Joint Estimation of Channel and IQ Imbalance in Media-based Modulation

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***Abstract*—In direct conversion radio frequency (RF) front-end architecture, RF impairments such as IQ imbalance (IQI), DC offset, flicker noise, and oscillator leakage can affect the performance. In this work, we study the performance of media-based modulation (MBM), an attractive channel modulation scheme, in the presence of transmit and receiver side IQI and propose efficient compensation techniques. MBM is shown to be more resilient to IQI compared to conventional modulation. A scheme which jointly estimates and compensates the channel and IQI parameters using widely linear least squares estimation is proposed. The proposed scheme is shown to alleviate the transmit and receive IQI-induced BER degradation in MBM.**

***Index Terms*—Media-based modulation, IQ imbalance, IQI compensation, widely linear processing.**

I. Introduction

The use of direct conversion architecture (also called the homodyne architecture) in the analog front-end in wireless transceivers is a promising approach to achieve highly integrated, low cost, and low power wireless hardware [1]. In direct conversion receivers, the received RF signal is down-converted to base band without any intermediate frequency (IF) stage, unlike in heterodyne receivers which have an IF stage. An advantage of this approach is that there is no need for an image rejection filter since the IF is zero in direct conversion receivers. Further, the use of low pass filters and baseband amplifiers in homodyne architecture (instead of bandpass image reject filters in heterodyne architecture) allows monolithic integration, and hence better form factor. Despite these advantages, the homodyne architecture leads to non-idealities such as DC offset, IQ mismatch, flicker noise, and LO leakage. Although the homodyne architecture can eliminate the image in the ideal sense, this is not the case in practice. For instance, there are amplitude and phase imbalances in the analog front-end between the in phase (I) and quadrature phase (Q) branches due to the finite tolerances of the analog components used. These imbalances result in frequency translation and hence mixing of signal and image components [2], leading to degradation in performance. Characterization of this performance degradation and compensation techniques have been investigated in the literature when conventional modulation schemes such as QAM/PSK, OFDM are used [2],[3],[4].

In this paper, we address the issue of IQ imbalance and compensation in 'media-based modulation' (MBM), a recently proposed modulation scheme where information bits are conveyed not only through QAM/PSK symbols but also through the indices of RF mirrors that are used as digitally controlled scatterers [5]-[11]. We briefly introduce MBM as follows. MBM uses digitally controlled parasitic elements, called RF mirrors, in the near field of the transmit antenna. These RF mirrors act as RF signal scatterers that define the propagation environment near the transmit antenna. Each of these mirrors either reflects (in mirror ON state) the RF signal radiated by the antenna or allows (in mirror OFF state) the RF signal to pass through. If there are m_{rf} RF mirrors, then there are $2^{m_{rf}}$ possible ON and OFF combinations. Each such combination, called the 'mirror activation pattern' (MAP), results in a different near-field geometry experienced by the transmitted RF signal. In a rich scattering environment, a small perturbation in the near field of the transmit antenna gets augmented by random reflections, resulting in different channel fade realizations for different MAPs at a receiver in the far field. Therefore, corresponding to m_{rf} RF mirrors, $2^{m_{rf}}$ different independent channel fades can be created by activating different MAPs. The transmitter chooses one of the $2^{m_{rf}}$ MAPs based on the m_{rf} information bits. In addition, the antenna transmits a symbol from a conventional modulation alphabet $\mathbb{A}$ (e.g., QAM) based on $\log_2|\mathbb{A}|$ bits. Therefore, the achieved rate in MBM is given by $m_{rf} + \log_2|\mathbb{A}|$ bits per channel use (bpcu).

MBM has been shown to possess attractive performance, rate, and complexity attributes [6],[8]. However, in studying the performance of MBM, all the previous works have assumed ideal analog front-ends. It is of interest to know how sensitive is MBM to IQ imbalance (IQI) as well as to devise compensation techniques that can alleviate the performance degradation due to IQI. This paper addresses this issue. We first derive the system model of MBM in the presence of IQI and characterize how the presence of IQI can degrade the bit error rate (BER) performance of MBM. We show that MBM is more tolerant to IQI compared to conventional modulation. We then formulate the joint channel and IQI parameter estimation problem, where the channel and IQI parameters are estimated in the channel estimation phase. Widely linear least squares (WLLS) solution is obtained for this problem. Simulation results show that the channel and IQI parameters jointly estimated using WLLS technique when used for MBM signal detection achieves very good BER performance.

The rest of the paper is organized as follows. The MBM input-output system model in the presence of transmit and receive IQ imbalances is derived in Sec.II and the degradation in BER due to IQI is studied through simulation results. In Sec. III, we propose widely linear least squares solution for the joint channel and IQ estimation and compensation. Finally, conclusions are presented in Sec. IV.

II. MBM with IQ imbalance: system model

Consider an MBM system with a single transmit antenna and m_{rf} RF mirrors placed near it. Let n_r be the number of receive antennas. Corresponding to m_{rf} RF mirrors, $N_m \triangleq 2^{m_{rf}}$ MAPs are possible. Let $\mathbf{h}_k$ denote the $n_r \times 1$ channel gain vector corresponding to the kth MAP, where $\mathbf{h}_k = [h_k^1 \ h_k^2 \ \cdots \ h_k^{n_r}]^T$, h_k^i is the channel gain between the transmit antenna and the ith receive antenna when the kth MAP is chosen at the transmitter, $i = 1, \cdots, n_r$, $k = 1, \cdots, N_m$. The channel gains are assumed to be distributed i.i.d complex Gaussian with zero mean and unit variance, that is, $h_k^i \overset{\text{i.i.d}}{\sim} \mathcal{CN}(0,1)$ [6],[8]. The MBM channel matrix, denoted by $\mathbf{H}$, is the collection of the channel gain vectors corresponding to N_m MAPs, i.e., $\mathbf{H} = [\mathbf{h}_1 \mathbf{h}_2 \cdots \mathbf{h}_{N_m}]$. In a given channel use, one of the N_m MAPs is chosen based on m_{rf} information bits. Further, a symbol $x = x_I + jx_Q \in \mathbb{A}$ is transmitted from the antenna.

Define $\mathbb{A}_0 \triangleq \mathbb{A} \cup 0$. The MBM signal set, denoted by $\mathbb{S}_{\text{mbm}}$, is the set of $N_m \times 1$-sized MBM signal vectors, given by [8]

$$\begin{aligned}\mathbb{S}_{\text{mbm}} = \Big\{ & \mathbf{s}_k \in \mathbb{A}_0^{N_m} : k = 1, \cdots, N_m \Big\} \\ & \text{s.t } \mathbf{s}_k = [0 \cdots 0 \ \underbrace{x}_{k\text{th coordinate}} \ 0 \cdots 0]^T, \ x \in \mathbb{A}, \end{aligned} \tag{1}$$

where k is the index of the MAP. That is, an MBM signal vector $\mathbf{s}_k$ in (1) denotes that the complex symbol $x \in \mathbb{A}$ is transmitted on a channel whose gains are given by $\mathbf{h}_k$. The $n_r \times 1$ received signal vector when the MBM signal vector $\mathbf{s}_k$ is transmitted is given by

$$\begin{aligned}\mathbf{y} &= x\mathbf{h}_k + \mathbf{n} \\ &= \mathbf{H}\mathbf{s}_k + \mathbf{n},\end{aligned} \tag{2}$$

where $\mathbf{n}$ is the $n_r \times 1$ complex additive Gaussian noise vector whose entries are i.i.d $\mathcal{CN}(0, \sigma^2)$.

Consider that the transmit RF chain is impaired with IQI. Let g_T and ϕ_T denote the gain and phase imbalances, respectively. The transmitted symbol with IQI is given by [12],[13]

$$x_{IQ} = G_1 x + G_2 x^*, \tag{3}$$

where $G_1 \triangleq \frac{1+g_T e^{j\phi_T}}{2}$ and $G_2 \triangleq \frac{1-g_T e^{j\phi_T}}{2}$. For an ideal system with no IQI, $g_T = 1$ and $\phi_T = 0$. The MBM signal vector in the presence of transmit IQI is then given by

$$\begin{aligned}\mathbf{x}_{IQ} &= [0 \cdots 0 \ \underbrace{x_{IQ}}_{k\text{th entry}} \ 0 \cdots 0]^T \\ &= [0 \cdots 0 \ \underbrace{G_1 x}_{k\text{th entry}} \ 0 \cdots 0]^T + [0 \cdots 0 \ \underbrace{G_2 x^*}_{k\text{th entry}} \ 0 \cdots 0]^T \\ &= G_1 \mathbf{x} + G_2 \mathbf{x}^*,\end{aligned} \tag{4}$$

where $\mathbf{x} = [0 \cdots 0 \ \underbrace{x}_{k\text{th entry}} \ 0 \cdots 0]^T$ is the ideal MBM signal vector in the absence of IQI at the transmitter. The received signal vector (in the absence of IQI in the receive RF chain) is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x}_{IQ} + \mathbf{n}, \tag{5}$$

where $\mathbf{H}$ and $\mathbf{n}$, respectively, are the MBM channel matrix and the noise vector as described before.

Now, if the receive RF chains are also IQ impaired, then the received signal at the ith receive antenna is given by

$$y_{IQ,i} = K_{1,i} y_i + K_{2,i} y_i^*, \tag{6}$$

where y_i is the ith element of $\mathbf{y}$, $K_{1,i} \triangleq \frac{1+g_{R,i} e^{-j\phi_{R,i}}}{2}$, and $K_{2,i} \triangleq \frac{1-g_{R,i} e^{j\phi_{R,i}}}{2}$, where $g_{R,i}$ and $\phi_{R,i}$ are the gain and phase imbalances in the ith receive RF chain, respectively. For an ideal receive RF chain, $g_{R,i} = 1$ and $\phi_{R,i} = 0$. Define $\mathbf{K}_1 \triangleq \text{diag}(K_{1,1}, \cdots, K_{1,n_r})$ and $\mathbf{K}_2 \triangleq \text{diag}(K_{2,1}, \cdots, K_{2,n_r})$. The $n_r \times 1$ received signal vector with IQ imbalances at both the transmit and receive RF chains is then given by

$$\begin{aligned}&\mathbf{y}_{IQ} = \mathbf{K}_1\mathbf{y} + \mathbf{K}_2\mathbf{y}^* \\ &= (G_1\mathbf{K}_1\mathbf{H} + G_2^*\mathbf{K}_2\mathbf{H}^*)\mathbf{x} + (G_2\mathbf{K}_1\mathbf{H} + G_1^*\mathbf{K}_2\mathbf{H}^*)\mathbf{x}^* + (\mathbf{K}_1\mathbf{n} + \mathbf{K}_2\mathbf{n}^*) \\ &= \mathbf{H}_{eff}\mathbf{x} + \mathbf{H}_{int}\mathbf{x}^* + \tilde{\mathbf{n}},\end{aligned} \tag{7}$$

where $\mathbf{H}_{eff} \triangleq G_1\mathbf{K}_1\mathbf{H} + G_2^*\mathbf{K}_2\mathbf{H}^*$ is the effective channel for the desired signal $\mathbf{x}$, $\mathbf{H}_{int} \triangleq G_2\mathbf{K}_1\mathbf{H} + G_1^*\mathbf{K}_2\mathbf{H}^*$ is the channel for the *image signal* $\mathbf{x}^*$, and $\tilde{\mathbf{n}} \triangleq \mathbf{K}_1\mathbf{n} + \mathbf{K}_2\mathbf{n}^*$ is the effective noise vector. From (7), it can be seen that, the received signal vector consists of the desired signal component $\mathbf{H}_{eff}\mathbf{x}$ and the image component $\mathbf{H}_{int}\mathbf{x}^*$ that causes interference to the desired signal.

A. SImR in the presence of IQI

Due to IQI, a part of the signal energy is lost in the image signal and this results in the SNR degradation for the desired signal. It is generally desired to have the signal energy to be much higher than the energy in the image signal. This is characterized by the average received signal-to-image ratio (SImR), which is given by

$$\text{SImR} \triangleq \frac{\mathbb{E}\left\{\|\mathbf{H}_{eff}\mathbf{x}\|^2\right\}}{\mathbb{E}\left\{\|\mathbf{H}_{int}\mathbf{x}^*\|^2\right\}} = \frac{\sum_{i=1}^{n_r} \mathbb{E}\left(|(\mathbf{H}_{eff})_i\mathbf{x}|^2\right)}{\sum_{i=1}^{n_r} \mathbb{E}\left(|(\mathbf{H}_{int})_i\mathbf{x}^*|^2\right)}, \tag{8}$$

where $(\mathbf{H}_{eff})_i$ and $(\mathbf{H}_{int})_i$ denote the ith rows of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$, respectively. We have

$$\begin{aligned}\mathbb{E}\left(|(\mathbf{H}_{eff})_i\mathbf{x}|^2\right) &= \mathbb{E}\left\{|\left(G_1K_{1,i}(\mathbf{H})_i + G_2^*K_{2,i}(\mathbf{H}^*)_i\right)\mathbf{x}|^2\right\} \\ &= (|G_1|^2|K_{1,i}|^2 + |G_2|^2|K_{2,i}|^2)E_s,\end{aligned} \tag{9}$$

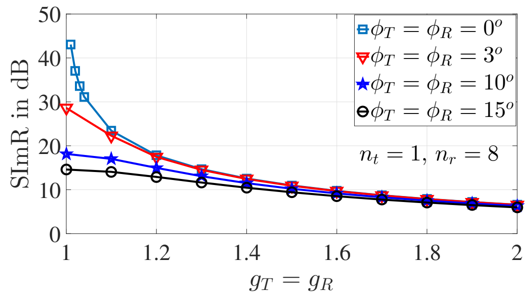
where $E_s \triangleq \mathbb{E}(|x|^2), x \in \mathbb{A}$. Similarly,

$$\begin{aligned}\mathbb{E}\left(|(\mathbf{H}_{int})_i\mathbf{x}^*|^2\right) &= \mathbb{E}\left\{|\left(G_2K_{1,i}(\mathbf{H})_i + G_1^*K_{2,i}(\mathbf{H}^*)_i\right)\mathbf{x}^*|^2\right\} \\ &= (|G_2|^2|K_{1,i}|^2 + |G_1|^2|K_{2,i}|^2)E_s.\end{aligned} \tag{10}$$

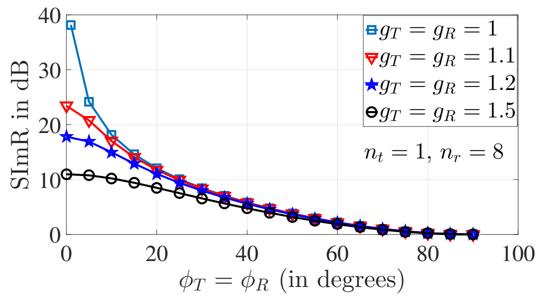
Therefore, the average SImR is given by

$$\begin{aligned}\text{SImR} &= \frac{\sum_{i=1}^{n_r}(|G_1|^2|K_{1,i}|^2 + |G_2|^2|K_{2,i}|^2)E_s}{\sum_{i=1}^{n_r}(|G_2|^2|K_{1,i}|^2 + |G_1|^2|K_{2,i}|^2)E_s} \\ &= \frac{|G_1|^2\,\text{Tr}(\mathbf{K}_1^H\mathbf{K}_1) + |G_2|^2\,\text{Tr}(\mathbf{K}_2^H\mathbf{K}_2)}{|G_2|^2\,\text{Tr}(\mathbf{K}_1^H\mathbf{K}_1) + |G_1|^2\,\text{Tr}(\mathbf{K}_2^H\mathbf{K}_2)},\end{aligned} \tag{11}$$

where $\text{Tr}(\cdot)$ denotes the trace operation. The image rejection ratio (IMRR), the ratio of average powers in the image and the signal, is related to the SImR by $\text{IMRR} = 1/\text{SImR}$.



(a) SImR vs gain imbalance



(b) SImR vs phase imbalance

Fig. 1: SImR as a function of (a) gain imbalance for different $\phi_T = \phi_R$, and (b) phase imbalance for different $g_T = g_R$.

Figures 1a and 1b show the variation of SImR as a function of gain imbalance (at different phase imbalances) and phase imbalance (at different gain imbalances). Figure 1a shows SImR variation with gain imbalance for phase imbalances of $0°, 3°, 10°$, and $15°$. An ideal value of infinite SImR is achieved when gain and phase are perfectly matched ($g_T = g_R = 1$ and $\phi_T = \phi_R = 0°$). For $\phi_T = \phi_R \neq 0$, even with ideal gain matching ($g_T = g_R = 1$), there is degradation in SImR. The SImR further degrades with increase in gain imbalance. A similar observation can be made from Fig. 1b, which shows the variation of SImR as a function of phase imbalance at various gain imbalance values of 1, 1.1, 1.2, and 1.5.

B. BER performance of MBM with IQI

We now present the BER performance of MBM in the presence of IQI when $\mathbf{H}_{eff}$ is assumed to be perfectly known at the receiver and the detection rule is given by

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}_{\text{mbm}}}{\text{argmin}} \|\mathbf{y}_{IQ} - \mathbf{H}_{eff}\mathbf{x}\|^2. \tag{12}$$

Figure 2 shows the uncoded and coded BER performance of MBM system with and without Tx-Rx IQ imbalances as a function of SNR. The considered MBM system uses $n_t = 1$, $m_{rf} = 4$, $n_r = 4$, and 16-QAM. The uncoded system achieves a rate of 8 bpcu. The coded MBM system uses rate-1/3 Reed-Solomon (RS) code and achieves a rate of 8/3 bpcu. The figure also shows the performance of the spatial multiplexing (SMP) system with and without Tx-Rx IQI. The considered SMP system uses $n_t = 2$, $n_r = 4$, and 16-QAM. The uncoded SMP system achieves the rate of 8 bpcu. Rate-1/3 RS code is used, achieving a rate of 8/3 bpcu for coded SMP. From

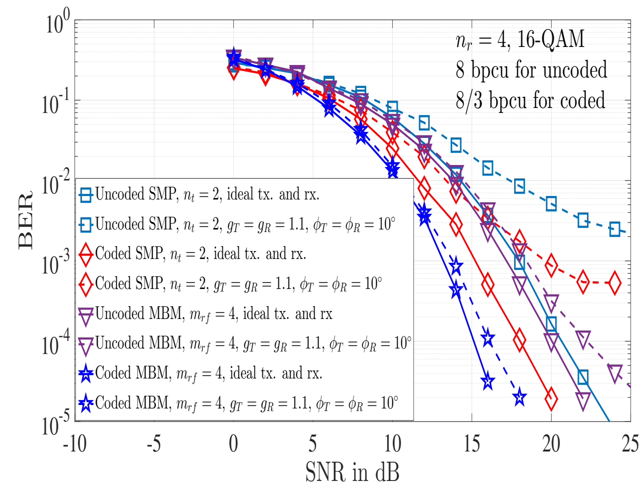


Fig. 2: Uncoded and coded BER performance of MBM and SMP systems without and with IQ imbalance.

Fig. 2, it can be seen that the BER performance degrades in both MBM and SMP due to the presence of IQI. However, it can be observed that, for the same QAM order (16-QAM), the degradation in MBM is less compared to that in SMP. For example, with transmit and receive IQI of $g_T = g_R = 1.1$ and $\phi_T = \phi_R = 10°$, the performance of uncoded MBM degrades by about 2.5 dB compared to uncoded MBM with ideal IQ branches. Whereas, for the same IQI values, the degradation is much severe in uncoded SMP (with BER flooring at about 10^{-3}). A similar trend can be seen in the coded setting.

The observed performance advantage in MBM compared to SMP in Fig. 2 is further highlighted in Figs. 3a and 3b, which demonstrate the better resilience of MBM to IQI. These figures show the SNR degradation in MBM and SMP systems as a function of rate (in bpcu), in the presence of IQI ($g_T = 1.1$, $\phi_T = 10°$) at a BER of 2.5×10^{-3}. Both the systems use the same modulation alphabet to achieve a given rate. It can be observed that MBM has less SNR degradation due to IQI compared to that in SMP, and that the performance gap between MBM and SMP becomes increasingly favorable to MBM with increasing rate. For example, at 10 bpcu, SMP with $n_t = 2$ and MBM using $m_{rf} = 5$, both systems using 32-QAM, the degradation in SNR is about 15 dB in SMP, while it is just about 3 dB in MBM. This better resilience of MBM to IQI is mainly because MBM conveys a part of information bits through indexing of RF mirrors, while SMP conveys all the information bits through complex modulation symbols which are susceptible to IQI effects.

III. Joint Channel and IQI Estimation and Compensation

The results shown in the previous section assumed that $\mathbf{H}_{eff}$ in (7) is perfectly known at the receiver. However, in practice, $\mathbf{H}_{eff}$ has to be estimated before it can be used for symbol detection. Here, we first present least squares (LS) estimation of $\mathbf{H}_{eff}$. It is known from (7) that there is an image signal

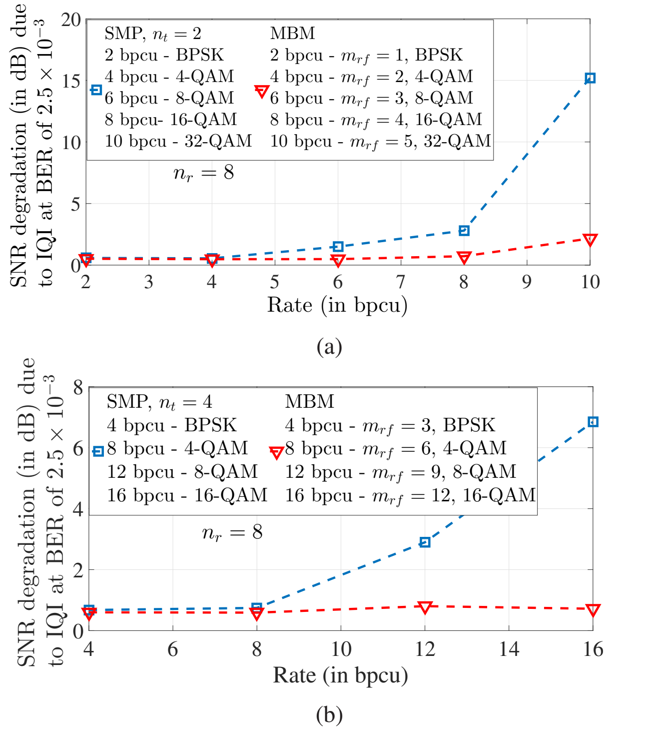


Fig. 3: SNR degradation as a function of rate in MBM and SMP systems at 2.5×10^{-3} BER.

$\mathbf{H}_{int}\mathbf{x}^*$ in the presence of IQI, which acts as interference. If $\mathbf{H}_{int}$ can also be estimated, then the image signal can also be used in the signal detection to achieve better performance. In this direction, we propose to do joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ using WLLS. The joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ is equivalent to joint channel and IQI estimation, since all the IQI parameters are embedded in $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$. Therefore, IQI need not be separately estimated and compensated at either the transmitter or the receiver.

A. LS estimation of $\mathbf{H}_{eff}$ (Method 1)

Let $\mathbf{P} = [\mathbf{p}_1, \cdots, \mathbf{p}_p]$ be the $N_m \times p$, $p \geq N_m$ training signal matrix for estimating $\mathbf{H}_{eff}$. The associated receive block in the presence of IQI is given by

$$\mathbf{Y}_{IQ} = \mathbf{H}_{eff}\mathbf{P} + \mathbf{H}_{int}\mathbf{P}^* + \tilde{\mathbf{N}}. \tag{13}$$

The LS channel estimate for $\mathbf{H}_{eff}$ considering $\mathbf{N} = \mathbf{H}_{int}\mathbf{P}^* + \tilde{\mathbf{N}}$ as the overall noise is [14]

$$\hat{\mathbf{H}}_{eff} = \mathbf{Y}\mathbf{P}^H(\mathbf{P}\mathbf{P}^H)^{-1}. \tag{14}$$

An optimal choice of training matrix $\mathbf{P}$ is one with orthogonal rows. It should be noted that, due to the structure of MBM signals, the pilot matrix is also constrained to be a sparse matrix with only a single non-zero entry in each column. For example, for $\mathbf{P} = \mathbf{I}_{N_m}$ with $p = N_m$, $\hat{\mathbf{H}}_{eff} = \mathbf{Y}_{IQ}$. Whereas, for $\mathbf{P} = [\mathbf{P}_1\mathbf{P}_2] = [\mathbf{I}_{N_m}\mathbf{I}_{N_m}]_{N_m \times 2N_m}$ with $p = 2N_m$,

$$\hat{\mathbf{H}}_{eff} = \frac{\mathbf{Y}_{IQ}^{(1)} + \mathbf{Y}_{IQ}^{(2)}}{2}. \tag{15}$$

The signal detection is then performed using $\hat{\mathbf{H}}_{eff}$ as the channel matrix.

B. Widely linear least squares based joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ (Method 2)

The presence of image signal $\mathbf{H}_{int}\mathbf{x}^*$ can degrade the BER performance of MBM even if we know $\mathbf{H}_{eff}$ perfectly. The degradation due to the presence of image is already demonstrated in the previous section. Jointly estimating $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ and using this estimate in signal detection leads to better performance. Further, since the effect of IQI is captured completely in $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$, IQI estimation and compensation by analog means can be eliminated. To perform joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$, we recognize the widely linear form [15] of the estimation problem and use the WLLS technique. Specifically, the MBM received signal vector in the presence of IQI in (7) is not strictly linear because of the presence of the image signal. But it has a specific form called 'widely linear' or 'linear conjugate-linear' form. In widely linear signal processing, this linear conjugate-linear form is converted to the complex augmented form and processing is done on this complex augmented form. The complex augmented vector $\underline{\mathbf{y}}_{IQ}$ corresponding to the complex received vector $\mathbf{y}_{IQ}$ in (7) is given by [15]

$$\underline{\mathbf{y}}_{IQ} = \underline{\mathbf{H}}\ \underline{\mathbf{x}}, \tag{16}$$

where $\underline{\mathbf{y}}_{IQ} \triangleq \begin{bmatrix} \mathbf{y}_{IQ} \\ \mathbf{y}_{IQ}^* \end{bmatrix}$, $\underline{\mathbf{H}} \triangleq \begin{bmatrix} \mathbf{H}_{eff} & \mathbf{H}_{int} \\ \mathbf{H}_{int}^* & \mathbf{H}_{eff}^* \end{bmatrix}$ is the augmented channel matrix in the presence of IQI, and $\underline{\mathbf{x}} \triangleq \begin{bmatrix} \mathbf{x} \\ \mathbf{x}^* \end{bmatrix}$ is the augmented transmit MBM signal vector. This form can be exploited for efficient joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$.

If $\mathbf{P} = [\mathbf{p}_1 \ldots \mathbf{p}_p]_{N_m \times p}$ is the pilot matrix, then the received signal matrix in the complex augmented form is given by

$$\underline{\mathbf{Y}}_{IQ} = \underline{\mathbf{H}}\ \underline{\mathbf{P}}, \tag{17}$$

where $\underline{\mathbf{Y}}_{IQ} \triangleq \begin{bmatrix} \mathbf{Y}_{IQ} \\ \mathbf{Y}_{IQ}^* \end{bmatrix}$, with $\mathbf{Y}_{IQ}$ as in (13) and $\underline{\mathbf{P}} \triangleq \begin{bmatrix} \mathbf{P} \\ \mathbf{P}^* \end{bmatrix}$. The WLLS estimate of $\underline{\mathbf{H}}$ is then given by

$$\widehat{\underline{\mathbf{H}}} = \underline{\mathbf{Y}}_{IQ}\ \underline{\mathbf{P}}^{\dagger}. \tag{18}$$

But

$$\widehat{\underline{\mathbf{H}}} = \begin{bmatrix} \widehat{\mathbf{H}}_{eff} & \widehat{\mathbf{H}}_{int} \\ \widehat{\mathbf{H}}_{int}^* & \widehat{\mathbf{H}}_{eff}^* \end{bmatrix}, \tag{19}$$

where $\widehat{\mathbf{H}}_{eff}$ and $\widehat{\mathbf{H}}_{int}$ are the WLLS estimates of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$, respectively. Therefore, to jointly estimate $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$, first (18) is computed and from this $\widehat{\mathbf{H}}_{eff}$ and $\widehat{\mathbf{H}}_{int}$ are extracted.

We now consider a simple pilot matrix $\mathbf{P} = [\mathbf{P}_1\ \mathbf{P}_2] = [\mathbf{I}_{N_m}\ j\mathbf{I}_{N_m}]_{N_m \times 2N_m}$, which is a sparse matrix with only one non-zero in each column, as required by the signal structure of MBM. The $N_m \times 2N_m$ received signal matrix is $\mathbf{Y}_{IQ} = [\mathbf{Y}_{IQ}^{(1)}\ \mathbf{Y}_{IQ}^{(2)}]$, where $\mathbf{Y}_{IQ}^{(1)}$ and $\mathbf{Y}_{IQ}^{(2)}$ are the $N_m \times N_m$ receive sub-matrices corresponding to $\mathbf{P}_1$ and $\mathbf{P}_2$, respectively. For the considered pilot $\mathbf{P}$, the augmented pilot $\underline{\mathbf{P}} = \begin{bmatrix} \mathbf{I}_{N_m} & j\mathbf{I}_{N_m} \\ \mathbf{I}_{N_m} & -j\mathbf{I}_{N_m} \end{bmatrix}$ and $\underline{\mathbf{P}}^{\dagger} = (\underline{\mathbf{P}}^H \underline{\mathbf{P}})^{-1} \underline{\mathbf{P}}^H$, which can be simplified to obtain

$$\underline{\mathbf{P}}^{\dagger} = \frac{1}{2} \begin{bmatrix} \mathbf{I}_{N_m} & \mathbf{I}_{N_m} \\ -j\mathbf{I}_{N_m} & \mathbf{I}_{N_m} \end{bmatrix}. \tag{20}$$

The WLLS estimate $\widehat{\underline{\mathbf{H}}}$ in (18) can be simplified to obtain

$$\begin{aligned} \widehat{\underline{\mathbf{H}}} &= \frac{1}{2} \begin{bmatrix} \mathbf{Y}_{IQ}^{(1)} & \mathbf{Y}_{IQ}^{(2)} \\ \mathbf{Y}_{IQ}^{(1)^*} & \mathbf{Y}_{IQ}^{(2)^*} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{N_m} & \mathbf{I}_{N_m} \\ -j\mathbf{I}_{N_m} & j\mathbf{I}_{N_m} \end{bmatrix} \\ &= \frac{1}{2} \begin{bmatrix} \mathbf{Y}_{IQ}^{(1)} - j\mathbf{Y}_{IQ}^{(2)} & \mathbf{Y}_{IQ}^{(1)} + j\mathbf{Y}_{IQ}^{(2)} \\ \mathbf{Y}_{IQ}^{(1)^*} - j\mathbf{Y}_{IQ}^{(2)^*} & \mathbf{Y}_{IQ}^{(1)^*} + j\mathbf{Y}_{IQ}^{(2)^*} \end{bmatrix}. \end{aligned} \tag{21}$$

From $\widehat{\underline{\mathbf{H}}} = \begin{bmatrix} \widehat{\mathbf{H}}_{eff} & \widehat{\mathbf{H}}_{int} \\ \widehat{\mathbf{H}}_{int}^* & \widehat{\mathbf{H}}_{eff}^* \end{bmatrix}$ and (21), the estimates for $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ are seen to be

$$\widehat{\mathbf{H}}_{eff} = \frac{\mathbf{Y}_{IQ}^{(1)} - j\mathbf{Y}_{IQ}^{(2)}}{2}, \quad \widehat{\mathbf{H}}_{int} = \frac{\mathbf{Y}_{IQ}^{(1)} + j\mathbf{Y}_{IQ}^{(2)}}{2}. \tag{22}$$

The signal detection is performed using $\widehat{\mathbf{H}}_{eff}$ and $\widehat{\mathbf{H}}_{int}$ as

$$\widehat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}_{\mathrm{mbm}}}{\operatorname{argmin}} \|\mathbf{y}_{IQ} - \widehat{\mathbf{H}}_{eff}\mathbf{x} - \widehat{\mathbf{H}}_{int}\mathbf{x}^*\|^2. \tag{23}$$

Figure 4 shows the BER performance of MBM using the estimation methods 1 and 2. The considered MBM system has $n_t = 1$, $m_{rf} = 4$, $n_r = 4$, 16-QAM, and 8 bpcu. For comparison purposes, we also show the performance of the MBM system with perfect IQ branches and ideal channel knowledge. It can be seen from the figure that, in an IQI-impaired MBM system, estimating only $\mathbf{H}_{eff}$ using LS estimation (method 1) and using it in the signal detection leads to significant performance degradation compared to the performance with LS estimation of $\mathbf{H}_{eff}$ in the MBM system with ideal IQ matching (i.e., $\mathbf{H}_{int} = 0$). The figure also shows that, in the same system with IQ impairment, the joint WLLS estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ as proposed in method 2 and using this estimate in the signal detection achieves almost the same performance as that of the LS estimation of $\mathbf{H}_{eff}$ in the MBM system with perfect IQ matching. This shows that, exploiting the widely linear structure of the received IQ-impaired MBM signal, in the joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ leads to very good performance.

IV. Conclusions

We studied MBM in the presence of IQI and showed that MBM is more tolerant to IQI compared to conventional modulation. This is because MBM conveys a part of information bits for a given bpcu through the index of the MAP, resulting in reduced number of bits conveyed through complex modulation symbols which are prone to IQI effects. Recognizing the widely linear form of the received MBM signal vector in the presence of IQI, we showed that using widely linear least squares for joint estimation of $\mathbf{H}_{eff}$ and $\mathbf{H}_{int}$ and using these estimates in signal detection can achieve good joint channel and IQI estimation and compensation. Investigation of other pilot structures, taking the non-circular nature of the noise into account for estimation/compensation, and switching effects of RF mirrors can be considered for future work.

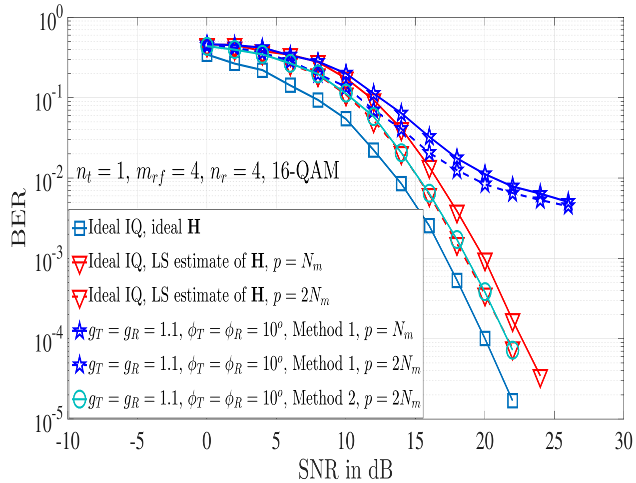


Fig. 4: BER performance of IQI-impaired MBM with the proposed channel/IQI estimation using methods 1 and 2.

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