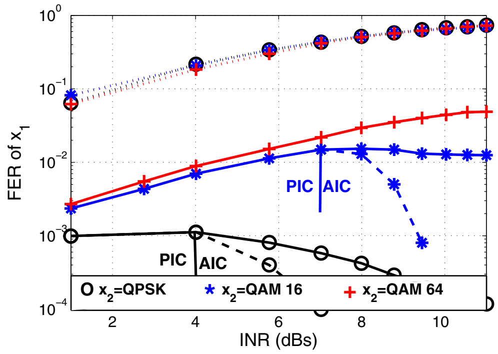

Fig. 5. Desired stream x_1 is QAM16 while interference stream x_2 is from QPSK, QAM16 and QAM64. SNR is 11 dB. INR is defined as $\mathrm{E}\left\{\|\mathbf{h}_2 x_2\|^2\right\}/\mathrm{E}\left\{\|\mathbf{z}\|^2\right\}$. Continuous lines indicate PIC while dashed lines indicate AIC approach. Dotted lines indicate MMSE approach. $64-$state, rate $1/2$ Convolutional Code is used

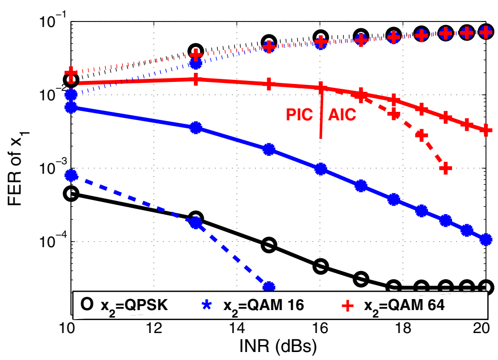

Fig. 6. Desired stream x_1 is QAM 64. SNR is 20 dB. Convolutional code is used.

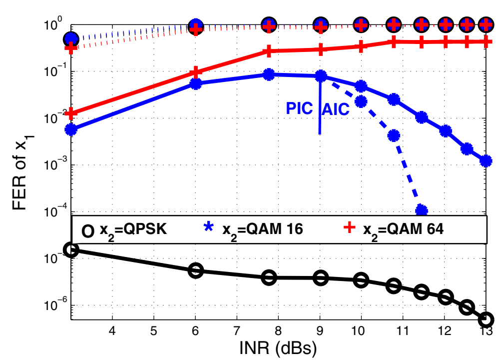

Fig. 7. Desired stream x_1 is QAM 64. SNR is 13 dB. 3GPP turbo code is used with 5 decoding iterations.

PIC approach based on the metric (10) outperforms the MMSE based detection. It is observed that for a given interference level, the performance is generally degraded as the rate of the interfering stream increases. Performance gap with respect to MMSE decreases as desired and the interference streams grow in constellation size which can be attributed to the relative proximity to Gaussianity of larger sized constellations due to their high peak to average power ratio and to the optimality of MMSE for Gaussian alphabets.

VI. Conclusions

We have focused in this paper on the spatial interference cancellation in single frequency cellular networks as 3GPP LTE. We have proposed a low complexity interference cancellation algorithm in the presence of one interferer. Depending on the strength and the rate of the interference stream, this algorithm encompasses two strategies for interference cancellation as PIC and AIC which outperform the standard interference cancellation solutions based on MMSE.

Acknowledgments

Eurecom's research is partially supported by its industrial partners: BMW, Bouygues Telecom, Cisco Systems, France Télécom, Hitachi Europe, SFR, Sharp, ST Microelectronics, Swisscom, Thales. The research work leading to this paper has also been partially supported by the European Commission under the IST FP7 research network of excellence NEWCOM++.

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