Transceiver Impairments on the Performance of the LMMSE-PIC Iterative Receiver and its Mitigation

Xiaoming Dai, Runmin Zou, Shaohui Sun, and Yingmin Wang

***Abstract*—This work investigates the impact of inherent residual transceiver impairments of multiple-input multiple-output (MIMO) systems on the performance of linear minimum mean-squared error filtering and parallel interference cancellation (LMMSE-PIC) based iterative receiver. The residual transceiver impairments are first modeled as Gaussian noise at the transmitter in this work. Then a residual-transceiver-impairments-aware technique with empirically determined transmitter noise is proposed to mitigate the performance loss associated with the residual transceiver impairments. Numerical results based on MIMO systems with typical residual transceiver impairments show that the proposed method achieves significant performance gain over the conventional one which is designed for *ideal* transceivers.**

***Index Terms*—Linear minimum mean-squared error filtering based parallel interference cancellation (LMMSE-PIC), multiple-input multiple-output (MIMO), residual transceiver impairments.**

I. Introduction

ITERATIVE detection and decoding (IDD) technique based on linear minimum mean-squared error filtering based parallel interference cancellation (LMMSE-PIC) has received considerable attention recently due to its good performance-complexity tradeoff in academia [1] as well as in industry [2] for MIMO systems with *ideal* transceivers. Practical implementations of radio-frequency (RF) transceivers, however, suffer from a large number of impairments, such as aperture and clock jitter, quantization noise, sampling offset, phase noise, [particularly severe for orthogonal frequency-division multiplexing (OFDM) based systems], I/Q imbalance, and non-linearity of the high power amplifier. The impact of some of these impairments can be partially alleviated at the transmitter through calibration or pre-distortion, or at the receiver using sophisticated compensation algorithms [3], [6], [7], [8] [9].

However, there is still a certain amount of residual transceiver impairments that remain unaccounted for due to the inherent parameter estimation errors in compensation algorithms (e.g., caused by thermal noise at the receiver), mismatch between the physical RF-chain and the model assumed for impairment compensation, or just implementation constraints [3], [6], [7], [8] [9]. These residual transceiver impairments are conventionally overlooked in information theoretical studies and are also neglected in recent field-programmable gate-array (FPGA) based [4] and application specific integrated circuits (ASIC) based [5] implementations of the LMMSE-PIC iterative receiver in practical multi-antenna systems. In [6], the influence of the residual transceiver impairments on the performance of non-iterative based MIMO detection algorithms [i.e., linear and list sphere detector (LSD)] in practical wireless multi-antenna systems was reported. Reference [7] studied the impact of the transceiver impairments on the iterative MIMO receiver. Studer *et al.* proposed a noise-whitening technique to alleviate the transceiver impairments for non-iterative based MIMO detection algorithms in [8].

This work shows that the residual transceiver impairments of multi-antenna systems exert a significant impact on the performance of the LMMSE-PIC iterative receiver in high signal-to-noise-ratio (SNR) region.[1] A formula that takes the residual transceiver impairment into account is introduced into the conventional LMMSE-PIC iterative receiver [1] to alleviate its (i.e., the residual transceiver impairment) degrading effects for practical applications. Numerical results demonstrate that the detrimental effects of the residual transceiver impairments are significantly mitigated based on the proposed technique. The proposed method also achieves slightly better performance than the existing noise-whitening technique [8] even with reduced complexity.

II. System Model with Residual Transceiver Impairments

We consider a MIMO system with bit-interleaved coded modulation (BICM) employing N_T transmit and $N_R = N_T$ receive antennas. The information bits $\mathbf{a} = [a_1, a_2, \cdots, a_K]^T$ with length K are encoded using a code rate-$\frac{K}{N}$ error-correcting encoder and are then passed through a bitwise interleaver Π. The interleaved code bits $\mathbf{x} = [x_1, x_2, \cdots, x_N]^T$ are demultiplexed into N_T streams. In each layer, groups of M_c code bits are mapped [10] to 2^{M_c}-ary quadrature amplitude modulation (QAM) complex symbols $\mathbf{s}$, where M_c is the number of bits per constellation symbol. The standard complex baseband model (i.e., with ideal transceiver) between the transmitted and received signals is given by

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{1}$$

where $\mathbf{y} \in C^{N_R \times 1}$ is the received vector, $\mathbf{H} \in C^{N_R \times N_T}$ denotes channel matrix, $\mathbf{s} \in \mathcal{X}^{N_T \times 1}$ represents the transmitted vector

[1]In practical commercial wireless systems various code rates are normally applied to opportunistically exploit the channel conditions. For example, code rates ranging from 0.1 to 0.93 (designed for high SNR scenarios) are specified in the third generation partnership project (3GPP) long-term-evolution (LTE) system [10].

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with power $\mathbb{E}[|s_i|^2] = 1$, and $\mathbf{n} \in C^{N_R \times 1}$ is the independent and identically distributed (i.i.d.) complex circular Gaussian random noise introduced by the receivers with variance σ^2 (which will be referred to as the Rx-noise hereafter). Slightly abusing common terminology, we denote the entries of $\mathbf{x}$ as $x_{i,b}$ $(i = 1, \cdots, N_T,\ b = 1, \cdots, M_c)$, where the indices i and b refer to the b-th bit in the label of the constellation point corresponding to the i-th entry of $\mathbf{s}$.

Based on the analysis and measurements in [6], [9], the combined influence of residual impairments is modeled by additive distortion to the transmitted signal $\mathbf{s}$ on the baseband with a variance that scales with transmit signal power. The generalized MIMO system model accounting for residual transceiver impairments is given by [6], [9]

$$\mathbf{y} = \mathbf{H}\tilde{\mathbf{s}} + \mathbf{n} = \mathbf{H}(\mathbf{s} + \boldsymbol{\eta}) + \mathbf{n} = \mathbf{H}\mathbf{s} + \mathbf{H}\boldsymbol{\eta} + \mathbf{n} \tag{2}$$

where the transmitter distortion $\boldsymbol{\eta} \in C^{N_T \times 1}$ denotes the mismatch between the intended signal $\mathbf{s}$ and the impaired transmitted signal $\tilde{\mathbf{s}}$ actually generated by the transmitter and is referred to as Tx-noise in the remainder of this letter. The Tx-noise encompasses different impairment effects such as sampling offset, phase noise and nonlinearity of RF amplifiers and/or quantization and clipping of digital to analog converters [3]. As observed in [6], [9] the Tx-noise is adequately modeled by an additive Gaussian noise since it results from the sum of a large number of residual transmit impairments. Furthermore, sufficient decoupling of the Tx-RF chains is assumed such that the relevant impairments are statistically independent across transmit antennas, i.e., $\boldsymbol{\eta} \sim \mathcal{CN}(\mathbf{0}, \sigma_t^2 \mathbf{I}_{N_T})$. The error vector magnitude (EVM) is a metric routinely used to characterize the quality of the transmitted signal in the RF-literature which is given by EVM $= \frac{\mathbb{E}\left[\|\tilde{\mathbf{s}}-\mathbf{s}\|^2\right]}{\mathbb{E}\left[\|\mathbf{s}\|^2\right]}$. It is apparent that EVM $= \sigma_t^2$.

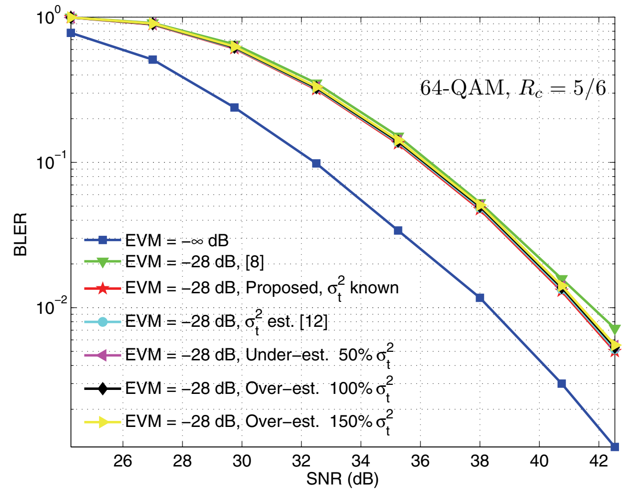
III. Mitigation of Residual Transceiver Impairments for LMMSE-PIC Iterative Receiver

1) Computation of Soft-Symbols: The soft-symbols $\hat{s}_i$ for the transmitted symbols s_i are computed [1] as $\hat{s}_i = \mathbb{E}[s_i] = \sum_{i=1}^{Q} \mathrm{Prob}[s_i = s]s$, where $\mathrm{Prob}[s_i = s] = \prod_{b=1}^{M_c} \mathrm{Prob}[x_{i,b} = x]$ denotes the *a priori* probability of the symbol $s \in \mathcal{X}$ with $x_{i,b} = [s]_b$ referring to the b-th bit associated with the symbol s. The probability of the transmitted bit $x_{i,b}$ is given by $\mathrm{Prob}[x_{i,b} = x] = \frac{\exp(\frac{1}{2} x L_{i,b}^A)}{\exp(\frac{1}{2} x L_{i,b}^A) + \exp(-\frac{1}{2} x L_{i,b}^A)}$, where $L_{i,b}^A$ denotes the *a priori* LLR of the coded bit $x_{i,b}$ feedback from the channel decoder. The *a priori* information $L_{i,b}^A$ is set to zero in the first iteration, i.e., $L_{i,b}^A = 0, \forall i, b$. The error between the transmitted symbol s_i and the soft-symbol $\hat{s}_i$ is defined as $e_i = s_i - \hat{s}_i$. The reliability of each soft-symbol $\hat{s}_i$ is characterized by its variance

$$E_i = \mathrm{Var}[s_i] = \mathbb{E}[|e_i|^2]. \tag{3}$$

2) Parallel Interference Cancelation: The parallel interference cancellation (PIC) process considers each stream separately and cancels the interference in $\mathbf{y}$ induced by all other streams $j \neq i$ as follows:

$$\begin{aligned}\hat{\mathbf{y}}_i &= \mathbf{y} - \sum\nolimits_{j,j\neq i} \mathbf{h}_j \hat{s}_j = \mathbf{h}_i s_i + \mathbf{H}\boldsymbol{\eta} + \sum\nolimits_{j,j\neq i} \mathbf{h}_j e_j + \mathbf{n} \\ &= \mathbf{h}_i s_i + \underbrace{\sum\nolimits_{j,j\neq i} \mathbf{h}_j (e_j + \eta_j) + \mathbf{h}_i \eta_i + \mathbf{n}}_{\text{interference-plus-}\textit{composite}\text{-noise}} = \mathbf{h}_i s_i + \tilde{\mathbf{n}}_i \end{aligned} \tag{4}$$



(a)

Fig. 1: The influence of the σ_t^2 on the BLER performance of the proposed LMMSE-PIC receiver with Out-it =4 and In-it=2.

where $\mathbf{h}_j$ denotes the j-th column of $\mathbf{H}$ and $\tilde{\mathbf{n}}_i = \mathbf{h}_i \eta_i + \sum_{j,j\neq i} \mathbf{h}_j (e_j + \eta_j) + \mathbf{n}$ refers to the residual interference plus the *composite* noise (including the influence of the Tx-noise).

3) MMSE Filtering Considering the Tx-Noise: Based on (4), the N_T MMSE filter vectors minimizing the mean-squared error (MSE) between the filtered (and interference-cancelled) vector $\hat{\mathbf{y}}_i$ and the transmitted symbol on the i-th stream are computed

$$\begin{aligned}\tilde{\mathbf{w}}_i^H &= \mathbf{h}_i^H \left(\mathbf{h}_i \mathbf{h}_i^H + \sum\nolimits_{j,j\neq i} (E_j + \sigma_t^2) \mathbf{h}_j \mathbf{h}_j^H + \sigma_t^2 \mathbf{h}_i \mathbf{h}_i^H + \sigma^2 \mathbf{I}_{N_R}\right)^{-1} \\ &= \mathbf{h}_i^H \left(\mathbf{H} \tilde{\boldsymbol{\Lambda}}_i \mathbf{H}^H + \sigma^2 \mathbf{I}_{N_R}\right)^{-1}\end{aligned} \tag{5}$$

where $\tilde{\boldsymbol{\Lambda}}_i$ is a real-valued $N_T \times N_T$ diagonal matrix having entries

$$\tilde{\boldsymbol{\Lambda}}_{j,j} = \left\{ \begin{array}{ll} E_j + \sigma_t^2, & j, j \neq i \\ 1 + \sigma_t^2, & j = i. \end{array} \right\} \tag{6}$$

The i-th result of the MMSE filtering process is given by $\tilde{z}_i = \tilde{\mathbf{w}}_i^H \hat{\mathbf{y}}_i = \tilde{\mu}_i s_i + \tilde{\mathbf{w}}_i^H \tilde{\mathbf{n}}_i$, where $\tilde{\mu}_i = \tilde{\mathbf{w}}_i^H \mathbf{h}_i$.

4) Extrinsic LLR Computation: The extrinsic LLRs of the transmitted bits are then computed as $L_{i,b}^E \approx \min_{s \in \mathcal{X}_{i,b}^{(0)}} \left(\frac{|\tilde{z}_i - \tilde{\mu}_i s|^2}{\tilde{\nu}_i^2} + \sum_{k=1, k\neq b}^{M_c} \frac{(2x_{i,k}-1)}{2} L_{i,k}^A \right) - \min_{s \in \mathcal{X}_{i,k}^{(1)}} \left(\frac{|\tilde{z}_i - \tilde{\mu}_i s|^2}{\tilde{\nu}_i^2} + \sum_{k=1, k\neq b}^{M_c} \frac{(2x_{i,k}-1)}{2} L_{i,k}^A \right)$ where $\mathcal{X}_{i,b}^{(0)}$ and $\mathcal{X}_{i,b}^{(1)}$ designate the sets of candidate symbol vectors corresponding to $x_{i,b} = 0$ and $x_{i,b} = 1$, respectively, and $\tilde{\nu}_i^2 = \mathrm{Var}[\tilde{z}_i] = \tilde{\mathbf{w}}_i^H \left(\sum_{j,j\neq i} (E_j + \sigma_t^2 \mathbf{h}_j \mathbf{h}_j^H) + \sigma_t^2 \mathbf{h}_i \mathbf{h}_i^H + \sigma^2 \mathbf{I}_{N_R} \right) \tilde{\mathbf{w}}_i$.

IV. Simulation Comparison

In this section, we evaluate the performance of the proposed LMMSE-PIC iterative receiver and the conventional one with different EVMs[2] over the extended vehicular (EVA) model.

[2]The 3GPP LTE standard [11] specifies the minimum EVM requirements of −18.06 and −21.93 dB, respectively, for 16-QAM and 64-QAM. EVM-values used in this work were based the minimum EVM requirements specified in established standards and from publications of state-of-the art implementations.

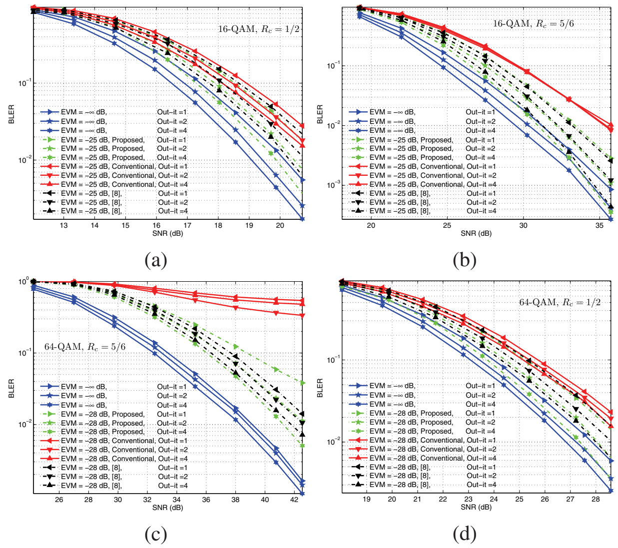


Fig. 2: BLER comparisons of the proposed method, Tx-noise whitening method [8] and the conventional one with different EVMs.

The simulation parameters are closely conforming to the 3GPP LTE standard [10]. We consider a turbo-coded $N_T = N_R = 4$ MIMO-OFDM multiplexing system with code rates $R_c = 1/2$ or $R_c = 5/6$ [10]. Imperfect channel estimation with estimation error-to-signal ratio (ESR) = 1/SNR was assumed, where the ESR is the ratio of the energy of the elements of $\Delta\mathbf{H}$ to the energy of the elements of $\mathbf{H}$, i.e., ESR = $\frac{\mathbb{E}\{|\Delta\mathbf{H}_{i,j}|^2\}}{\mathbb{E}\{|\mathbf{H}_{i,j}|^2\}}$. Note that Out-it in Fig. 1 stands for the outer parallel interference cancellation iteration and In-it denotes the number of turbo decoding iterations. The number of inner iteration of the turbo decoder was set to be 2 in all cases.

A. Impacts of σ_t^2

Since the proposed transceiver-impairments-aware method requires the *a prior* information of the Tx-noise power, we first investigated the impact of the accuracy of the estimated Tx-noise power on the block error rate (BLER) performance of the proposed LMMSE-PIC iterative receiver with different EVMs. We utilized the method proposed in [12] to estimate the EVM. The legend "Tx-noise est. [12]" indicates that the transmitter noise power is estimated with the technique introduced in [12]. We also provided numerical results based on empirically determined Tx-noise power. The legend "Under/Over-est. 50% σ_t^2" denotes that σ_t^2 is set to be 50% lower/larger than the true Tx-noise power. Fig. 1 illustrates that the degradation caused by the underestimation or overestimation of the ideal Tx-noise (even up to 150%) is negligible for 64-QAM with code rate-5/6 and EVM of −28 dB. The proposed method with 50% overestimation of the true Tx-noise power performs slightly better than that with the 50% underestimation of the Tx-noise power.

It is also shown in Fig. 1 that the Tx-noise estimated method achieves almost identical performance to the case with perfectly known Tx-noise power. Since the Tx-noise at the transmitter side changes slowly, the estimation of the Tx-noise power is low duty-cycled (e.g., frame based). The overhead of the SNR-based Tx-noise power estimation method [12] is therefore negligible compared with that of the iterative detection. The detailed computational complexity analysis is not provided in this work due to lack of space. (Furthermore, the SNR estimation is normally required for other receiver sub-block processing, e.g., channel quality indicator feedback.)

Remark 1: Numerical results (not fully shown due to the space constraints) shows that the proposed method (based on estimated Tx-noise power or empirically determined Tx-noise power) exhibits great resilience to the error of the transmitter noise power σ_t^2 (either estimation based [12] or the proposed empirically determined). Based on these results, the minimum EVM requirements specified in established standards and the publications of state-of-the-art implementations, we can select $\sigma_t^2 = -25$ dB as a conservative pre-set choice for practical applications.

B. Comparisons with the Tx-noise Whitening Method and the Conventional One

The BLER performance of the 16-QAM and 64-QAM are depicted, respectively, in Figs. 2a–2b and Figs. 2c–2d. The σ_t^2 was set to be −25 dB for the proposed LMMSE-PIC iterative receiver based on the analysis of Section IV-A.

For 16-QAM with code rate-1/2, Fig. 2a shows that the conventional LMMSE-PIC iterative receiver with Out-it = 1 and In-it = 2 suffers from a performance loss of about 1.5 dB at BLER of 10^{-1} for the EVM of −25 dB compared with the ideal system (i.e., $-\infty$ dB EVM). For the high code rate-5/6, the degradation caused by residual transceiver impairments is more pronounced, i.e., about 4.3 dB at BLER of 10^{-1} due to the greater dominance of the Tx-noise $\boldsymbol{\eta}$ in the high-SNR regime (compared with that of the rate-1/2) as shown in Fig. 2b. The proposed LMMSE-PIC iterative receiver yields about 0.5 dB improvement at BLER of 10^{-1} over the conventional one for the code rate-1/2. A greater performance gain of approximately 1.9 dB at BLER of 10^{-1} is obtained for the high code rate-5/6 in the high-SNR region where the contribution of the Tx-noise to the overall noise is more significant. It is also shown in Fig. 2a that the proposed method achieves greater performance gain over the conventional one as the number of iterations increases in the medium-SNR region for 16-QAM with code rate 1/2. This is attributed to the ignorance of the Tx-noise of the conventional method which leads to undesirable disturbance in the iterative detection process, thus retarding the convergence of the iterative detection (of the conventional one). It is shown in Fig. 2b that the BLER results of the conventional method even fail to converge in the high SNR region (the BLER of the Out-it of 4 is even worse than that of the Out-it of 2). This is because the unattended spatially-colored Tx-noise which is a dominant factor in the high SNR region ruined the iterative detection (in the high SNR regime).

Fig. 2a illustrates that the proposed method with Out-it = 4 achieves performance gain of about 0.5 dB at BLER of 10^{-2} over the Tx-noise whitening method [8]. We explain the results as follows. Since the *instantaneous* statistics of the whitened noise vector of the non-ideal transceiver is only quasi-Gaussian distributed (i.e. *approximated* as that of the Gaussian one of the ideal transceiver), there is still a certain amount of *residual* spatially-colored Tx-noise elements after the noise-whitening operation. The residual spatially-colored Tx-noise components at the receiver exhibit different degrees of intensities on the effects of the BLER performance in different SNR regions. For code rate-1/2, the advantageous effects derived from the noise-whitening operation is less prominent than that of the proposed Tx-noise-aware technique in the medium-SNR region. For 16-QAM with code rate-5/6, Fig. 2b illustrates that the Tx-noise whitening approach with Out-it = 1 slightly outperforms the proposed method due to the greater influence of the noise-whitening operation in the higher SNR regime. As the IDD proceeds, the proposed Tx-noise-aware operation becomes more effective in mitigating the detrimental impact of the Tx-noise and thus achieves a better performance than the noise-whitening approach after 2 outer iterations. It is also shown in Fig. 2b that the performance gain of the proposed method over the noise-whitening approach is slightly less for code rate-5/6 (compared with code rate-1/2) due to the greater influence of the noise-whitening operation in higher SNR regions.

As expected, the conventional LMMSE-PIC iterative receiver is more sensitive to the residual transceiver impairments for 64-QAM and code rate-5/6 as illustrated in Fig. 2c. Even for a more stringent EVM of −28 dB, the degradation is about 9.5 dB at BLER of 4×10^{-1} compared with that of the ideal case with Out-it = 1 and In-it = 2. The proposed LMMSE-PIC iterative receiver achieves a significant performance gain of approximately 5.5 dB over the conventional one at BLER of 3×10^{-1} since the Tx-noise $\boldsymbol{\eta}$ dominates in the high SNR regime. Similar to that of the 16-QAM, the degradation caused by residual transceiver impairments for the low code rate-1/2 is smaller, i.e., about 1.9 dB at BLER of 10^{-1} due to the greater influence of the Rx-noise (in that region) as illustrated in Fig. 2d. The proposed method obtains about 0.7 dB performance gain over the conventional one at BLER of 1×10^{-1} for the same reason as that of the 16-QAM.

It is shown in Fig. 2c that the Tx-noise whitening approach with Out-it = 1 achieves more performance gain over the proposed method for code rate-5/6 compared with 16-QAM due to the greater influence of the noise-whitening operation in the first iteration. Similar to that of the 16-QAM, the proposed Tx-noise-aware method excels in later iterations for its greater Tx-noise mitigation properties over the noise-whitening approach. For 64-QAM with code rate-1/2, the BLER results of the Tx-noise whitening method [8] exhibit a similar trend as that of 16-QAM as shown in Fig. 2d and Fig. 2b.

Remark 2: Numerical results show that the performance of the conventional transceiver-impairments-agnostic LMMSE-PIC iterative receiver degrades significantly in high SNR scenarios for practical MIMO systems (with residual transceiver impairments). As expected, the proposed transceiver-impairments-aware LMMSE-PIC iterative receiver achieves greater performance gain in the *Tx-noise-limited* region (i.e., high SNR regime) than that in the *Rx-noise-limited* one.

V. Conclusion

In this work, it was revealed that (even small) residual transceiver impairments severely degrade the performance of the LMMSE-PIC iterative receiver in high SNR scenarios and should therefore be considered in the corresponding performance analysis and system design. We proposed a transceiver-impairments-aware technique to mitigate the detrimental effects of the imperfections of the non-ideal hardware for realistic implementations. Numerical results demonstrated that the proposed LMMSE-PIC iterative receiver based on estimated or empirically determined Tx-noise achieves significant performance gain over the conventional one for practical MIMO systems (with residual transceiver impairments) and exhibits great resilience to the error of the estimation of the transmitter noise power. The attendant cost of the proposed method based on empirically determined Tx-noise power is negligible [c.f. (6)] and its implementation has no effect on the architecture of the LMMSE-PIC algorithms (c.f. [4], [5]). These properties render the proposed mitigation method suitable for implementation in practical systems.

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