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A NOVEL APPROACH ON PERFORMANCE OPTIMIZATION OF HARDWARE CONSTRAINED RELAYING SYSTEMS

K. Avinash kumar
Asst. Professor, Dept. of ECE,
DIET, Anakapalle, A.P.

V. Sony Prasanna
Department of ECE,
DIET, Anakapalle, A.P.

Abstract

Abstract- **Hardware constraints have been seen in transceivers which create buckle thus degrading the communication system performance. In this work we have presented the impact of hardware faults on the Bi-hop relaying system for amplify and forward (AAF) and decode and forward (DAF) protocols in wireless system. Also Signal to noise distortion ratio is computed which is a function of probability outage (PO). In our work we have derived the expressions for exact probability outages accounting for hardware constraints at source, relay and destination. In this work we have assumed that the two networks are independent and are not disturbed non-identically. This work proves that the performance loss is small at low rates otherwise it can be very sizeable. It is also been proved that the SDNR tends to meet deterministic constant which is inversely proportional to level of constraints or impairments. This stands in converse in ideal hardware case. Finally, we provide primary intend strategy meant for selecting hardware that satisfies the rations of a realistic relaying structure.**

Keywords: *DAF, PO, SDNR, impairments*

I. INTRODUCTION

RECENTLY, research efforts have been focused on the investigation of multi-hop wireless communications systems, which seem to extend the coverage without using large power at the transmitter and increase connectivity and capacity in wireless networks. Multi-hop wireless communications systems are able to provide a potential for broader and more efficient coverage in bent pipe satellites and microwave links, as well as modern ad-hoc, cellular, WLAN, and hybrid wireless networks. In multi-hop networks, intermediate nodes operate as relays between the source and the destination terminal. Generally, there are two main categories of multi-hop wireless communication systems: Non regenerative and regenerative systems. In the regenerative systems, the relay re-encodes and retransmits the signal towards the destination after demodulating and decoding the received signal from the source. At the destination, the receiver can employ a variety of diversity combining techniques to benefit from the multiple signal replicas available from the relays and the source. Non regenerative systems use less complex relays that just amplify and re-transmit the information signal without performing any sort of decoding. Moreover, relays in non-regenerative systems can in their turn be classified into two subcategories, namely, channel state information (CSI)-assisted relays and blind relays. Non-regenerative systems with CSI-assisted relays use instantaneous CSI of the first hop to control the gain introduced by the relay. However, in practice, hardware suffers from several types of impairments; for example, phase noise, I/Q imbalance, and high power amplifier (HPA) nonlinearities among others. The impact of hardware impairments on various types of single-hop systems was analyzed. For instance, I/Q imbalance was considered in and it was shown to attenuate the amplitude and rotate the phase of the desired constellation. Moreover, it creates an additional image signal from the mirror subcarrier, which leads to a symbol error rate floor. In addition, characterized the effect of non-linear HPAs as a distortion of the constellation position plus an additive Gaussian noise. The authors therein showed that, in the presence of HPA non-linearities, the bit-error-rate increases compared to linear HPAs; for severe non-linearities, an irreducible error floor emerges. Hardware impairments are typically mitigated by compensation algorithms, but there are always residual impairment. As a general conclusion, hardware impairments have a deleterious impact on the achievable performance. This effect is more pronounced in high-rate systems, especially those employing inexpensive hardware. Recent works in information theory have demonstrated that non-ideal hardware severely affects multi-antenna systems; more specifically, proved that there is a finite capacity limit at high signal-to-noise ratio (SNR), while provided a general resource allocation framework where existing signal processing algorithms are redesigned to account for impairments.

We introduce a general model to account for transceiver hardware impairments in relaying. Unlike the works of which examined the impact of a single type of impairments, we herein take a macroscopic look and investigate the aggregate impact of hardware impairments. After obtaining the instantaneous end-to-end signal-to noise-plus-distortion ratios (SNDRs) for both AF and DF relaying, we derive new closed-form expressions for the exact outage probability (OP) of the system. This enables us to characterize the impact of impairments for any arbitrary SNR value. New upper bounds on the ergodic capacity are also provided. Note that our analysis considers Nakagami-m fading, which has been extensively used in the performance analysis of communication systems. In order to obtain more engineering insights, we elaborate on the high-SNR regime and demonstrate the presence of a so-called SNDR ceiling. This fundamental ceiling is explicitly quantified and its value is shown to be inversely proportional to the level of impairments. This observation manifests that both AF and DF relaying systems are intimately limited by hardware impairments—especially at high SNRs and when high rates are desirable. On a similar note, the ergodic capacity exhibits a so-called capacity ceiling. In the last part of the paper, we provide some design guidelines for optimizing the performance of hardware constrained relaying systems. These results are of particular importance when it comes down to finding the lowest hardware quality (i.e., highest level of impairments) that can theoretically meet stipulated requirements. The routine limits of hardware-constrained relaying systems in the high-SNR management are examined and some essential aim guidelines are also obtained. Our numerical results are provided.

II. CONCEPT

We first describe a generalized system model for single-hop transmission Suppose an information signal $s \in C$ is put across over a flat-fading wireless conduit $h \in C$ with additive noise $v \in C$. This channel can, for example, be one of the subcarriers in a multi-carrier system based on orthogonal frequency-division multiplexing. The received signal is conventionally modeled as

$$y = hs + v \qquad (1)$$

where h, s, and are statistically independent. However, physical radio-frequency (RF) transceivers suffer from impairments that are not accurately captured in this way. Informally speaking, such impairments 1) create a mismatch between the intended signal s and what is actually generated and emitted; and 2) distort the received signal during the reception process . This calls for the inclusion of additional distortion noise sources that are statistically dependent on the signal power and channel gain.

The distortion noises are defined as

$$\eta_t \approx CN\left(0, k_t^2 P\right), \eta_x \approx CN\left(0, k_x^2 P|h|^2\right) \quad (2)$$

The joint Gaussianity in (2) is explained by the aggregate effect of much impairment. For a given channel realization h, the aggregate distortion seen at the receiver has power

$$E_{\eta_t,\eta_x}\left\{|h\eta_t + \eta_x|^2\right\} = P|h|^2\left(k_t^2 + k_r^2\right) \qquad (3)$$

Thus, it depends on the average signal power $P = E_s\left\{|s|^2\right\}$ and the instantaneous channel gain $|h|^2$. Note that this dependence is not supported by the classical channel model in (1), because the effective distortion noise is correlated with the channel and is not Gaussian distributed

III. RELAYING WITH NON-IDEAL HARDWARE

Consider the dual-hop relaying scenario in Fig. 1. Let the transmission parameters between the source and the relay have subscript 1 and between relay and destination have subscript 2. Using the generalized system model , the received signals at the relay and destination are

$$y = h(s+\eta)+v \qquad i=1,2.. \qquad (4)$$

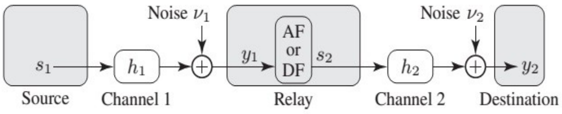

Fig. 1 Dual-hop relaying scenario

Where $s_1, s_2 \in C$ are the transmitted signals from the source and relay, respectively. The channel magnitudes $|h_i|$ are modeled as independent but non-identically distributed Nakagami-m variates, such that the channel gains $\rho_i \overset{\Delta}{=} |h_i|^2 \approx Gamma(\alpha_i, \beta_i)$. In this case, the cumulative distribution functions (cdfs) and probability distribution functions (pdfs) of the channel gains ρ_i are

$$F_{\rho i}(x) = 1 - \sum_{j=0}^{\alpha_i - 1} \frac{e^{-\frac{x}{\beta_i}}}{j!}\left(\frac{x}{\beta_i}\right)^j, x \geq 0 \qquad (5)$$

For i=1,2. Note that most of the analysis in this paper is generic and applies for any fading distribution. The choice of Nakagami-m fading is only exploited for deriving closed-form expressions for quantities such as the OP and ergodic capacity. For any fading distribution, the quantity

$$SNR_i = \frac{P_i E_{\rho i}\{\rho_i\}}{N_i} \qquad (6)$$

is referred to as the average SNR, for i = 1,2.

IV. AMPLIFY-AND-FORWARD RELAYING

The information signal s$_1$ should be acquired at the destination. In the AF relaying protocol, the transmitted signal s$_2$ at the relay is simply an amplified version of the signal y$_1$ received at the relay: $s_2 = G_{y1}$ for some amplification factor $G > 0$. The received signal at the destination is now obtained as

$$\begin{aligned} y_2 &= h_2 G_{ni}\left(h_1(s_1+\eta_1)+v_1\right)+h_2\eta_2+v_2 \\ &= G_{ni}h_1h_2s_1 + G_{ni}h_1h_2\eta_1 + G_{ni}h_2v_1 + h_2\eta_2 + v_2 \end{aligned} \qquad (7)$$

where the amplification factor G_{ni} is selected at the relay to satisfy its power constraint. The source needs no channel knowledge. For fixed and variable gain relaying G_{ni} reads respectively as

$$G_{ni}^{f} \overset{\Delta}{=} \sqrt{\frac{P_2}{P_1 E_{\rho 1}\{\rho_1\}(1+k_1^2)+N_1}} \qquad (8)$$

$$G_{ni}^{v} \overset{\Delta}{=} \sqrt{\frac{P_2}{P_1 \rho_1 (1+k_1^2)+N_1}} \qquad (9)$$

Where $E_{\rho 1}\{\rho_1\} = \alpha_1\beta_1$ Nakagami-m fading.

V. OUTAGE PROBABILITY ANALYSIS

This section derives new closed-form expressions for the exact OPs under the presence of transceiver impairments. The OP is denoted by $P_{out}(x)$ and is the probability that the channel fading makes the effective end-to-end SNDR fall below a certain threshold, x, of acceptable communication quality. Mathematically speaking, this means that

$$P_{out}(x) \overset{\Delta}{=} \Pr\{\gamma \leq x\} \qquad (10)$$

Where γ is the effective end-to-end SNDR.

VI. A SYMPTOTIC SNR ANALYSIS

To obtain some insights on the fundamental impact of impairments, we now elaborate on the high-SNR regime. Recall the SNR definition,

$$SNR_i = \frac{P_i E_{\rho i}\{\rho_i\}}{N_i} \text{ for } i = 1, 2 \qquad (11)$$

For the ease of presentation, we assume that $SNR1 = \mu SNR2$ grow large with for some fixed ratio

$$0 < \mu < \infty \qquad (12)$$

such that the relay gain remains finite and strictly positive.

The SNDR ceiling for dual-hop relaying is

$$\gamma^* \overset{\Delta}{=} \begin{cases} \dfrac{1}{k_1^2 + k_2^2 + k_1^2 k_2^2} \, forAFprotocol, \\ \dfrac{1}{\max\left(k_1^1, k_2^2\right)} \, forDFprotocol, \end{cases} \qquad (13)$$

which is inversely proportional to the squares of k_1, k_2. This validates that transceiver hardware impairments dramatically affect the performance of relaying channels and should be taken into account when evaluating relaying systems. The ceiling is, roughly speaking, twice as large for DF relaying as for AF relaying this implies that the DF protocol can handle practical applications with twice as large SNDR constraints without running into a definitive outage state. Apart from this, the impact of k_1 and k_2 on the SNDR ceiling is similar for both relaying protocols, since γ^* is a symmetric function of k_1, k_2. We now turn our attention to the ergodic capacity in the high-SNR regime. In this case, the following result is of particular importance.

VI. DESIGN GUIDELINES FOR RELAYING SYSTEMS

The parameter k_1 can be decomposed as

$$k_i = \sqrt{k_{i,t}^2 + k_{i,r}^2} \qquad (14)$$

Where $k_{i,t}, k_{i,r}$ are the levels of impairments (in terms of EVM) in the transmitter and receiver hardware, respectively. The hardware cost is a decreasing function of the EVMs, because low-cost hardware has lower quality and thus higher EVMs. Hence, it is of practical interest to find the EVM combination that maximizes the performance for a fixed cost.

The following corollary provides insights for hardware design.

Suppose $\sum_{i=1}^{2} \zeta\left(k_{i,r}\right) = T_{\max}$ for some given cost $T_{\max} \geq 0$. The SNDR ceilings are both maximized by

$$k_{1,t} = k_{1,r} = k_{2,r} = \zeta^{-1}\left(\frac{T_{\max}}{4}\right) \qquad (14)$$

The above shows that it is better to have the same level of impairments at every transceiver chain, than mixing high quality and low-quality transceiver chains. In particular, this tells us that the relay hardware should ideally be of the same quality as the source and destination hardware. As a consequence, we provide the following design guidelines on the highest level of impairments that can theoretically meet stipulated requirements.

Consider a relaying system optimized according to above condition, To support a given SNDR threshold x it is necessary to have $k_i^2 \leq \sqrt{\frac{1}{x} + 1} - 1$ for AF relaying and $k_i^2 \leq \frac{1}{x}$ for DF relaying for i = 1, 2.

This corollary shows that hardware requirements are looser for DF than for AF, which is also illustrated If the SNDR threshold is substituted as $x = 2^{2R} - 1$ then we achieve the corresponding necessary conditions for achieving an ergodic capacity of R bits/channel use.

Observe that the guidelines in conditions above are necessary, while the sufficiency only holds asymptotically in the high SNR regime. Thus, practical systems should be more conservatively designed to cope with finite SNRs and different channel fading conditions.

VII. OUTPUTS

In this section, the theoretical results are validated by a set of Monte-Carlo simulations. Furthermore, the concepts of SNDR and capacity ceilings and the practical design guidelines as in above conditions.

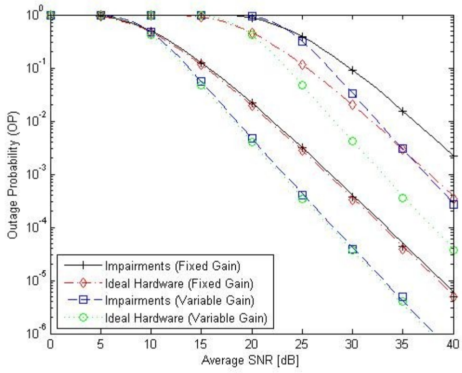

Fig. 2 Outage probability for AF relaying with ideal hardware and with hardware impairments of $k_1 = k_2 = 0$:1

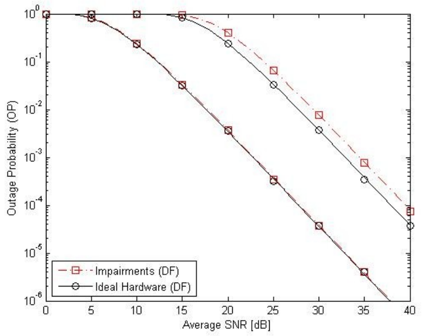

Fig. 3 Outage probability for DF relaying with ideal hardware and with hardware impairments of $k_1 = k_2 = 0$:1

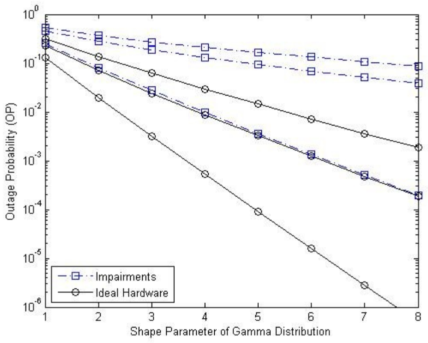

Fig. 4 Outage probability for fixed gain AF relaying with ideal hardware and with hardware impairments of $k_1 = k_2$ = 0:3. Different shape parameters α_1; α_2 are considered in the fading distributions and different asymmetric SNR_s: $SNR_1 =_{\mu} SNR$ 2. The strongest channel has an SNR of 20 dB

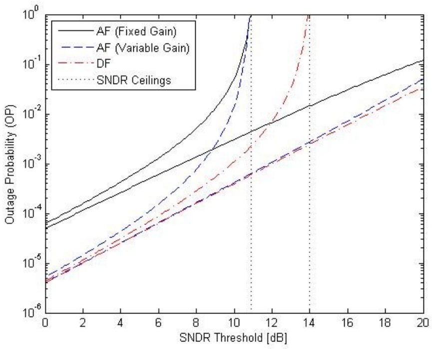

Fig. 5 Outage probability for AF and DF relaying for different thresholds x. As proved in defined conditions, there exist SNDR ceilings under transceiver hardware impairments $k_1 = k_2 = 0.20$

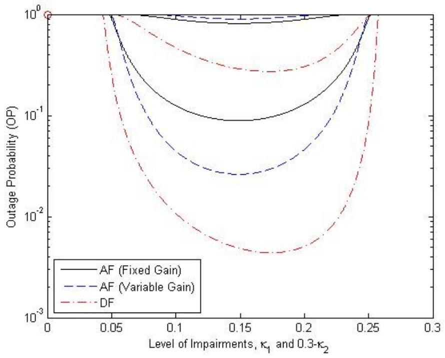

Fig. 6 Outage probability for AF and DF relaying for different levels of impairments k_1; k_2 for which $k_1 + k_2 =$ 0:3. The minimal value at each curve is marked with a ring

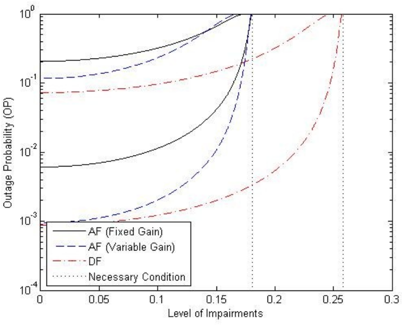

Fig. 7 Outage probability for AF and DF relaying for different symmetric levels of impairments $k_1 = k_2$.

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Based on these insights, we now convoluted on the case with symmetric levels of impairments: $k_1 = k_2$. Suppose our method should operate using $x = 2^4 - 1 = 15$ (i.e., 2 bits/channel use) and we want to accomplish a certain value on the outage prospect. Fig. 8 shows the Ops for AF and DF relaying at two different average SNRs: $SNR_1 = SNR_2 = 2 \{20; 30\}$ dB. We can identify three possible hardware working regimes from Fig. 8:

1) Fixed gain AF relaying with $k_1 = k_2 \leq 0{:}091$;

2) Variable gain AF relaying with $k_1 = k_2 \leq 0{:}149$;

3) DF relaying with $k_1 = k_2 \leq 0{:}218$.

The different acceptable levels of impairments show that difficult protocols (AF with variable gain relaying or, preferably, DF relaying) are more vigorous to hardware impairments and, thus, can operate with hardware of lower quality. Fig. 8 also shows the necessary conditions, which act as upper limits on the level of impairments that can probably achieve an OP below 1.Even if not sufficient, these necessary background provide a violent estimate of where the level of impairments must lie.

VIII. CONCLUSION

Physical transceiver hardware introduces impairments that distort the emitted and received signals in any communication system. While the impact of being hardware impairments (e.g., phase noise, I/Q imbalance, and HPA non-linearities) have been well investigated in the consequent literature, it is the cumulative impact of all hardware impairments and the respective reparation algorithms that agree on the practical system concert. Motivated by this, we considered a global impairment model that has been validated in prior works for single-hop communications and applied it on flat-fading dual-hop relaying, allowing for both AF and DF protocols. Our analytical and statistical results manifested that the performance of dual-hop relaying is markedly affected by these hardware impairments, particularly when high achievable rates are required. Closed-form expressions for the accurate and asymptotic OPs were consequent under Nakagami-*m* fading, along with tractable upper bounds and approximations for the ergodic capacities. These terms effectively characterize the impact of impairments and exhibit the existence of essential SNDR and capacity ceilings that cannot be crossed by increasing the signal powers or varying the fading conditions. Note that even very small hardware impairments will ultimately limit the performance. These observations also hold true for every entity subcarrier in dual-hop OFDM systems. We finally derived some useful design guidelines for optimizing the performance of hardware-constrained relaying systems: 1) Use the same hardware eminence on all transceivers; 2) Follow the necessary conditions to find hardware qualities that can achieve the essential system performance; and 3) More sophisticated relaying protocols (e.g., DF) are also more robust to hardware impairments

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