Outage Probability under I/Q Imbalance and Cascaded Fading Effects

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***Abstract*—Direct-conversion architectures (DCA) can offer highly integrated low-cost hardware solutions to communication transceivers. However, DCA devices are sensitive to radio frequency (RF) imperfections such as amplifier non-linearities, phase noise and in-phase/quadrature-phase imbalances (IQI), which typically lead to a severe degradation of the performance of such systems. Motivated by this, we quantify and evaluate the impact of RF IQI on wireless communications in the context of cascaded fading channels. Novel closed form expressions are derived for the corresponding outage probability for the case of ideal transmitter (TX) and receiver (RX), ideal TX and I/Q imbalanced RX, I/Q imbalanced TX and ideal RX, and joint I/Q imbalanced TX/RX. The offered analytic results have a relatively convenient algebraic representation and their validity is extensively justified through simulations. Based on these, it is shown that cascaded fading leads to considerable degradation in the system performance and that assuming ideal RF front-ends at the TX and RX induces non-negligible errors in the outage probability that can exceed 20% in several communication scenarios. We further demonstrate that the effects by cascaded multipath fading conditions are particularly severe, as they typically result to considerable performance losses of around or over an order of magnitude.**

I. Introduction

The rising demand for high data rate applications and multimedia services has led to the design and the development of flexible and software-configurable transceivers that are capable of supporting the required quality of service. In this context, the direct-conversion transceivers constitute an attractive radio frequency (RF) front-end solution, as they demand neither external intermediate frequency filters nor image rejection filters [1], [2]. Additionally, their architectures are low-cost and easily on-chip integrated, which render them excellent candidates for modern wireless technologies [3]–[5]. However, direct-conversion transceivers are sensitive to RF front-end related imperfections, which are often inevitable due to components mismatch and manufacturing defects [6], [7]. An indicative example is the in-phase and quadrature (I/Q) imbalance (IQI) which corresponds to the fundamental problem of amplitude and phase mismatch between the I and Q branches of transceivers and leads to imperfect image rejection that incurs considerable performance limitations [8], [9].

On the contrary, due to the different nature of fading conditions, several statistical models have been proposed for characterizing and modeling fading envelopes under short-term, long-term, and composite fading channels. For example, the Nakagami-m and lognormal distributions have been extensively used for accounting for short-term fading, also known as multipath fading, and long-term fading, also known as shadowing, respectively. Likewise, several composite fading models have been proposed for accounting for the simultaneous occurrence of multipath fading and shadowing effects (see [10]–[23] and references therein). Furthermore, multiplicative cascaded fading models have been more recently introduced in [24]–[26]. The physical interpretation of these models is justified by considering received signals generated by the product of a large number of rays reflected via N statistically independent scatterers [24]. Based on this, the N*Nakagami$-m$ distribution was introduced in [25] corresponding to the product of N statistically independent, but not necessarily identically distributed Nakagami$-m$ random variables (RVs). This model is generic as it includes several special cases of more elementary cascaded fading models. For example, for the specific case of $N = 2$ and $m = 1$, it reduces to the double Rayleigh distribution, which has been shown useful in modeling fading effects in mobile-to-mobile communications [27].

In spite of the paramount importance of RF front-ends on the performance of wireless communication systems, the detrimental effects of RF impairments have been overlooked

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in the vast majority of reported analyses. The effect of RF impairments was investigated in [4], [28]–[36], while performance degradation due to IQI was investigated in [37]–[42]. Specifically, the authors in [37], [38] quantified the effect of IQI on the performance of multiple-input multiple-output (MIMO), whereas the authors in [39]–[41] investigated the performance of relaying systems in the presence of IQI.

Nevertheless, to the best of the authors' knowledge no analyses have been reported in the open technical literature on the detrimental effects of IQI in wireless communications over cascaded fading channels. Motivated by this, the present work is devoted to the analysis and quantification of IQI effects in the context of wireless transmission over arbitrary N Nakagami-m fading channels. To this end, novel analytic expressions are derived for the corresponding OP considering the following three scenarios: i) ideal TX with I/Q imbalanced RX; ii) I/Q imbalanced TX with ideal RX; iii) joint I/Q imbalanced TX and RX. The derived expressions are validated extensively through simulations and are subsequently employed in analyzing the corresponding performance providing useful insights for the design and deployment of wireless communication systems over cascaded fading channels. Moreover,to justify their importance and practical usefulness in the context of emerging wireless communication systems, note that these expressions are also valid in the context of vehicular-to-vehicular (V2V) communications.

II. System and signal model

In this section, we revisit the ideal signal model, which is, henceforth, referred to as ideal RF, as well as the realistic IQI signal models for the case that TX and RX are equipped with a single antenna.

A. Ideal RF front-end

We assume a signal, x, transmitted over a flat wireless channel, h, with an additive white Gaussian noise (AWGN), w. The received RF signal is passed through various processing stages, also known as the RF front-end of the RX. These stages include filtering, amplification, analog I/Q demodulation, down-conversion to baseband and sampling. To this effect, the corresponding baseband equivalent received signal can be expressed as $y_{\rm id} = hx + w$. It is assumed that the transmitted signal experiences cascaded fading conditions modeled by a N*Nakagami-m process, which is composed of $N \geq 1$ independent, but not necessarily identical, Nakagami-m random variables. Based on this, the instantaneous signal to noise ratio (SNR) per symbol at the RX input can be given by $\gamma_{\rm id} = \frac{E_s}{N_0} |h|^2$, where, E_s, denotes the energy per transmitted symbol and N_0 is the single-sided AWGN power spectral density (PSD). Therefore, the corresponding average SNR is $\overline{\gamma} = \frac{E_s}{N_0} \prod_{i=1}^{N} \Omega_i$, with Ω_i denoting the scaling parameter of the i^{th} Nakagami-m process [25].

B. I/Q imbalance Model

The time-domain baseband representation of the IQI impaired signal can be obtained as [4]

$$g_{\rm IQI} = K_1^{t/r} g_{\rm id} + K_2^{t/r} g_{\rm id}^* \tag{1}$$

where $g_{\rm id}$ denotes the baseband IQI$-$free signal and $g_{\rm id}^*$ arises due to the involved IQI effects. Furthermore, the IQI coefficients $K_1^{t/r}$ and $K_2^{t/r}$ are expressed as

$$K_1^{t/r} = \frac{1 + \epsilon^{t/r} e^{\pm j\phi^{t/r}}}{2} \tag{2}$$

and

$$K_2^{t/r} = \frac{1 - \epsilon^{t/r} e^{\mp j\phi^{t/r}}}{2} \tag{3}$$

where the positive and negative signs in (2) and the t/r superscripts denote the up and down conversion processes, respectively, whereas the $\epsilon^{t/r}$ and $\phi^{t/r}$ terms account for the TX/RX amplitude and phase mismatch, respectively. It is also noted that the IQI parameters are algebraically linked to each other as $K_2^{t/r} = 1 - \left(K_1^{t/r}\right)^*$. The $K_1^{t/r}$ and $K_2^{t/r}$ coefficients are associated with the corresponding image rejection ratio (IRR) which determines the amount of attenuation of the image frequency band and is expressed as $IRR_{t/r} = \left|K_1^{t/r}\right|^2 / \left|K_2^{t/r}\right|^2$. It is recalled here that for practical analog RF front-end electronics, the value of IRR is typically in the range of 20dB$-$40dB [3], [43]–[47]. Furthermore, the second term $K_2^{t/r} g_{\rm id}^*$ is caused by the associated imbalances and in the case of single-carrier transmission it represents the self-interference effect, whereas in multi-carrier transmission it denotes the image *aliasing* effect, which results to crosstalk between the mirror-frequencies in the down-converted signal.

1) TX impaired by IQI: In this scenario, it is assumed that TX experiences IQI while the RF front-end of the RX is ideal. To this effect, it follows from (1) that the baseband equivalent transmitted signal is expressed as

$$x_{\rm IQI} = K_1^t x + K_2^t x^* \tag{4}$$

whereas the baseband equivalent received signal is given by

$$y = h x_{\rm IQI} + w = K_1^t h x + K_2^t h x^* + w. \tag{5}$$

Furthermore, the instantaneous SINR per symbol at the input of the RX is expressed as

$$\gamma = \frac{|K_1^t|^2 \, |h|^2 \, E_s}{|K_2^t|^2 \, |h|^2 \, E_s + N_0} \tag{6}$$

which after basic algebraic manipulations can be re-written as follows:

$$\gamma = \frac{1}{\frac{1}{IRR_t} + \frac{1}{\left|K_1^t\right|^2} \frac{1}{\gamma_{\rm id}}}. \tag{7}$$

In the context of direct-conversion transmitter, the IQI effect can be considered as the so-called self-image problem, which is the case when the baseband equivalent transmitted signal is essentially interfered by its own complex conjugate [6].

2) RX impaired by IQI: In this scenario, it is assumed that the RX experiences IQI while the TX RF front-end is ideal. Based on (1), the baseband equivalent received signal can be obtained as

$$y = K_1^r h x + K_2^r h^* x^* + K_1^r w + K_2^r w^*. \tag{8}$$

The corresponding instantaneous SINR per symbol at the input of the RX is expressed as

$$\gamma = \frac{\left|K_1^r\right|^2 |h|^2 E_s}{\left|K_2^r\right|^2 |h|^2 E_s + \left(\left|K_1^r\right|^2 + \left|K_2^r\right|^2\right) N_0} \tag{9}$$

which after basic algebraic manipulations can equivalently be expressed as

$$\gamma = \frac{1}{\frac{1}{IRR_r} + \left(1 + \frac{1}{IRR_r}\right)\frac{1}{\gamma_{\rm id}}}. \tag{10}$$

3) Joint TX/RX impaired by IQI: In this scenario, it is assumed that both TX and RX experience IQI. To this effect and based on (1), it follows that the baseband equivalent received signal can be expressed as

$$y{=}\left(\xi_{11} h + \xi_{22} h^*\right) x + \left(\xi_{12} h + \xi_{21} h^*\right) x^* + K_1^r w + K_2^r w^* \tag{11}$$

where $\xi_{11} = K_1^r K_1^t$, $\xi_{22} = K_2^r \left(K_2^t\right)^*$, $\xi_{12} = K_1^r K_2^t$ and $\xi_{21} = K_2^r \left(K_1^t\right)^*$.

Based on this, the instantaneous SINR per symbol at the input of the RX is given by

$$\gamma = \frac{|Z|^2 E_s}{|W|^2 E_s + \left(\left|K_1^r\right|^2 + \left|K_2^r\right|^2\right) N_0} \tag{12}$$

with

$$|Z|^2 = \left|\xi_{11} h + \xi_{22} h^*\right|^2 \tag{13}$$

and

$$|W|^2 = \left|\xi_{12} h + \xi_{21} h^*\right|^2 \tag{14}$$

$$= \left|\xi_{12}\right|^2 |h|^2 + \left|\xi_{21}\right|^2 |h|^2 + 2\Re\left\{\xi_{12}\xi_{21}h^2\right\} \tag{15}$$

whereas $\left|\xi_{22}\right|^2 / \left|\xi_{11}\right|^2 = 1/(IRR_r IRR_t)$, which practically lies in the range of $[-43, -28\text{dB}]$. As a result, it can be accurately assumed that $|Z|^2 \approx \left|\xi_{11}\right|^2 |h|^2$, while due to the inequality $2\Re\left\{\xi_{12}\xi_{21}h^2\right\} << \left|\xi_{12}\right|^2 |h|^2 + \left|\xi_{21}\right|^2 |h|^2$, Eq. (15) can be accurately represented as $|W|^2 \approx \left|\xi_{12}\right|^2 |h|^2 + \left|\xi_{21}\right|^2 |h|^2$. To this effect, it follows that (12) can be also re-written as

$$\gamma \approx \frac{\left|\xi_{11}\right|^2}{\left|\xi_{12}\right|^2 + \left|\xi_{21}\right|^2 + \left(\left|K_1^r\right|^2 + \left|K_2^r\right|^2\right)\frac{1}{\gamma_{\rm id}}}. \tag{16}$$

It is noted here that (16) is particularly accurate since the relative error does not exceed 1%.

III. Outage Probability in Wireless Transmission over Cascaded Fading Channels

It is recalled that the OP can be defined as the probability that the symbol error rate is greater than a certain quality of service level and is computed as the probability that the instantaneous SNR or SINR falls bellow the corresponding pre-determined threshold [48]. In what follows, we derive a novel analytic expressions for the OP over cascaded fading channels subject to the aforementioned IQI scenarios in wireless communication systems. The offered analytic expressions are validated through extensive comparisons with respective results from computer simulations.

A. Ideal RF front-end

In the case of N*Nakagami-m fading channels, the CDF of $\gamma_{\rm id}$ is given by [25, eq. (13)]

$$F_{\gamma_{\rm id}}(\gamma) = \frac{G_{1,N+1}^{N,1}\left(\frac{\gamma}{\bar{\gamma}}\prod_{i=1}^{N} m_i \,\middle|\, \begin{matrix} 1 \\ m_1, m_2, \cdots, m_N, 0 \end{matrix}\right)}{\prod_{i=1}^{N}\Gamma\left(m_i\right)} \tag{17}$$

where $\Gamma(\cdot)$ and $G_{s,t}^{v,w}(\cdot)$ denote the gamma function and the Meijer's G-function [49]. Based on this, the corresponding PDF of $\gamma_{\rm id}$ is expressed as [25, eq. (14)], namely

$$f_{\gamma_{\rm id}}(\gamma) = \frac{G_{0,N}^{N,0}\left(\frac{\gamma}{\bar{\gamma}}\prod_{i=1}^{N} m_i \,\middle|\, \begin{matrix} - \\ m_1, m_2, \ldots, m_N \end{matrix}\right)}{\gamma\prod_{i=1}^{N}\Gamma\left(m_i\right)}. \tag{18}$$

B. TX impaired by IQI

Using (7) and (17), it follows that the OP is given by

$$P_{\rm o} = F_{\gamma_{\rm id}}\left(\frac{1}{\left|K_1^t\right|^2\left(\frac{1}{\gamma_{th}} - \frac{1}{IRR_t}\right)}\right) \tag{19}$$

with $\gamma_{th} \leq IRR_t$.

C. RX impaired by IQI

Using (10) and (17), the corresponding OP is given by

$$P_{\rm o} = F_{\gamma_{\rm id}}\left(\frac{1 + \frac{1}{IRR_r}}{\frac{1}{\gamma_{th}} - \frac{1}{IRR_r}}\right) \tag{20}$$

with $\gamma_{th} \leq IRR_r$.

D. Joint TX/RX impaired by IQI

Using (16) and (17), the OP in this case is expressed as

$$P_{\rm o} = F_{\gamma_{\rm id}}\left(\frac{\left|K_1^r\right|^2 + \left|K_2^r\right|^2}{\frac{\left|\xi_{11}\right|^2}{\gamma_{th}} - \left(\left|\xi_{12}\right|^2 + \left|\xi_{21}\right|^2\right)}\right) \tag{21}$$

with $\gamma_{th} \leq \frac{\left|\xi_{11}\right|^2}{\left|\xi_{12}\right|^2 + \left|\xi_{21}\right|^2}$.

IV. Numerical Results

In this section, we evaluate and illustrate the effects of IQI on the performance of wireless communications over cascaded Nakagami-m fading channels in terms of the corresponding OP. The notation $m = \{m_1, m_2, \cdots, m_N\}$ denotes up to N*Nakagami-m channels, i.e. $m = \{m_1, m_2, m_3\}$ for $N = 3$, with fading $m-$parameters of m_1, m_2, and m_3, respectively. We also consider that the SNR is normalized with respect to $\gamma_{\rm th}$, which implies that the OP is evaluated as a function of $\gamma/\gamma_{\rm th}$. Furthermore, it is important to note that, in the following figures, the numerical results are shown with continuous lines, while markers are employed to illustrate the simulation results.

To this end, Fig. 1 illustrates the OP versus the normalized SNR for the different considered TX/RX scenarios. Specifically, we compare the OP between the ideal RF front-end,

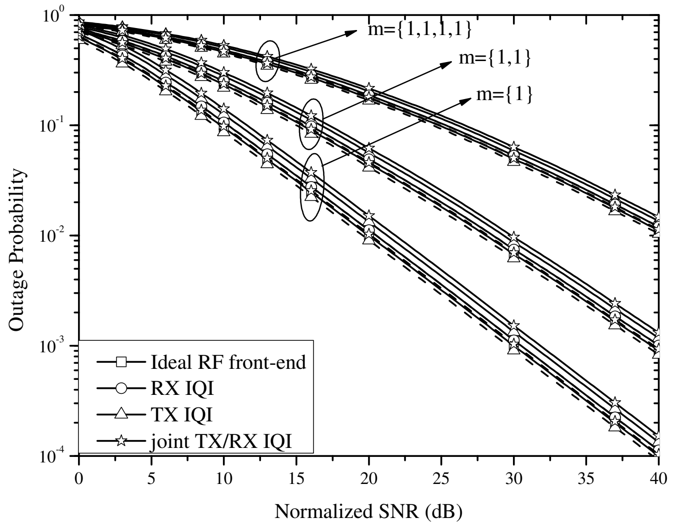

Fig. 1. OP as a function of the normalized SNR, when $\mathrm{IRR} = 20\mathrm{dB}$, $\phi = 3^o$, $\epsilon \simeq 0.824$ (continuous lines), and $\epsilon \simeq 1.21364$ (dashed lines).

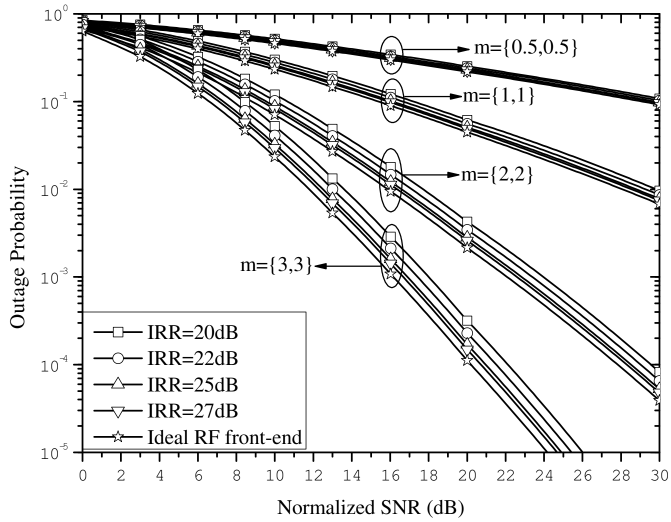

Fig. 2. OP as a function of the normalized SNR, for different values of IRR, when $\epsilon < 1$, and $\phi = 3^o$.

the RX I/Q imbalanced, the TX I/Q imbalanced and joint TX/RX I/Q imbalanced cases when the $IRR = 20\mathrm{dB}$, and $\phi = 3^o$. We consider the two cases of $\epsilon < 1$ (continuous lines), and $\epsilon > 1$ (dashed lines). Furthermore, different channels have been considered, where $m = 1$, $m = \{1, 1\}$ and $m = \{1, 1, 1, 1\}$ correspond to the Rayleigh, double Rayleigh and N*Rayleigh with $N = 4$ channels respectively. It is shown that the performance degradation due to IQI is somewhat less severe compared to the detrimental effects of cascaded fading. For instance, for the case of $\gamma/\gamma_{th} = 10\mathrm{dB}$, the OP in the case of Rayleigh fading is nearly half the OP value in the case of double Rayleigh fading. In addition, in the case of double Rayleigh fading channels, the assumption of ideal RF front-end results to around 20% error in the corresponding OP. These results highlight the importance of both accurate channel characterization and modeling as well as accounting for RF impairments, in the realistic performance analysis and design of wireless communication systems. Interestingly, when $\epsilon < 1$, the effects of TX IQI only on the OP degradation are more severe than the corresponding effects of RX IQI only. The underlying reason is that the SINR is higher in the case of RX IQI only than in the case of TX IQI only, since the noise is multiplied by $\left(|K_1^r|^2 + |K_2^r|^2\right)$, which for $\epsilon < 1$ does not exceed 1. Moreover, it is worth mentioning that in case of $\epsilon > 1$, the RX IQI effects are the most severe since the noise is multiplied by $\left(|K_1^r|^2 + |K_2^r|^2\right)$, which in this case is greater than 1. Additionally, in case of $\epsilon > 1$, the TX IQI only system outperforms even the corresponding ideal RF front-end system. As can be drawn from (2), when $\epsilon > 1$, it follows that $|K_1^t|^2 > 1$, and for practical levels of IQI $|K_2^t|^2 \to 0$. Therefore, (6) can be tightly approximated as $\gamma \approx |K_1^t|^2 \gamma_{\mathrm{id}}$ which, for $\epsilon > 1$, is greater than γ_{id}.

Fig. 2 shows the impact of IQI on the OP, considering double Rayleigh and double Nakagami-m, with $m = \{0.5, 0.5\}$, $m = \{2, 2\}$ and $m = \{3, 3\}$ fading conditions with joint TX/RX IQI. It is evident that the OP decreases as the m values are increased, for a fixed SNR value, while, as expected, the OP is improved when the IRR is increased. For example, for the case of double Nakagami$-m$ conditions with $\overline{\gamma} = 10\mathrm{dB}$, taking an RF front-end with an IRR of $27\mathrm{dB}$ instead of $20\mathrm{dB}$, decreases the corresponding OP by 30%. Notably, since the IRR of practical RF front-ends lies in the range of $20 - 40\mathrm{dB}$, these results indicates the importance of taking RF impairments such as the IQI into consideration. Likewise, it is also shown that it is of paramount importance to take into account the effects of cascaded fading conditions, as the difference in comparison with non-multiplicative fading is about an order of magnitude in the entire SNR range.

V. Conclusions

The present paper investigated the OP performance of wireless communication systems over cascaded channels in the presence of IQI at the RF front-end. We considered three scenarios in our analysis corresponding to ideal TX with I/Q imbalanced RX, I/Q imbalanced TX with ideal RX, and joint I/Q imbalanced TX and RX. The ideal case was also taken into consideration for comparison and the derived analytic results were validated through extensive comparisons with respective results from computer simulations. It was shown that the severity of fading affects significantly the corresponding performance and that the assumption of ideal RF front-end results to around 20% error in the corresponding OP. This highlights the importance of both accurate channel characterization and consideration for RF impairments, in realistic analysis, design and deployment of wireless communication systems.

References

[1] A. Abidi, “Direct-conversion radio transceivers for digital communications,” *IEEE J. Solid-State Circuits*, vol. 30, no. 12, pp. 1399–1410, Dec 1995.

[2] S. Mirabbasi and K. Martin, “Classical and modern receiver architectures,” *IEEE Commun. Mag.*, vol. 38, no. 11, pp. 132–139, Nov 2000.

[3] B. Razavi, *RF microelectronics*. Prentice Hall New Jersey, 1998, vol. 1.

[4] T. Schenk, *RF Imperfections in High-Rate Wireless Systems*. The Netherlands: Springer, 2008.

[5] T. T. Duy, T. Duong, D. Benevides da Costa, V. N. Q. Bao, and M. Elkashlan, "Proactive relay selection with joint impact of hardware impairment and co-channel interference," *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1594–1606, May 2015.

[6] P. Rykaczewski, M. Valkama, and M. Renfors, "On the connection of I/Q imbalance and channel equalization in direct-conversion transceivers," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1630–1636, May 2008.

[7] A. Gokceoglu, Y. Zou, M. Valkama, P. Sofotasios, P. Mathecken, and D. Cabric, "Mutual information analysis of ofdm radio link under phase noise, IQ imbalance and frequency-selective fading channel," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 3048–3059, June 2013.

[8] M. Valkama, M. Renfors, and V. Koivunen, "Advanced methods for I/Q imbalance compensation in communication receivers," *IEEE Trans. Signal Process.*, vol. 49, no. 10, pp. 2335–2344, Oct 2001.

[9] A. ElSamadouny, A. Gomaa, and N. Al-Dhahir, "Likelihood-based spectrum sensing of OFDM signals in the presence of Tx/Rx I/Q imbalance," in *IEEE Global Communications Conf.*, Dec 2012, pp. 3616–3621.

[10] A. Abdi and M. Kaveh, "K distribution: an appropriate substitute for rayleigh-lognormal distribution in fading-shadowing wireless channels," *Electronics Letters*, vol. 34, no. 9, pp. 851–852, Apr. 1998.

[11] P. Bithas, N. Sagias, P. Mathiopoulos, G. Karagiannidis, and A. Rontogiannis, "On the performance analysis of digital communications over generalized-K fading channels," *IEEE Commun. Lett.*, vol. 10, no. 5, pp. 353–355, May 2006.

[12] P. C. Sofotasios, and S. Freear, "The $\kappa-\mu$/gamma extreme composite distribution: A physical composite fading model," *in IEEE WCNC '11*, Cancun, Mexico, Mar. 2011.

[13] P. Bithas, "Weibull-gamma composite distribution: alternative multipath/shadowing fading model," *Electronics Letters*, vol. 45, no. 14, pp. 749–751, Jul. 2009.

[14] P. C. Sofotasios, and S. Freear, "On the $\kappa-\mu$/gamma composite distribution: A generalized multipath/shadowing fading model," *in IEEE IMOC '11*, Natal, Brazil, Oct. 2011.

[15] S. Harput, P. C. Sofotasios, and S. Freear, "A novel composite statistical model for ultrasound applications," *in IEEE IUS '11*, Orlando, FL, USA, Oct. 2011.

[16] P. Sofotasios, T. Tsiftsis, M. Ghogho, L. Wilhelmsson, and M. Valkama, "The $\eta-\mu$/IG distribution: A novel physical multipath/shadowing fading model," in *IEEE International Conference on Communications (ICC)*, Jun. 2013, pp. 5715–5719.

[17] J. Zhang, M. Matthaiou, Z. Tan, and H. Wang, "Performance analysis of digital communication systems over composite $\eta-\mu$ /gamma fading channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 3114–3124, Sep. 2012.

[18] P. Sofotasios, T. Tsiftsis, K. H. Van, S. Freear, L. Wilhelmsson, and M. Valkama, "The $\kappa-\mu$/inverse-gaussian composite statistical distribution in rf and fso wireless channels," in *IEEE 78th Vehicular Technology Conference (VTC Fall)*, Sept 2013, pp. 1–5.

[19] S. Ki Yoo, P. C. Sofotasios, S. L. Cotton, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The $\eta-\mu$ / Inverse gamma composite fading model," *in IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015.

[20] P. C. Sofotasios, and S. Freear, "The $\eta-\mu$/gamma and the $\lambda-\mu$/gamma multipath/shadowing distributions," *in ATNAC '11*, Melbourne, Australia, Nov. 2011.

[21] S. Ki Yoo, S. L. Cotton, P. C. Sofotasios, M. Matthaiou, M. Valkama, and G. K. Karagiannidis, "The $\kappa-\mu$ / Inverse gamma fading model," *in IEEE PIMRC '15*, Hong Kong, Aug/Sep. 2015.

[22] P. C. Sofotasios, and S. Freear, "The $\alpha-\kappa-\mu$/gamma composite distribution: A generalized non-linear multipath/shadowing fading model," *in IEEE INDICON '11*, Hyderabad, India, Dec. 2011.

[23] J. Paris, "Statistical characterization of $\kappa-\mu$ shadowed fading," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 518–526, Feb 2014.

[24] J. B. Andersen, "Statistical distributions in mobile communications using multiple scattering," in *Proc. 27th URSI General Assembly*, 2002.

[25] G. K. Karagiannidis, N. C. Sagias, and P. T. Mathiopoulos, "N*Nakagami: A novel stochastic model for cascaded fading channels," *IEEE Trans. on Commun.*, vol. 55, no. 8, pp. 1453–1458, Aug 2007.

[26] P. Sofotasios, L. Mohjazi, S. Muhaidat, M. Al-Qutayri, and G. Karagiannidis, "Energy detection of unknown signals over cascaded fading channels," *IEEE Antennas Wireless Propag. Lett.*, vol. PP, no. 99, 2015.

[27] V. Erceg, S. J. Fortune, J. Ling, A. Rustako, and R. A. Valenzuela, "Comparisons of a computer-based propagation prediction tool with experimental data collected in urban microcellular environments," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 4, pp. 677–684, 1997.

[28] C. Studer, M. Wenk, and A. Burg, "MIMO transmission with residual transmit-RF impairments," in *Int. ITG Workshop on Smart Antennas*, Bremen, Feb 2010, pp. 189–196.

[29] E. Bjornson, P. Zetterberg, and M. Bengtsson, "Optimal coordinated beamforming in the multicell downlink with transceiver impairments," in *IEEE Global Communications Conf.*, California, Dec 2012, pp. 4775–4780.

[30] E. Bjornson, A. Papadogiannis, M. Matthaiou, and M. Debbah, "On the impact of transceiver impairments on af relaying," in *IEEE Int. Conf. on Acoustics, Speech and Signal Processing*, Vancoucer, May 2013, pp. 4948–4952.

[31] E. Bjornson, P. Zetterberg, M. Bengtsson, and B. Ottersten, "Capacity limits and multiplexing gains of MIMO channels with transceiver impairments," *IEEE Commun. Lett.*, vol. 17, no. 1, pp. 91–94, January 2013.

[32] E. Bjornson, M. Matthaiou, and M. Debbah, "A new look at dual-hop relaying: Performance limits with hardware impairments," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4512–4525, November 2013.

[33] A.-A. A. Boulogeorgos, N. Chatzidiamantis, G. K. Karagiannidis, and L. Georgiadis, "Energy detection under RF impairments for cognitive radio," in *Proc. IEEE International Conference on Communications - Workshop on Cooperative and Cognitive Networks (ICC - CoCoNet)*, London, United Kingdom, Jun. 2015.

[34] A.-A. A. Boulogeorgos, N. D. Chatzidiamantis, and G. K. Karagiannidis, "Spectrum sensing under hardware constraints," *CoRR*, vol. abs/1510.06527, 2015. [Online]. Available: http://arxiv.org/abs/1510.06527

[35] A. Gokceoglu, S. Dikmese, M. Valkama, and M. Renfors, "Energy Detection under IQ Imbalance with Single- and Multi-Channel Direct-Conversion Receiver: Analysis and Mitigation," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 3, pp. 411–424, March 2014.

[36] E. Bjornson, M. Matthaiou, and M. Debbah, "A new look at dual-hop relaying: Performance limits with hardware impairments," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4512–4525, November 2013.

[37] J. Qi and S. Aissa, "Analysis and compensation of I/Q imbalance in MIMO transmit-receive diversity systems," *IEEE Trans. Commun.*, vol. 58, no. 5, pp. 1546–1556, May 2010.

[38] Y. Zou, M. Valkama, and M. Renfors, "Digital compensation of I/Q imbalance effects in space-time coded transmit diversity systems," *IEEE Trans. Signal Process.*, vol. 56, no. 6, pp. 2496–2508, JUN 2008.

[39] J. Qi, S. Aissa, and M.-S. Alouini, "Dual-hop amplify-and-forward cooperative relaying in the presence of Tx and Rx in-phase and quadrature-phase imbalance," *IET Communications*, vol. 8, no. 3, pp. 287–298, Feb 2014.

[40] J. Li, M. Matthaiou, and T. Svensson, "I/Q imbalance in AF dual-hop relaying: Performance analysis in Nakagami-m fading," *IEEE Trans. Commun.*, vol. PP, no. 99, pp. 1–12, 2014.

[41] M. Mokhtar, A.-A. A. Boulogeorgos, G. K. Karagiannidis, and N. Al-Dhahir, "OFDM Opportunistic Relaying Under Joint Transmit/Receive I/Q Imbalance," *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1458–1468, May 2014.

[42] C. Studer, M. Wenk, and A. Burg, "System-level implications of residual transmit-RF impairments in MIMO systems," in *Proc. of the 5th European Conf. on Antennas and Propagation*, April 2011, pp. 2686–2689.

[43] S. Mirabbasi and K. Martin, "Classical and modern receiver architectures," *IEEE Commun. Mag.*, vol. 38, no. 11, pp. 132–139, Nov 2000.

[44] L. Anttila, M. Valkama, and M. Renfors, "Circularity-based I/Q imbalance compensation in wideband direct-conversion receivers," *IEEE Trans. Veh. Commun.*, vol. 57, no. 4, pp. 2099–2113, July 2008.

[45] M. Valkama, J. Pirskanen, and M. Renfors, "Signal processing challenges for applying software radio principles in future wireless terminals: an overview," *Int. J. Commun. Syst.*, vol. 15, no. 8, pp. 741–769, 2002.

[46] A.-A. A. Boulogeorgos, V. M. Kapinas, R. Schober, and G. K. Karagiannidis, "I/Q-imbalance self-interference coordination," *IEEE Trans. Wireless Commun.*, vol. PP, no. 99, pp. 1–1, 2016.

[47] A.-A. A. Boulogeorgos, H. Bany Salameh, and G. K. Karagiannidis, "On the effects of I/Q imbalance on sensing performance in Full-Duplex cognitive radios," in *IEEE Wireless Communications and Networking Conference WS 8: IEEE WCNC'2016 International Workshop on Smart Spectrum (IWSS) (IEEEWCNC2016-IWSS)*, Doha, Qatar, Apr. 2016.

[48] S. J. Grant and J. K. Cavers, "Analytical calculation of outage probability for a general cellular mobile radio system," in *IEEE Vehicular Technology Conf.*, vol. 3. Amsterdam: IEEE, 1999, pp. 1372–1376.

[49] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. New York: Academic, 2000.