Performance Analysis of Coherent and Noncoherent Modulation under I/Q Imbalance Effects

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ABSTRACT

In this paper, we investigate the effects of in-phase/quadrature-phase imbalance (IQI) on the performance of different modulation schemes under multipath fading channels. In particular, a comprehensive framework for the analysis of coherent and noncoherent modulation with IQI is proposed. Specifically, new moment generating function (MGF) expressions for both point-to-point and multiple antenna systems are derived for the cases of transmitter IQI, receiver IQI, and joint transmitter/receiver IQI. Based on the derived MGFs, new analytical expressions for the corresponding symbol error rate (SER) are derived and are subsequently used to provide deep insights into the effects of IQI on the system performance. It is shown that, while in some cases the SER performance degradation due to IQI is marginal, in other cases, this impairment is more pronounced. Accordingly, IQI compensation is of paramount importance as it can guarantee a reliable communication link. This is particularly important in demanding communication technologies where reduction of latency and complexity are essential.

INDEX TERMS

I/Q imbalance, coherent detection, noncoherent detection, RF impairments, symbol error rate.

I. INTRODUCTION

The idea of connecting every single device or "thing" to the Internet has led to the development of a revolutionary technology, dubbed as the Internet of things (IoT), that is progressively conquering every aspect of our modern lives. Indeed, given the substantial benefits that can be drawn from this simple, yet mighty, idea, numerous derivatives have emerged, such as the industrial IoT (IIoT), the Internet of vehicles (IoV), the Internet of healthcare things (IoHT), etc. Consequently, future radio networks are envisioned to support heterogeneous devices belonging to different sets of standards and services, which demands for software reconfigurable transceivers that can be adaptive enough to support the associated quality of service requirements. Therefore, given their suitability for high levels of integration as well as their low cost and power consumption, direct conversion transceivers, which do not require any external intermediate frequency/image rejection filters, have attracted considerable attention.

However, from a practical perspective, these transceiver architectures unavoidably experience radio-frequency (RF) front-end related impairments, such as phase noise, DC offset, and in-phase/quadrature-phase imbalances (IQI), which affect the system performance [1]. Here, IQI denotes the mismatch of amplitude and phase between the I/Q branches of direct conversion transceivers, resulting in imperfect image rejection, and hence, degradation in performance [2, 3].

Detection schemes can be classified into coherent as well as noncoherent modulation, which depend on the receiver’s (RX) ability to extract the carrier phase. In the former, a complete knowledge of the channel state information (CSI) is required at the receiver, which ultimately constitutes a sig-
nificant issue in emerging communication technologies that are characterized by demanding quality of service requirements, including particularly low latencies. On the contrary, noncoherent detection, which does not require information about the CSI, reduces the receiver complexity by eliminating the need for channel estimation and tracking [4], [5]. Thus, such schemes can be useful in low-power IoT devices [6]. However, this comes at a cost of lower spectral efficiency and/or higher error rate, thus the choice of the best modulation scheme greatly depends on the targeted application. For instance, it was shown that, due to the pilot overhead, noncoherent detection can lead to better spectral efficiency in massive multi-input multi-output (MIMO) systems [7]. The same is the case for low power devices and for ultra low latency telecommunication applications.

A. RELATED WORK

Direct conversion architectures are widely utilized in modern communication transceivers which, due to the problem of mismatch between the I/Q branches, results in residual interference from the image band. Therefore, to address this practical concern, numerous works have been proposed to model, mitigate, or even take advantage of this impairment, see [8] and the references therein.

In [9], the symbol error probability (SEP) of M-ary phase shift keying (PSK) under IQI was investigated for Gaussian channels. Assuming differential quadrature phase shift keying (DQPSK) and Rayleigh fading, the bit error rate (BER) under IQI was derived for single-carrier systems in [10] and multi-carrier systems in [11]. Moreover, in [12], assuming single-carrier modulation, the effects of IQI on the SER of different coherent and noncoherent modulations was investigated. Under the assumption of Weibull fading channels and IQI at the receiver only, the average symbol error rate (SER) of M-ary quadrature amplitude modulation (M-QAM) was derived in [13]. Similarly, for M-QAM modulation and Rayleigh fading channels, the error performance of multi-carrier systems and OFDM systems was investigated in [14], [16] and [17], respectively. For the case of Nonakagami- fading, the authors in [18] quantified the effects of IQI on the outage probability of both single-carrier and multi-carrier systems.

Finally, in [19–23], the authors analyzed the effects of IQI on the outage performance of non-orthogonal multiple access. IQI has also been studied in half-duplex and full duplex amplify-and-forward and decode-and-forward cooperative systems [24–28], two-way relay systems and multi-antenna systems [29–37], as well as cognitive radio systems [38]. Finally, the effects of IQI on uplink transmission have been analyzed in the context of massive multi-user MIMO in [39].

B. CONTRIBUTION

To the best of our knowledge, apart from some sporadic results [12], [40], the effects of IQI on noncoherent modulation have been overlooked by the scientific community. Addi-

tionally, the existing results on coherent detection consider case-specific scenarios. Thus, they do not provide a holistic treatment of IQI in single and multi-carrier coherent systems. Motivated by this fact, in this article, we extend our work in [12] and investigate the performance of single-carrier and multi-carrier based coherent and noncoherent systems under IQI.

The main objective of this paper is to present a comprehensive framework for the analysis of coherent and noncoherent modulation with different IQI scenarios. To this end, both single-carrier and multi-carrier systems are considered, where, based on the MGF approach, the effects of TX IQI, RX IQI and joint TX/RX IQI on M-PSK, M-DPSK and M-FSK constellations are quantified. The key contributions in this paper are summarized as follows:

- Assuming single-carrier systems over Rayleigh fading channels with TX and/or RX IQI, we derive novel analytic expression for the probability distribution function (PDF) of the signal-to-interference-noise ratio (SINR), based on which the cumulative distribution function (CDF) and MGF expressions are further derived.
- We extend our analysis to the case of multi-carrier transmissions with TX and/or RX IQI and derive novel closed form expressions for the SINR PDF, CDF, and MGF.
- We derive MGF expressions for L-branch MRC receivers and differential Alamouti Space-Time Block Codes (STBC)-OFDM systems under different IQI scenarios.
- Using the derived MGFs, we derive the corresponding SER expressions for M-DPSK, M-PSK and M-FSK constellations.

We quantify the achievable performance of the considered scenarios and develop useful insights of theoretical and practical importance which will be useful in highly demanding emerging technologies. To the best of our knowledge, the contributions of this work are novel and have not been reported in the literature.

C. ORGANIZATION AND NOTATIONS

The rest of this paper is organized as follows: Section II provides a brief overview of the considered modulation schemes. In Sections III and IV, the SINR PDF, CDF, and MGF are derived for single-carrier and multi-carrier systems with IQI, respectively. In addition, Section V presents the SER of M-DPSK, M-PSK, and M-FSK under IQI. The extension to the multiple antenna case is given in Section VI whereas the corresponding numerical results and discussions are elaborated in Section VII. Finally, closing remarks are given in Section VIII.

Notations

In this article, the subscripts $t/r$ denote the up/downconversion process at the TX/RX, respectively. In addition, $(\cdot)^*$ stands for conjugation and $j = \sqrt{-1}$. The operators $E[\cdot]$
denotes statistical expectation while $|\cdot|$ symbolizes absolute value operations. Finally, $f_X(x)$ and $F_X(x)$ represent the PDF and CDF of $X$, respectively while $\mathcal{M}_X(s)$ corresponds to the MGF associated with $X$.

II. SYSTEM MODEL
Considering a single antenna TX/RX where an information symbol $s$ is transmitted over a fading channel $h$ and the noise $n$ is assumed to be additive white Gaussian (AWGN). In the following, we briefly review the signal model of $M$-ary DPSK, PSK, and FSK modulation schemes.

A. COHERENT DETECTION OF $M$-PSK SYMBOLS
Assuming $M$-PSK modulation, it is recalled that

$$\theta_m = \frac{(2m-1)\pi}{M}, \quad m = 1, 2, \ldots, M$$

(1)

Hence, the complex baseband signal at the transmitter in the $l^{th}$ symbol interval is given by

$$s_l = A_c \exp(j\theta_l)$$

(2)

where $\theta_l \in \theta_m$ is the information phase in the $l^{th}$ symbol. Assuming that the receiver has perfect knowledge of the CSI as well as carrier phase and frequency, the complex baseband signal at the receiver is represented as

$$x_l = A_c \exp(j\theta_l) + n_l.$$  

(3)

B. NONCOHERENT DETECTION OF $M$-DPSK SYMBOLS
In DPSK, the information in (1) is encoded using the phase difference between two adjacent transmitted phases. Considering that the channel remains constant over two consecutive symbols, the information sequences at the receiver are decoded without the knowledge of the carrier phase by taking the difference between two adjacent phases [41]. In this context, the information phases $\Delta \theta_l$ are first differentially encoded as:

$$\theta_l = (\theta_{l-1} + \Delta \theta_l) \mod 2\pi$$

(4)

and $\Delta \theta_l$ is the information phase in the $l^{th}$ symbol. The modulated symbol $s_l$ is then obtained by applying a phase offset to the previous symbol $s_{l-1}$, namely,

$$s_l = s_{l-1} \exp(j\theta_l)$$

(6)

where $s[1] = 1$. Finally, the decision variable is extracted from the phase difference between two consecutive received symbols as follows

$$\hat{s}_l = r_{l-1}^* r_l.$$  

(7)

C. NONCOHERENT DETECTION OF $M$-FSK SYMBOLS
Assuming $M$-FSK modulation, the $M$ information frequencies are given by

$$f_m = (2m-1-M)\Delta f, \quad m = 1, 2, \ldots, M$$

(8)

and thus the $l^{th}$ complex baseband symbol at the transmitter is given by

$$s_l(t) = A_c \exp(jf_l(t - lT_s)).$$

(9)

where $f_l \in f_m$ is the frequency of the $l^{th}$ transmitted symbol and $T_s$ is the symbol period. The decision variable at the receiver is then obtained by multiplying the received signal by the set of complex sinusoids

$$\exp(-j2\pi f_m(t - lT_s)), \quad m = 1, 2, \ldots, M,$$

passing them through $M$ matched filters. For orthogonal signals, the frequency spacing is chosen as $\Delta f = N/T_s$, where $N$ is an integer.

III. MGF OF SINGLE-CARRIER SYSTEMS
Single-carrier modulation is receiving increasing attention due to its resilience against RF impairments compared to multi-carrier modulation, see [42] and the references therein. Hence, it is considered more suitable for low complexity and low power applications. Assuming single antenna transceivers, we derive unified closed form expressions for the SINR PDF, CDF, and MGF over flat fading Rayleigh channels and under the influence of IQI at the TX and/or RX.

At the receiver side, the bandpass signal received by the RF front end is passed through processing stages including I/Q demodulation (i.e., down-conversion). Under the assumption of ideal RF front end, the baseband equivalent of the received signal can be written as

$$r_{id} = hs + n$$

(10)

where the index $l$ is dropped for convenience. Moreover, $h \sim CN(0,1)$ represents the channel fading gain and $n \sim CN(0, N_0)$ is the additive white noise term. The instantaneous signal-to-noise ratio (SNR) per symbol is expressed as

$$\gamma_{id} = \frac{E_s}{N_0} |h|^2$$

(11)

where $E_s$ symbolizes the energy per transmitted symbol. The time-domain baseband representation of the IQI impaired signal is expressed by [43]

$$g_{qid} = \mu_{t/r} g_{id} + \nu_{t/r} g_{id}^*$$

(12)

where $g_{id}$ is the ideal baseband signal and $g_{qid}$ arises due to IQI. In addition, the corresponding IQI coefficients $\mu_{t/r}$ and $\nu_{t/r}$ are written as

$$\mu_t = \frac{1}{2} (1 + \epsilon_t \exp(j\phi_t)),$$

(13)

$$\nu_t = \frac{1}{2} (1 - \epsilon_t \exp(-j\phi_t)),$$

(14)

$$\mu_r = \frac{1}{2} (1 + \epsilon_r \exp(-j\phi_r)),$$

(15)

and

$$\nu_r = \frac{1}{2} (1 - \epsilon_r \exp(j\phi_r)).$$

(16)
where $\epsilon_{t/r}$ and $\phi_{t/r}$ correspond to the TX/RX amplitude and phase mismatch levels, respectively. In this work, frequency-independent IQI is assumed; however, the extension to the frequency-dependent case is straightforward, following the approach in [44], [45]. For the ideal case, $\phi_{t/r} = 0^\circ$ and $\epsilon_{t/r} = 1$, which corresponds to $\mu_{t/r} = 1$ and $\nu_{t/r} = 0$. In addition, the TX/RX image rejection ratio (IRR), which quantifies the attenuation of the image band, is given by

$$IRR_{t/r} = \frac{\vert\mu_{t/r}\vert^2}{\vert\nu_{t/r}\vert^2}. \quad (17)$$

### A. RECEIVED SINR UNDER IQI

This subsection considers three different cases of practical communication scenarios.

- **Joint TX/RX IQI:** When the TX and RX are impaired by IQI, the SINR can be approximated as [18]

$$\gamma_{IQI} \approx \frac{\vert\xi_{11}\vert^2 + \vert\xi_{22}\vert^2}{\vert\xi_{12}\vert^2 + \vert\xi_{21}\vert^2 + \frac{\Lambda}{\gamma_{id}}} \quad (18)$$

where

$$\xi_{11} = \mu_{t}\mu_{r}, \quad \xi_{22} = \nu_{t}\nu_{r}, \quad \xi_{12} = \nu_{t}\mu_{r}, \quad \xi_{21} = \mu_{t}\nu_{r} \quad (19)$$

and

$$\xi_{11} = \mu_{t}\mu_{r}^*, \quad \xi_{22} = \nu_{t}\nu_{r}^*, \quad \xi_{12} = \nu_{t}\mu_{r}^*, \quad \xi_{21} = \mu_{t}\nu_{r}^* \quad (20)$$

- **Ideal TX and RX IQI:** In the case of ideal TX RF front-end and RX IQI. We have $\mu_{t} = 1$ and $\nu_{r} = 0$, and therefore the instantaneous SINR per symbol is expressed as [18]

$$\gamma_{IQI} = \frac{\vert\mu_{t}\vert^2}{\vert\nu_{r}\vert^2 + \frac{1}{\gamma_{id}}} \quad (21)$$

where $\Lambda = \vert\mu_{r}\vert^2 + \vert\nu_{r}\vert^2$.

- **Ideal RX and TX IQI:** We assume ideal RX RF front-end, while the TX experiences IQI. In this case $\mu_{t} = 1$ and $\nu_{r} = 0$, thus the instantaneous SINR at the receiver is given by [18]

$$\gamma_{IQI} = \frac{\vert\mu_{t}\vert^2}{\vert\nu_{r}\vert^2 + \frac{1}{\gamma_{id}}} \quad (22)$$

### B. SINR DISTRIBUTION

From (24), (23) and (18), the SINR of single-carrier systems under IQI can be expressed as

$$\gamma_{IQI} = \frac{\alpha}{\beta + \frac{\Lambda}{\gamma_{id}}} \quad (25)$$

where the parameters $\alpha$, $\beta$, and $A$ are given in Table 1.

| Joint TX/RX IQI | $|\xi_{11}|^2 + |\xi_{22}|^2$ | $|\xi_{12}|^2 + |\xi_{21}|^2$ | $\Lambda$ |
|-----------------|-----------------|-----------------|-------|
| RX IQI          | $|\mu_{t}|^2$    | $|\nu_{r}|^2$    | $\Lambda$ |
| TX IQI          | $|\mu_{t}|^2$    | $|\nu_{r}|^2$    | 1      |

Hence, the CDF of $\gamma_{IQI}$ is obtained as

$$F_{\gamma_{IQI}}(x) = F_{\gamma_{id}}\left(\frac{A}{x - \beta}\right) \quad (26)$$

where $\gamma_{id}$ is the IQI free SNR. Since we assume Rayleigh fading, $\gamma_{id}$ follows an exponential distribution, and therefore, the corresponding SINR CDF is given by

$$F_{\gamma_{IQI}}(x) = 1 - \exp\left(-\frac{A}{\gamma \left(\frac{x}{\gamma} - \beta\right)}\right), \quad 0 \leq x \leq \frac{\alpha}{\beta} \quad (27)$$

where $\gamma = E_s/N_0$ is the average SNR. Given that $f_{\gamma_{IQI}}(x) = \frac{A}{\gamma x} F_{\gamma_{IQI}}(x)$, the SINR PDF, under IQI, is given by

$$f_{\gamma_{IQI}}(x) = \frac{\alpha A}{\gamma (\alpha - x\beta)^{\frac{\alpha}{\beta}}} \quad (28)$$

which is valid for $0 \leq x \leq \frac{\alpha}{\beta}$.

### C. MOMENT GENERATING FUNCTION

The MGF is extensively used in the analysis of fading channels [41]. In the following subsection, taking into account the IQI at the TX and/or RX, we derive a generalized closed form expression of the SINR MGF of single-carrier systems. This will be then useful in quantifying the corresponding overall system performance.

**Proposition 1.** The MGF of the instantaneous SINR of single-carrier systems under IQI is given by

$$M_{\gamma_{IQI}}(s) = \exp\left(\frac{\alpha}{\beta} s + \frac{A}{\beta \gamma}\right) \Gamma\left(1 + \frac{\alpha A}{\beta \gamma}, \frac{s \alpha A}{\beta \gamma^2}\right) \quad (29)$$

where $\Gamma(\alpha; x; b)$ denotes the extended upper incomplete Gamma function given by [46]

$$\Gamma(\alpha; x; b) = \int_{x}^{\infty} t^{\alpha - 1} \exp\left(-t - \frac{b}{t}\right) \ dt. \quad (30)$$

**Proof.** See Appendix A. \square

### IV. MGF OF MULTI-CARRIER SYSTEMS

Multi-carrier systems divide the signal bandwidth among $K$ subcarriers, which provides several advantages including enhanced robustness against multipath fading. Orthogonal frequency division multiplexing (OFDM), a multi-carrier modulation technique, is employed for downlink transmission in Long-Term Evolution (LTE). In this subsection, we derive the SINR PDF, CDF, and MGF of multi-carrier systems over frequency selective channels in the presence of IQI. Let $S = \{-K, \cdots, -1, 1, \cdots, K\}$ be the set of signals, assuming that all the subcarriers are populated with data and that the channel responses at a given subcarrier and its image

---

**TABLE 1: Single-carrier systems impaired by IQI parameters**

| Joint TX/RX IQI | $|\xi_{11}|^2 + |\xi_{22}|^2$ | $|\xi_{12}|^2 + |\xi_{21}|^2$ | $\Lambda$ |
|-----------------|-----------------|-----------------|-------|
| RX IQI          | $|\mu_{t}|^2$    | $|\nu_{r}|^2$    | $\Lambda$ |
| TX IQI          | $|\mu_{t}|^2$    | $|\nu_{r}|^2$    | 1      |
are uncorrelated [18]. In single-carrier systems, IQI causes interference to the signal from its own complex conjugate while in multi-carrier systems, IQI generates interference from the image signal, i.e., the subcarrier $k$ is distorted by the signal at subcarrier $-k$.

**A. JOINT TX/RX IMPAIRED BY IQI**

Here, we consider the general and most realistic scenario of joint TX/RX IQI. Here, the instantaneous SINR per symbol can be approximated as [18]

$$
\gamma \approx \frac{\|e\|^2 + \|e_t\|^2 \gamma_{id}(-k)}{\|e_t\|^2 + \|e\|^2 \gamma_{id}(-k)}
$$  \hspace{1cm} (31)

where

$$
\gamma_{id}(-k) = \frac{E_s}{N_0} |h(-k)|^2.
$$  \hspace{1cm} (32)

Therefore, for the case of given $\gamma_{id}(-k)$ and with the aid of (31), the conditional SINR CDF can be expressed as

$$
F_{\gamma_{IQI}}(x|\gamma) = 1 - \exp \left( \frac{-x (\|e_t\|^2 + \gamma_{id}(-k)) - \|e\|^2 \|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right)
$$  \hspace{1cm} (33)

where $y = \gamma_{id}(-k)$. Consequently, the unconditional CDF is derived by integrating (33) over the Rayleigh PDF, yielding

$$
F_{\gamma_{IQI}}(x) = 1 - \frac{\exp \left( -\frac{x}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right)}{1 + \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)}} , \quad 0 \leq x \leq \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2}
$$  \hspace{1cm} (34)

whereas the SINR PDF is obtained as

$$
f_{\gamma_{IQI}}(x) = \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \exp \left( -\frac{x}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right)
$$

$$
\times \left( \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} + x \left( \|e\|^2 + \|e\|^2 \gamma_{id}(-k) \right) \right),
$$  \hspace{1cm} (35)

which is valid for $0 \leq x \leq \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2}$, while $C$ and $d$ are given by

$$
C = \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)}
$$  \hspace{1cm} (36)

and

$$
d = \|e\|^2 \|e\|^2 \gamma_{id}(-k) - \|e\|^2 \|e\|^2 \gamma_{id}(-k). 
$$  \hspace{1cm} (37)

**Proposition 2.** The MGF of multi-carrier systems impaired by joint TX/RX IQI is given by

$$
M_{\gamma_{IQI}}(s) = C + \frac{\|e\|^2 \|e\|^2 \gamma_{id}(-k)}{s (\|e\|^2 \|e\|^2 \gamma_{id}(-k))} \exp \left( s \left( \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right) \right)
$$

$$
\times \left( \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} + \frac{\gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right)
$$

$$
\times \gamma \left( 2, s \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 - \|e\|^2 \gamma_{id}(-k)} \right),
$$  \hspace{1cm} (38)

for

$$
\|e\|^2 = \|e_t\|^2.
$$

**B. RX IMPAIRED BY IQI**

Assuming only the RX is impaired by IQI yields the following received instantaneous SINR

$$
\gamma_{IQI} = \frac{\|e_t\|^2 \gamma_{id}(-k)}{\|e\|^2 \gamma_{id}(-k) + \frac{\gamma_{id}(-k)}{\|e\|^2}}.
$$  \hspace{1cm} (42)

Hence, substituting $\mu_t = 1$ and $\nu_t = 0$ in (34), one obtains

$$
F_{\gamma_{IQI}}(x) = 1 - \frac{\|e\|^2 \gamma_{id}(-k)}{\|e_t\|^2 + \|e\|^2} \exp \left( -\frac{x}{\|e\|^2} \left( 1 + \frac{\|e\|^2}{\|e_t\|^2} \right) \right),
$$  \hspace{1cm} (43)

which is valid for $0 \leq x \leq \infty$. By applying algebraic manipulations on (35), the respective SINR PDF is deduced

$$
f_{\gamma_{IQI}}(x) = \frac{1 + \frac{\|e\|^2}{\|e_t\|^2}}{\|e\|^2} \exp \left( -\frac{x}{\|e\|^2} \left( 1 + \frac{\|e\|^2}{\|e_t\|^2} \right) \right)
$$

$$
\times \left( \frac{\|e\|^2 + \|e\|^2}{\|e\|^2} \right),
$$  \hspace{1cm} (44)

which is valid for $0 \leq x \leq \infty$. Finally, from (65) and (44), the corresponding MGF is obtained as

$$
M_{\gamma_{IQI}}(s) = \frac{1 + \frac{\|e\|^2}{\|e_t\|^2}}{\|e\|^2} \int_{0}^{\infty} \exp \left( -\frac{x}{\|e\|^2} + \frac{\|e\|^2}{\|e_t\|^2} - s \right) dx
$$

$$
+ \int_{0}^{\infty} \exp \left( -\frac{x}{\|e\|^2} + \frac{\|e\|^2}{\|e_t\|^2} - s \right) dx
$$

$$
\times \left( \frac{\|e\|^2}{\|e_t\|^2} \right)^{2}.
$$  \hspace{1cm} (45)
which with the aid of [47, eq. (3.352.4)] and [47, eq. (3.353.3)], eq. (45) can be expressed by the following closed-form representation

\[
\mathcal{M}_{\gamma_{IQI}}(s) = 1 - s \frac{\mu_r^2}{|\mu_r|^2} \exp \left( \frac{1}{\gamma} + \frac{|\mu_r|^2}{|\mu_r|^2} - s \frac{|\mu_r|^2}{|\nu_r|^2} \right) \exp \left( \frac{1}{\gamma} - \frac{|\mu_r|^2}{|\nu_r|^2} + s \frac{|\mu_r|^2}{|\nu_r|^2} \right) \times \text{Ei} \left( \frac{1}{\gamma} - \frac{|\mu_r|^2}{|\nu_r|^2} + s \frac{|\mu_r|^2}{|\nu_r|^2} \right) \quad (46)
\]

where \(\text{Ei}(z)\) denotes the exponential integral function given by [47]

\[
\text{Ei}(z) = - \int_{-\infty}^{\infty} \frac{\exp(-t)}{t} \, dt \quad (47)
\]

**C. TX IMPAIRED BY IQI**

Assuming that the TX is subjected to IQI while the RX is ideal, the received instantaneous SINR is obtained as

\[
\gamma_{IQI} = \frac{|\mu_t|^2}{|\nu_t|^2 + \frac{1}{\gamma_{d(t)}}} \quad (48)
\]

Hence, by setting \(\mu_r = 1\) and \(\nu_r = 0\) in (34), it follows that

\[
F_{\gamma_{IQI}}(x) = 1 - \exp \left( -\frac{1}{\gamma} \left( \frac{|\mu_t|^2}{x} - |\nu_t|^2 \right) \right), \quad 0 \leq x \leq \frac{|\mu_t|^2}{|\nu_t|^2} \quad (49)
\]

which yields straightforwardly the corresponding SINR PDF, namely

\[
f_{\gamma_{IQI}}(x) = \frac{|\mu_t|^2 \exp \left( -\frac{1}{\gamma} \left( \frac{|\mu_t|^2}{x} - |\nu_t|^2 \right) \right)}{\gamma \left( |\mu_t|^2 - x \right)^2} \quad (50)
\]

which is valid for \(0 \leq x \leq \frac{|\mu_t|^2}{|\nu_t|^2}\). It is noted that (50) is similar to (28) for \(\alpha = |\mu_t|^2, \beta = |\nu_t|^2,\) and \(A = 1\). Hence, with the aid of (29), the instantaneous SINR MGF of multi-carrier systems experiencing TX IQI only is given by

\[
\mathcal{M}_{\gamma_{IQI}}(s) = \exp \left( \frac{|\mu_t|^2}{|\nu_t|^2} s + \frac{1}{|\nu_t|^2} \right) \Gamma \left( 1, \frac{1}{\gamma} \frac{|\mu_t|^2}{|\nu_t|^2} \right) \quad (51)
\]

which is also novel. The different MGF expressions derived are summarized in Table II. It is noted that with the aid of the derived MGFs, the SER of various \(M\)-ary modulation schemes under different IQI effects as well as multi-channel reception schemes can be readily determined.

**V. SYMBOL ERROR RATE ANALYSIS**

In this section, we analyze various coherent and noncoherent \(M\)-ary modulation schemes and evaluate their SER performance for both single-carrier and multi-carrier-based systems under the effects of IQI.

**A. COHERENT M-PSK**

The SER of coherently detected \(M\)-ary PSK signals in AWGN channels is given by [41, eq. (8.22)]. Assuming fading channels, the average SER is evaluated by averaging [41] eq. (8.22)] over the considered channel’s SNR PDF, namely

\[
P_{s,PSK} = \frac{1}{\pi} \int_{0}^{\frac{\pi}{2}} \mathcal{M}_{\gamma_{IQI}} \left( -\frac{g}{\sin^2(\theta)} \right) \, d\theta. \quad (52)
\]

where \(\bar{M} = (M - 1)\pi/M\) and \(g = \sin^2 \left( \frac{\theta}{2} \right)\). Therefore, assuming PSK modulation under IQI, the average SER of the different impairment scenarios considered for both single-carrier and multi-carrier systems, can be obtained by substituting the derived MGFs from Table II in (52), which, for single-carrier systems, is given by

\[
P_{s,PSK} = \frac{1}{\pi} \int_{0}^{\frac{\pi}{2}} \exp \left( -\frac{g\alpha}{\sin^2(\theta)\beta} + \frac{A}{\beta^2} \right) \times \Gamma \left( 1, \frac{A}{\gamma\beta^2} - \frac{g\alpha A}{\sin^2(\theta)\beta^2} \right) \, d\theta \quad (53)
\]

**B. COHERENT M-QAM**

For \(M\)-QAM modulation, the SER of AWGN channels is given by [41, eq. (8.13)]. Under fading conditions and IQI, the average SER is obtained as

\[
P_{s,QAM} = \frac{4}{\pi M} \int_{0}^{\frac{\pi}{2}} \mathcal{M}_{\gamma_{IQI}} \left( \frac{3}{2 (M - 1) \sin^2(\theta)} \right) \, d\theta
\]

\[
- \frac{4}{\pi M^2} \int_{0}^{\frac{\pi}{2}} \mathcal{M}_{\gamma_{IQI}} \left( \frac{3}{2 (M - 1) \sin^2(\theta)} \right) \, d\theta. \quad (54)
\]

where \(\bar{M} = \left( \sqrt{M - 1} \right)/\sqrt{M}\). The average SER of the different impairment scenarios considered for both single-carrier and multi-carrier systems, can be obtained by substituting the derived MGFs from Table II into (54), which, for single-carrier systems, reduces to

\[
P_{s,QAM} = \frac{4}{\pi M} \int_{0}^{\frac{\pi}{2}} \exp \left( \frac{3\alpha}{2\beta (M - 1) \sin^2(\theta)} + \frac{A}{\beta^2} \right) \times \Gamma \left( 1, \frac{A}{\gamma\beta^2} - \frac{3\alpha A}{2\beta (M - 1) \sin^2(\theta)} \right) \, d\theta
\]

\[
- \frac{4}{\pi M^2} \int_{0}^{\frac{\pi}{2}} \exp \left( \frac{3\alpha}{2\beta (M - 1) \sin^2(\theta)} + \frac{A}{\beta^2} \right) \times \Gamma \left( 1, \frac{A}{\gamma\beta^2} - \frac{3\alpha A}{2\beta (M - 1) \sin^2(\theta)} \right) \, d\theta. \quad (55)
\]

**C. DIFFERENTIAL M-PSK**

The SER of \(M\)-ary PSK with differential detection is given by [41, eq. (8.166)]. Hence, the average SER of \(M\)-DPSK under IQI can be evaluated by substituting the derived MGFs from Table II, which, for multi-carrier systems with TX IQI only,
Multi-carrier systems

Multi-carrier systems with RX IQI only, is given by

\[ M_{\gamma IQI} (s) = \exp \left( \frac{|\mu_1|^2}{|\nu_1|^2} s + \frac{1}{|\nu_1|^2} \right) \Gamma \left( 1, \frac{s |\mu_1|^2}{|\nu_1|^2} \right) \]

Substituting the derived is given by

\[ M_{\gamma IQI} (s) = 1 - s \frac{|\mu_1|^2}{|\nu_1|^2} \exp \left( \frac{s |\mu_1|^2}{|\nu_1|^2} \right) \times \text{Ei} \left( - \frac{1}{\frac{s |\mu_1|^2}{|\nu_1|^2} + \frac{1}{|\nu_1|^2}} \right) \]

Join IQI

\[ M_{\gamma IQI} (s) = \exp \left( \frac{\xi_{11}^2 + \xi_{22}^2}{s (\xi_{12}^2 + \xi_{21}^2)^2} \right) \times \Gamma \left( 1, \frac{\Delta}{s (\xi_{12}^2 + \xi_{21}^2)^2} \right) \gamma \left( 2 + \frac{s |\mu_1|^2}{\xi_{12}^2}, \frac{\Delta}{\xi_{12}^2} \right) \]

TABLE 2: SINR MGFs

<table>
<thead>
<tr>
<th>TX IQI</th>
<th>Single-carrier systems</th>
<th>Multi-carrier systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX IQI</td>
<td>( M_{\gamma IQI} (s) = \exp \left( \frac{</td>
<td>\mu_2</td>
</tr>
<tr>
<td>Joint IQI</td>
<td>( M_{\gamma IQI} (s) = \exp \left( \frac{\xi_{11}^2 + \xi_{22}^2}{s (\xi_{12}^2 + \xi_{21}^2)^2} \right) \times \Gamma \left( 1, \frac{\Delta}{s (\xi_{12}^2 + \xi_{21}^2)^2} \right) \gamma \left( 2 + \frac{s</td>
<td>\mu_1</td>
</tr>
</tbody>
</table>

is given by

\[ P_{s,DP} = \frac{1}{\pi} \int_{0}^{\hat{M}} \exp \left( - \frac{|\mu|^2 g}{|\nu|^2 (1 + \rho \cos \theta)} + \frac{1}{|\nu|^2} \right) \times \Gamma \left( 1, \frac{\Delta}{|\nu|^2 (1 + \rho \cos \theta)} \right) \frac{1}{|\nu|^2} d\theta \]  

(56)

where \( \rho = \sqrt{1 - g} \).

D. NONCOHERENT M-FSK

The SER of noncoherent detection of orthogonal signals, i.e., M-FSK is given by [41], eq. (8.158)]. Substituting the derived MGF expressions from Table II in [41], eq. (8.158)] yields the average SER of single-carrier and multi-carrier systems in the presence of IQI, which, for example, for the case of multi-carrier systems with RX IQI only, is given by

\[ P_{s,F} = \sum_{k=1}^{M-1} \left( -1 \right)^{k+1} \frac{(M-1)!}{k!} \left( 1 + \frac{k |\mu|^2 \text{Ei} \left( \frac{\Delta}{|\nu|^2}, \frac{k |\mu|^2}{(k+1) |\nu|^2} \right)}{\exp \left( \frac{\Delta}{|\nu|^2}, \frac{k |\mu|^2}{(k+1) |\nu|^2} \right) \left( k+1 \right) |\nu|^2} \right) \]  

(57)

VI. EXTENSION TO MIMO SYSTEMS

In this section, we provide deep insights into the performance of multichannel receivers. To this end, we consider the case of an independent but not identically distributed (i.n.i.d.) \( L \)-branch MRC diversity receiver for coherently detected M-PSK and M-QAM modulations and the case of differential STBC.

A. MAXIMUM RATIO COMBINING

The MRC scheme, which requires the knowledge of the channel fading parameters at the receiver, is the optimal combining scheme at the expense of increased complexity [41], [48]. Here, the receiver coherently combines all received signals, resulting in the following MGF

\[ M_{\gamma RC} (s) = \mathbb{E} \left[ e^{-s \sum_{k=1}^{L} \gamma_k} \right] \]  

(58)

\[ = \prod_{k=1}^{L} M_{\gamma_k} (s), \]  

(59)

where \( \gamma_k \) is the instantaneous SNR of the \( k \)th branch.

B. DIFFERENTIAL STBC

Here, we consider the differential Alamouti Space-Time Block Codes (STBC)-OFDM system with two transmit antennas and a single receive antenna. Assuming that both the TX and RX are impaired by IQI, the instantaneous SINR at the \( k \)th subcarrier is given by [40], [49]

\[ \gamma_{IQI} (k) \approx \frac{(1 - \epsilon_{TX})^2 (\gamma_{id1} (k) + \gamma_{id2} (k))}{4 \left( \frac{1}{|\nu|^2} + \frac{|\mu|^2}{|\nu|^2} \right)} \]  

(60)

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where $\gamma_{id,k}$ is the ideal instantaneous SNR of subcarrier $k$ at the $i^{th}$ antenna and

$$
\epsilon_{TX} = 2.5 \left( 1 + \cot \left( \frac{\pi}{M} \right) \right) \frac{|\nu_k|^2}{|\mu_k|^2}.
$$

From (60), the corresponding SINR MGF is obtained as

$$
\mathcal{M}_{\gamma_{id}} (s) = \mathcal{M}_{\gamma_{id,1}} (s\Gamma) \mathcal{M}_{\gamma_{id,2}} (s\Gamma)
$$

where

$$
\Gamma = \frac{(1 - \epsilon_{TX})^2}{4 \left( \frac{1}{|\nu_k|^2} + \frac{|\nu_k|^2}{|\mu_k|^2} \right)}
$$

and $\mathcal{M}_{\gamma_{id,j}}$, $j \in \{1, 2\}$ is the MGF of the IQI free SNR given by (41)

$$
\mathcal{M}_{\gamma_{id,j}} (s\Gamma) = \frac{1}{1 - s\Gamma}
$$

Hence, the corresponding SER is obtained by substituting (62) in the general SER expression for PSK signals in (52). It is noted that the analysis can be easily extended to more than two antenna scenarios [40]. Moreover, the cases of TX IQI only and RX IQI only can be obtained by setting $|\mu_k|^2 = 1$, $|\nu_k|^2 = 0$ and $|\mu_k|^2 = 0$, $|\nu_k|^2 = 1$, respectively. To the best of the authors’ knowledge, the analytic expressions derived in this section have not been reported in the open technical literature.

## VII. SIMULATION AND NUMERICAL RESULTS

In this section, we study the effect of IQI on the performance of single-carrier and multi-carrier systems, assuming $M$-PSK, $M$-DPSK, $M$-QAM, and $M$-FSK systems over Rayleigh fading channels. To this end, semi-analytical simulations were carried out where random samples of the channel are generated and the corresponding SER is calculated and averaged over a large sample size, i.e., $5 \times 10^5$ iterations. For a fair comparison, we normalize the transmitted signal by $|\mu_k|^2 + |\nu_k|^2$, $|\mu_k|^2 + |\nu_k|^2$, and $(|\mu_k|^2 + |\nu_k|^2)(|\mu_k|^2 + |\nu_k|^2)$ for TX IQI only, RX IQI only, and joint TX/RX IQI, respectively.

Figs. 1 and Figs. 2 illustrate the SER for single-carrier systems and multi-carrier systems, respectively. Numerical results are shown with lines, while markers represent computer simulation results. For both single-carrier and multi-carrier systems, it is clear that the analytical expressions perfectly match the simulation results for the cases of TX and RX IQI; while for the case of joint TX/RX IQI, the approximation adopted in [18] and [31] and the assumption of uncorrelated subcarriers do not seem to have significant impact on the accuracy of the SER analysis. Furthermore, we notice that, in most cases, the simulation results match the numerical analysis; however, an error that does not exceed 30% is observed in some cases of joint TX/RX IQI, see Figs. 3 and 5.

### A. SINGLE-CARRIER SYSTEMS

Assuming single-carrier transmission over flat Rayleigh fading channels, it is first noticed that the impact of RX IQI is more pronounced on the system performance compared to TX IQI. This is due to the fact that RX IQI impairs both the signal and the noise while TX IQI affects the information signal only. However, when the modulation order is increased, as shown in Figs. 12, the degradation induced by TX IQI becomes comparable to that observed for the case of RX IQI.

It is also observed that the performance degradation due to IQI greatly depends on the underlying modulation scheme. For instance, in Fig. 4 it is observed that joint TX/RX IQI
slightly affects the performance of 32-FSK, while the other three candidate modulation schemes are subject to an error floor. As shown in Fig. 3 this error floor is manifested in both single-antenna and multi-antenna receivers. This is due to the constant tone spacing in FSK, regardless of the modulation order. Hence, unlike PSK, DPSK, and QAM modulations, it is apparent that the effect of IQI on FSK does not depend on the modulation order. However, for larger M, FSK transmission bandwidth is increased. This is not the case for the other three modulation schemes where the distance between constellation points is highly affected by the modulation order. Consequently, for the considered SNR range, IQI can be considered somehow acceptable i.e., does not cause an error floor, only for \( M = 4 \) for DPSK and PSK based systems. In fact, for single-carrier systems, for \( M = 16 \), an error floor is noticed around an SNR of 35dB for PSK modulation with joint TX/RX IQI, while for the
case of DPSK, the error floor is observed around an SNR
of 30 dB for TX and/or RX IQI. It is also worth noting that
for joint TX/RX IQI, the error floor is at a SER of $6 \times 10^{-2}$
for PSK versus $2 \times 10^{-1}$ for DPSK. Moreover, it is observed
that the level of performance degradation greatly depends on
the modulation scheme and/or order and phase and amplitude
mismatch level. In particular, it is observed that, in some
cases, IQI compensation will only result in added complexity,
since the effects of the impairment are negligible. This is
evident, particularly when the phase and amplitude mismatch
are relatively low, in FSK modulation and low order modu-
lation orders of PSK and DPSK, where the distance between
symbols in the constellation is large enough to tolerate the
error induced by IQI. However, as the mismatch increases,
the effects of this impairment become more noticeable and
could cause error floor in high modulation orders of phase
modulation schemes, which entails compensation in order to
achieve a reliable communication link.

B. MULTI-CARRIER SYSTEMS
Here, we assume a multipath channel with 8 independent and
identically distributed taps where each tap is a zero-
mean complex Gaussian random variable [50]. Without loss
of generality, we assume that the number of subcarriers is
$K = 32$ and that the SNR reflects the power per subcarrier.
Even though the effects of IQI on the different modulation
schemes follow the same trend in multi-carrier systems as
in single-carrier systems, it is observed that the impact of
IQI on the latter is more pronounced. This is because IQI
in multi-carrier systems causes interference from the image
subcarrier, which could benefit from better fading conditions
than the desired signal. An interesting example is the case of
M-FSK constellation, where an error floor is observed in Fig.
9, regardless of the modulation order, for the cases of RX IQI
only and joint TX/RX IQI cases. This error floor, which is
due to the interference from the image subcarrier in multi-
carrier systems, is not observed in single-carrier FSK. In the
same context, the error floor for 4-PSK appears at around
25 dB. This error floor is observed for FSK, DPSK, and in 2-
FIGURE 10: Multi-carrier system average SER versus normalized $E_s/N_0$ for $L$-branch 32-QAM MRC receiver when $IRR_t = IRR_r = 20$ dB and $\phi = 3^\circ$.

FIGURE 11: Differential Alamouti STBC OFDM SER versus normalized $E_s/N_0$ for 2-branch receiver when $IRR_t = IRR_r = 20$ dB and $\phi = 3^\circ$.

branch Differential Alamouti STBC OFDM systems as well. The latter is particularly sensitive to the impairment where it is observed, in Fig. [11] that in case of joint TX/RX IQI, the SER is almost flat for $M = 16$. Moreover, we notice that 4-FSK is the most robust to IQI among the considered modulations, since the error floor appears at around 30 dB.

It is also noted that for $IRR_t = IRR_r = 20$ dB, in multi-carrier systems, the effects of IQI at the RX should be compensated in order to achieve a reliable communication link, even in the case of the relatively simple binary modulation schemes and multi-antenna receivers. For these scenarios the amount of performance degradation observed depends on the modulation order, the SNR, the impairment scenario and the IQI level. Hence, in particular cases, such

FIGURE 12: Multi-carrier system average SER versus $IRR$ for $M$-PSK, $M$-DPSK and $M$-FSK, with RX IQI only, when $E_s/N_0 = 25$ dB and $\phi = 2^\circ$.

FIGURE 13: Multi-carrier system average SER versus $IRR$ for $M$-PSK and $M$-DPSK, with RX IQI only, when $E_s/N_0 = 40$ dB and $\phi = 1^\circ$. 
as in low modulation orders of PSK and DPSK modulations, as well as M-FSK, compensation can be implemented at the RX front-end only in order to achieve a reliable performance. On the contrary, in other cases compensation of both TX/RX IQI is required in order to achieve a reliable communication link.

Finally, Fig. 12 and Fig. 13 demonstrate the effects of the IRR on the SER of the different considered modulation schemes, when SNR = 25dB and SNR = 40dB, respectively. It is assumed that both TX and RX are IQI-impaired and that IRRx = IRRy. The phase imbalance assumed is 1° in Fig. 12 and 2° in Fig. 13. It is also noted that the continuous lines and dashed lines correspond to the IQI-impaired and ideal cases, respectively. For moderate SNR values, one can see that IQI affects the different modulations schemes in a different manner. For instance, joint TX/ RX IQI exhibits a constant loss in the SER performance of M-FSK regardless of the modulation order, which is not the case for lower SNR values, the effects of IQI vanish when the IRR is increased; while, for higher SNR values and given that IQI effects dominate noise effects at high SNR, there is a noticeable performance degradation even when considering high IRR values.

VIII. CONCLUSION

We presented a framework for the SER analysis of coherent and noncoherent modulation schemes under the effects of IQI. We studied several interesting scenarios, in which TX IQI only, RX IQI only, and joint TX/RX IQI were analyzed and the respective average SER expressions of the underlying schemes were derived for both single-carrier and multi-carrier transmissions. The derived analytical results were corroborated with the corresponding computer simulation results. It was shown that the performance degradation caused by IQI considerably depends on the system’s parameters including the modulation scheme. Moreover, it was demonstrated that increasing the modulation order amplifies the impact of IQI on the system for both coherent and noncoherent systems, while it does not affect the degradation observed in frequency modulation. Additionally, it was shown that the effects of IQI can be quite significant on the SER performance; hence, the optimal compensation strategy greatly depends on the system’s parameters. This highlights the importance of accurate IQI characterization in order to achieve a reliable communication link with minimal added complexity.

APPENDIX A DERIVATION OF MGF FOR SINGLE-CARRIER SYSTEMS IMPAIRED BY IQI

By recalling that \[ M_{\gamma IQI}(s) = \int_0^\infty \exp(sx) f_{\gamma IQI}(x) \, dx \] (65)

and substituting (28) into (65) yields

\[ M_{\gamma IQI}(s) = \int_0^\infty \exp(sx) \frac{\alpha A \exp \left( -\frac{A}{\gamma(x - \beta)} \right)}{\gamma(\alpha - x\beta)^2} \, dx. \] (66)

Taking \( \gamma = \alpha - \gamma \beta \) and after some mathematical manipulations, one obtains

\[ M_{\gamma IQI}(s) = \frac{\alpha A \exp \left( -\frac{A}{\gamma y + \beta} \right)}{\gamma \beta} \int_0^\alpha \exp \left( -\frac{sy}{\gamma} - \frac{A}{\beta y} \right) \, dy. \] (67)

Finally, by taking \( z = \frac{\alpha A}{\beta \gamma y} \), (29) is deduced, which completes this proof.

APPENDIX B DERIVATION OF MGF FOR MULTI-CARRIER SYSTEMS IMPAIRED BY JOINT TX/RX IQI

From (65) and (35), taking \( u = \exp(s \gamma) \) and \( dv = f_\gamma(\gamma) \) and integrating by parts, one obtains

\[ M_{\gamma IQI}(s) = C + s \int_0^{\frac{\xi_{11}^2}{\xi_{12}^2}} \frac{\xi_{11}^2 - x |\xi_{12}|^2}{|\xi_{11}|^2 + x (|\xi_{21}|^2 - |\xi_{12}|^2)} \times \exp(sx) \exp \left( -\frac{x}{\gamma} \left( \frac{\Lambda}{|\xi_{11}|^2 - x |\xi_{12}|^2} \right) \right) \, dx \] (68)

For the case of \(|\xi_{21}|^2 = |\xi_{12}|^2\) and setting \( z = \frac{|\xi_{11}|^2 - x |\xi_{12}|^2}{\gamma} \), equation (68) simplifies to

\[ M_{\gamma IQI}(s) = C + \frac{s \gamma \Lambda}{|\xi_{12}|^2 |\xi_{11}|^2} \exp \left( \frac{\xi_{11}^2}{|\xi_{12}|^2} + \frac{\Lambda}{|\xi_{12}|^2} \right) \times \int_0^{\frac{\xi_{11}^2}{|\xi_{12}|^2}} z \exp \left( -\frac{z}{\gamma} \left( \frac{\Lambda}{|\xi_{11}|^2 - \xi_{12}^2} \right) \right) \, dz \] (70)

which considering the change of variable \( y = \frac{z}{\gamma |\xi_{12}|^2} \), is equivalent to (38). On the contrary, for \(|\xi_{12}|^2 \neq |\xi_{21}|^2\), taking the change of variable in (69), equation (68) becomes

\[ M_{\gamma IQI}(s) = C + \frac{s \exp \left( \frac{\Lambda}{|\xi_{12}|^2} + \frac{|\xi_{11}|^2}{|\xi_{12}|^2} \right)}{|\xi_{12}|^2 - |\xi_{12}|^2} \times \int_0^{\frac{|\xi_{11}|^2}{|\xi_{12}|^2}} z \exp \left( -\frac{|\xi_{11}|^2 A}{|\xi_{12}|^2 - |\xi_{12}|^2} - \frac{z}{|\xi_{12}|^2} \right) \, dz \] (71)

where \( d \) is given in (37). For the case of \(|\xi_{11}|^2 |\xi_{21}|^2 - |\xi_{12}|^2 |\xi_{12}|^2 |\xi_{21}|^2 |\xi_{12}|^2 < |\xi_{11}|^2 \)
we expand the involved binomial which yields

\[ \mathcal{M}_{1|QI}(s) = C + \sum_{k=0}^{\infty} (-1)^k s^k d^k \exp \left( \frac{\lambda}{\xi_{12}^2} s + \frac{\xi_{11}^2}{\xi_{12}^2} \right) \times \int_0^{\xi_{11}^2} z^{-k} \exp \left( -\frac{\xi_{11}^2 A}{\xi_{12}^2 s^2} - s z \right) dz \]

By setting more \( y = xs/\xi_{12}^2 \), equation (39) is deduced. Meanwhile for \( \left| \frac{\xi_{11}^2}{\xi_{12}^2} - \frac{\xi_{22}^2}{\xi_{21}^2} \right| > \xi_{11}^2 \)

and expanding the binomial in (71), one obtains the following analytic expression

\[ \mathcal{M}_{1|QI}(s) = C + \sum_{k=0}^{\infty} s^k \exp \left( \frac{\lambda + \xi_{11}^2}{\xi_{12}^2} \right) \frac{\xi_{11}^2}{\xi_{12}^2} \times \int_0^{\xi_{11}^2} \xi_{11}^2 z^{-k+1} \exp \left( -\frac{\xi_{11}^2 A}{\xi_{12}^2 s^2} - s z \right) dz. \]

Finally, equation (40) is obtained by taking \( y = sz/\xi_{12}^2 \).

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