Energy efficient bandwidth and power allocation for type-I HARQ under the Rician channel

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***Abstract*—We address the problem of joint bandwidth and power allocation for Type-I HARQ when the objective is to maximize the energy efficiency of the network under the Rician channel. We consider a per link minimum goodput constraint. Our derivations take into account practical modulation and coding schemes and we consider that only statistical channel state information is available to perform the resource allocation (RA). Through simulations, we show the advantage of explicitly taking into account the Rician channel during the RA process instead of the conventional Rayleigh one.**

I. Introduction

The hybrid automatic repeat request (HARQ) combines the strengths of automatic repeat request (ARQ) protocol and forward error correction (FEC), allowing to increase the robustness of wireless communications by taking advantage of the diversity offered by time varying channels. This mechanism is used in several standards taking place in multiuser context, including 4G long term evolution (LTE) [1]. When designing a communications system, the resource allocation (RA) problem is an important task and has to take into account the presence of HARQ. Among the resource to allocate are the modulation and coding schemes (MCS), the bandwidth and the transmit power. In this paper, we focus on the allocation of these two latter resources.

The RA is generally obtained by maximizing or minimizing a criterion subject to constraints. Two conventional criteria are the maximization of the sum of the links' data rate [2], or the minimization of the links' transmit power [3]. More recently, another metric called energy efficiency (EE) has gained interest from the scientific community [4], [5]. The EE is a measure of the amount of information that can be reliably transmitted per consumed unit of energy, and is expressed in bits/joule. This metric is of interest as long as minimizing the energy consumption is the objective of system designers. In this paper, we are interested in performing the RA with the objective of maximizing the EE of the network, called global EE (GEE). The corresponding criterion will be refereed to as the maximum GEE (MGEE).

Moreover device to device (D2D) communications will be of central importance within 5G networks [6]. In D2D communications, the RA can be performed either in a distributed fashion, i.e. the device perform their own RA, or in an assisted fashion i.e. there is a resource manager (RM) whose role is to perform the RA [7]. In this work, we are interested in assisted D2D communications. Since the RM has to centralize the channel state information (CSI) of the different links to perform the RA, it has access to outdated CSI. Therefore we assume that only statistical CSI is known and can be used to perform the RA [8]. Since we have only access to the statistical behaviour of the channel, the underlying statistical channel model is of importance. We hereafter focus on the Rician fading channel, which is known to accurately represent the statistical behavior of wireless channel in the presence of a line of sight (LoS) between the transmitter and the receiver [9]. The Rician channel model is nowadays of central interest in the literature due to its accuracy in the context of millimeter wave communications [10], which is a promising technology for 5G networks [11].

In the absence of HARQ, the RA problem related to EE maximization when considering practical MCS has been addressed in the single user context in [12], and the multiuser context in [13]. In [12], a low complex link adaptation for multiple input-multiple output orthogonal frequency division multiplexing (OFDM) is proposed under perfect CSI available at the transmitter side. In [13], the MGEE problem is solved for LTE downlink considering perfect CSI at the base station.

In the presence of HARQ, the EE in the multiuser context is investigated in [14]–[17] considering orthogonal frequency division multiple access (OFDMA). In [14], the GEE is optimized assuming perfect CSI at the transmitter and capacity achieving codes. In [15], EE is analyzed with respect to some predefined power allocation assuming capacity achieving codes. In [16], a suboptimal algorithm is proposed to optimize the harmonic mean of EE under the Rayleigh channel assuming relay assisted systems using OFDMA and type-I HARQ with statistical CSI at the transmitter and practical MCS. Finally, in [17], the sum of the EE under the Rayleigh channel is maximized assuming statistical CSI at the transmitter and practical MCS for type-II HARQ.

From the above discussion, we see there are only few works addressing the RA problem for HARQ with EE related metrics, practical MCS and statistical CSI in the multiuser context i.e. [16], [17]. Moreover, these works consider the Rayleigh channel. Our main contributions are the following ones. We provide low-complex algorithm to optimally solve the MGEE problem for type-I HARQ under the Rician channel hypothesis with statistical CSI and practical MCS. Through numerical simulations, we point out that substiantial gains in terms of GEE (and hence in terms of energy consumption) can be achieved by explicitly considering the Rician distribution if the channel is Rician-distributed rather than only the channel variance (as done in Rayleigh model) during the RA process.

The rest of the paper is organised as follows. In Section II, we present the system model and we formulate the RA problem. Section III is devoted to the optimal resolution of the MGEE problem. In Section IV, we investigate the results of the proposed algorithm through numerical simulations. Finally, in Section V, we draw concluding remarks.

II. System model and problem formulation

A. Channel model and HARQ mechanism

We consider a network with L active links sharing a bandwidth B, which is divided in N_c subcarriers. For the ease of presentation, the considered multi access technology is OFDMA, but our derivations extend straightforwardly to any multiple access multicarrier scheme and to single-carrier frequency division multiplexing as long as the packet error rate (PER) is a strictly decreasing convex function of the transmit energy (c.f. Section II-D). In the network, a RM collects the statistical CSI of the links, and perform the RA. We consider that each link can be modeled as a multipath Rician channel, which remains constant within one OFDMA symbol and varies independently from symbol to symbol. We denote by $\mathbf{h}_\ell(j) = [h_\ell(j,0), ..., h_\ell(j, M-1)]^T$ the sampled channel impulse response of link ℓ during the jth OFDMA symbol, with $(.)^T$ the transposition operator and M the length of this response. We assume that each tap of the channel is an independent random variable such that $\mathbf{h}_\ell(j) \sim \mathcal{CN}(\mathbf{a}_\ell, \Sigma_\ell)$, where $\mathcal{CN}(\mathbf{a}_\ell, \Sigma_\ell)$ stands for the multi-variate complex normal distribution with mean $\mathbf{a}_\ell := [a_\ell, 0, \cdots, 0]^T$ and covariance matrix $\Sigma_\ell := \mathrm{diag}_{M\times M}(\sigma^2_{\ell,0}, ..., \sigma^2_{\ell,M-1})$.

The received signal on link ℓ on the nth subcarrier at OFDMA symbol i is

$$Y_\ell(i,n) = H_\ell(i,n)X_\ell(i,n) + Z_\ell(i,n), \tag{1}$$

where $\mathbf{H}_\ell(i) = [H_\ell(i,0), ..., H_\ell(i, N_c-1)]^T$ is the Fourier transform of $\mathbf{h}_\ell(i)$, $X_\ell(i,n)$ is the transmitted symbol on the nth subcarrier of the ith OFDMA symbol and $Z_\ell(i,n) \sim \mathcal{CN}(0, N_0B/N_c)$, with N_0 the noise level in the power spectral density. The elements of $\mathbf{H}_\ell(i)$ are identically distributed random variables $H_\ell(i,n) \sim \mathcal{CN}(a_\ell, \zeta^2_\ell)$ where $\zeta^2_\ell := \mathrm{Tr}(\Sigma_\ell)$. We can now define the average gain-to-noise ratio (GNR) of link ℓ as

$$G_\ell := \frac{\mathbb{E}[|H_\ell(i,n)|^2]}{N_0} = \frac{\Omega_\ell}{N_0}, \tag{2}$$

with $\Omega_\ell := |a_\ell|^2 + \zeta^2_\ell$. The Rician K factor of link ℓ is then

$$K_\ell := \frac{|a_\ell|^2}{\zeta^2_\ell}. \tag{3}$$

It is assumed that the RM only knows the average GNR and the Rician K factor of each link to perform the RA. We further assume that a deep interleaved coded modulator is used in order the channel to be seen as fast fading, i.e. each modulated symbol experiments independent channel realization.

A type-I HARQ scheme is used at the medium access layer (MAC). The stream of information bits is arranged into packets of $\mathcal{L}_\ell$ bits. The same packet is sent on the channel at most L times. the MAC packets are obtained by encoding the bits by a FEC with rate R_ℓ. After the mth reception, the receiver decodes the information bits. Since we consider the use of type-I HARQ, only the mth received packet is used to decode the information bits i.e. the packets received in error are discarded.

B. Energy consumption model

We suppose that a quadrature amplitude modulation (QAM) with m_ℓ bits per symbol is used on link ℓ. Let $\gamma_\ell := n_\ell/N_c$ be the proportion of bandwidth allocated to link ℓ. Since only statistical CSI is available and all subcarriers are identically distributed, the same power is used on all the subcarriers. We then define $P_\ell := \mathbb{E}[|X_\ell(j,n)|^2]$ as the power allocated per subcarrier to the ℓth link.

The total energy consumed to send and receive one packet is the sum of the transmission energy and the circuitry consumption of both the transmitter and the receiver. The power used by link ℓ to send and receive one OFDMA symbol is

$$P_{T,\ell} := N_c\gamma_k\frac{P_\ell}{\kappa_\ell} + P_{ctx,\ell} + P_{crx,\ell}, \tag{4}$$

where $\kappa_\ell \leq 1$ is the power amplifier efficiency, and $P_{ctx,\ell}$ (resp. $P_{crx,k}$) is the circuitry power consumption of the transmitter (resp. receiver).

C. Energy efficiency

The GEE is the ratio of the sum of the users' goodput (i.e. the number of informations bits that can be transmitted without error per second) and the sum of their energy consumption, which writes

$$\mathcal{G} = \frac{\sum_{\ell=1}^{L}\eta_\ell}{\sum_{\ell=1}^{L}P_{T,\ell}}, \tag{5}$$

where η_ℓ is the goodput of link ℓ. From [18], we know that, for Type-I HARQ, the goodput is given by:

$$\eta_\ell = B\alpha_\ell\gamma_\ell(1 - q_\ell(G_\ell E_\ell)), \tag{6}$$

where $\alpha_\ell := R_\ell m_\ell$, $q_\ell(G_\ell E_\ell)$ is the PER of user ℓ and $E_\ell := N_cP_k/B$ is the transmit energy assigned to user ℓ. By plugging (6) and (4) into (5), we obtain the following expressions for the GEE:

$$\mathcal{G}(\mathbf{E}, \boldsymbol{\gamma}) = \frac{\sum_{\ell=1}^{L}\alpha_\ell\gamma_\ell(1 - q_\ell(G_\ell E_\ell))}{\sum_{\ell=1}^{L}(A_\ell\gamma_\ell E_\ell + B_\ell)}, \tag{7}$$

where, $\mathbf{E} := [E_1, \cdots, E_L]$, $\boldsymbol{\gamma} := [\gamma_1, \cdots, \gamma_L]$ are the optimization variables i.e. the resource that have to be assigned to the links, and $A_\ell := \kappa_\ell^{-1}$ and $B_\ell := (P_{ctx,\ell} + P_{crx,\ell})/B$ are independent of the optimization variables.

D. Assumptions on the packet error rate

For our derivations, we make an assumption on the PER q_ℓ.

Assumption 1. *$q_\ell(x)$ is a strictly decreasing convex function of the transmit energy.*

Assumption 1 is for instance compatible with the approximation of the PER developed in [19] for the Rician and Rayleigh fast fading channel.

E. Considered constraints

A constraint on the minimum goodput per link is considered leading to

$$\alpha_\ell \gamma_\ell (1 - q_\ell(G_\ell E_\ell)) \geq \eta_\ell^{(0)}, \quad \forall \ell. \tag{8}$$

From the definition of the bandwidth parameter, the following inequality holds

$$\sum_{\ell=1}^{L} \gamma_\ell \leq 1. \tag{9}$$

F. Problem formulation

Our objective is to solve the following MGEE problem.

Problem 1. *The MGEE problem writes*

$$\max_{\mathbf{E}, \boldsymbol{\gamma}} \quad \mathcal{G}(\mathbf{E}, \boldsymbol{\gamma}), \tag{10}$$

$$\text{s.t.} \quad (8), (9). \tag{11}$$

III. GEE MAXIMIZATION

Observing Problem 1 and (7), we see that the objective function $\mathcal{G}(\mathbf{E}, \boldsymbol{\gamma})$ is a ratio of functions. The problem of the maximization of a ratio of functions can be efficiently solved using the Dinkelbach's algorithm when the numerator is concave and denominator is convex, and the feasible set is convex [4]. We first propose the following change of variable such that we can apply this algorithm to Problem 1:

$$Q_\ell := \gamma_\ell E_\ell, \quad \forall \ell. \tag{12}$$

With these new variables, Problem 1 can be rewritten as:

Problem 2.

$$\max_{\mathbf{Q}, \boldsymbol{\gamma}} \quad \frac{\sum_{\ell=1}^{L} \gamma_\ell (1 - q_\ell(G_\ell Q_\ell / \gamma_\ell))}{\sum_{\ell=1}^{L} (A_\ell Q_\ell + B_\ell)}, \tag{13}$$

$$\text{s.t.} \quad \gamma_\ell (1 - q_\ell(G_\ell Q_\ell / \gamma_\ell)) \geq \eta_\ell^{(0)}, \quad \forall \ell, \tag{14}$$

$$\sum_{\ell=1}^{L} \gamma_\ell \leq 1. \tag{15}$$

In the following lemma whose proof is omitted for brevity, we give a characterization of Problem 2.

Lemma 1. *Problem 2 is the maximization of a ratio between a concave and a convex function, over a convex set.*

Problem 2 can thus be efficiently solved using the Dinkelbach's algorithm [4] which is iterative whose i-th iteration requires to solve the following problem.

Problem 3.

$$\max_{\mathbf{Q}, \boldsymbol{\gamma}} \quad \sum_{\ell=1}^{L} (\gamma_\ell (1 - q_\ell(G_\ell \frac{Q_\ell}{\gamma_\ell})) - \nu^{(i)} (A_\ell Q_\ell + B_\ell)), \tag{16}$$

$$\text{s.t.} \quad (14), (15). \tag{17}$$

with $\nu^{(i)} \geq 0$ depending on the optimal solution of the $(i-1)$th iteration. From Lemma 1, Problem 3 is the maximization of a concave function over a convex set. This problem can be optimally solved using the Karush-Kuhn-Tucker (KKT) conditions. Actually, we did not succeed to analytically solve these conditions. However, we managed to use them to find an algorithm enabling us to solve Problem 3 with a lower complexity than the interior point method (IPM). To write these conditions, let us define $[\delta_1, \cdots, \delta_L]$ and λ as the non-negative Lagrangian multipliers associated with constraints (14) and (15), respectively. The KKT conditions associated with Problem 3 are given by

$$G_\ell q_\ell'(G_\ell \frac{Q_\ell}{\gamma_\ell})(1 + \delta_\ell) + \nu^{(i)} A_\ell = 0, \tag{18}$$

$$(-1 + q_\ell(G_\ell \frac{Q_\ell}{\gamma_\ell}) - G_\ell \frac{Q_\ell}{\gamma_\ell} q_\ell'(G_\ell \frac{Q_\ell}{\gamma_\ell}))(1 + \delta_\ell) + \lambda = 0, \tag{19}$$

and the complementary slackness conditions are

$$\delta_\ell(\eta_\ell^{(0)} - \gamma_\ell(1 - q_\ell(G_\ell \frac{Q_\ell}{\gamma_\ell}))) = 0, \tag{20}$$

$$\lambda(\sum_{\ell=1}^{L} \gamma_\ell - 1) = 0. \tag{21}$$

In the following, we use (18)-(21) to find the optimal solution of Problem 3 with low complexity algorithm. We first consider the value of λ as known, and then we explain how to find it.

A. Resolution for known λ

We consider the optimal value of λ, denoted by λ^*, as known and the resolution procedure is organized as follows: we obtain the optimal value of $x_\ell^* := G_\ell Q_\ell^* / \gamma_\ell^*$ as a function of λ^* using the KKT conditions, where $\forall \ell$, Q_ℓ^* (resp. γ_ℓ^*) is the optimal value of Q_ℓ (resp. γ_ℓ) for link ℓ. Then, we plug x_ℓ^* into Problem 3, yielding a linear problem. To do so, from (18), we obtain the following relation:

$$1 + \delta_\ell = \frac{-A_\ell \nu^{(i)}}{G_\ell q_\ell'(x_\ell^*)}. \tag{22}$$

Then, by plugging (22) into (19), we get

$$\mathcal{F}_\ell(x_\ell^*) = \frac{\lambda}{A_\ell \nu^{(i)}}, \tag{23}$$

with $\mathcal{F}_\ell(x) := (-1 + q_\ell(x) - x q_\ell'(x))/(G_\ell q_\ell'(x))$. We can prove that $\mathcal{F}_\ell(x)$ is strictly increasing. Then, using (23), we obtain the unique optimal value of x_ℓ^* as:

$$x_\ell^* = \mathcal{F}_\ell^{-1}(\frac{\lambda}{\nu^{(i)} A_\ell}). \tag{24}$$

Notice that (24) gives the value of the ratio between Q_ℓ^* and γ_ℓ^*, which does not provide the optimal values of these parameters. Plugging (24) into Problem 3 leads to

Problem 4.

$$\max_{\boldsymbol{\gamma}} \quad \sum_{\ell=1}^{L}(\gamma_\ell(1-q_\ell(x_\ell^*)) - \nu^{(i)}(A_\ell \gamma_\ell x_\ell^* G_\ell^{-1} + B_\ell)), \tag{25}$$

$$s.t. \quad \eta_\ell^{(0)} - \gamma_\ell(1-q_\ell(x_\ell^*)) \leq 0, \quad \forall \ell, \tag{26}$$

$$\sum_{\ell=1}^{L} \gamma_\ell \leq 1. \tag{27}$$

Problem 4 is a linear problem depending only on the variables $\boldsymbol{\gamma}$, which can be solved with much less complexity than Problem 3. Indeed, Problem 4 can be solved in a greedy fashion (not discussed due to space limitation) with complexity $\mathcal{O}(L^2)$ while Problem 3 can be solved using the IPM with complexity $\mathcal{O}(\max((2L)^3, (2L)^2(L+1))\sqrt{L+1})$ [20].

B. Search for the optimal λ

To find the optimal value of λ, we need to identify two possibilities: either there exists at least one node with inactive goodput constraint (i.e. $\exists \ell$ such that $\delta_\ell = 0$), or all the nodes have active goodput constraint at the optimum (i.e. $\delta_\ell > 0$ for all ℓ). In the following, we discuss both cases.

Case 1: $\exists \ell$ such that $\delta_\ell = 0$. In the following lemma, we exhibit the optimal value of λ.

Lemma 2. *If there is at least one node ℓ_1 with $\delta_{\ell_1} = 0$, then*

$$\lambda^* = -\min_\ell \{\mathcal{H}_\ell(x_{\ell,\delta_\ell=0}^*)\}, \tag{28}$$

with $x_{\ell,\delta_\ell=0}^* := q_\ell'^{-1}(\frac{-\nu^{(i)}A_\ell}{G_\ell})$ and $\mathcal{H}_\ell(x) := -1 + q_\ell(x) - x q_\ell'(x)$.

Proof. First, due to (19), we are only interested in the solutions of Problem 3 yielding non positive values for $\mathcal{H}_\ell$. Second, if there exists at least one node ℓ_1 with $\delta_{\ell_1} = 0$, due to (18), the optimal value of x_{ℓ_1} is given by:

$$x_{\ell_1}^* = x_{\ell_1,\delta_{\ell_1}=0}^* = q_{\ell_1}'^{-1}(\frac{-\nu^{(i)}A_{\ell_1}}{G_{\ell_1}}). \tag{29}$$

Plugging (29) into (19) provides the optimal value of λ as:

$$\lambda^* = -\mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*) \geq 0. \tag{30}$$

To prove that $\ell_1 \in \arg\min_\ell\{\mathcal{H}_\ell(x_{\ell,\delta_\ell=0})\}$, we proceed by contradiction: we assume that $\exists \ell_2$ such that $\mathcal{H}_{\ell_2}(x_{\ell_2,\delta_{\ell_2}=0}^*) < \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*)$, and we prove that the KKT condition (19) cannot hold for ℓ_2. This condition writes:

$$\mathcal{H}_{\ell_2}(x_{\ell_2}^*)(1+\delta_{\ell_2}) - \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*) = 0. \tag{31}$$

To prove that (31) cannot hold, we upper bound it by a term strictly lower than 0. To this end, we can prove that, for all ℓ, $\mathcal{H}_\ell(x_\ell^*) \leq \mathcal{H}_\ell(x_{\ell,\delta_{\ell=0}}^*)$. Using this inequality, we can upper bound (31) as follows:

$$\begin{aligned} &\mathcal{H}_{\ell_2}(x_{\ell_2}^*)(1+\delta_{\ell_2}) - \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*) \\ &\leq \mathcal{H}_{\ell_2}(x_{\ell_2,\delta_{\ell_2}=0}^*)(1+\delta_{\ell_2}) - \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*). \end{aligned} \tag{32}$$

Since $\mathcal{H}_{\ell_2}(x_{\ell_2,\delta_{\ell_2}=0}^*) < \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*)$ by hypothesis, $\mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*) = -\lambda^* \leq 0$ and $\delta_{\ell_2} \geq 0$, (32) yields

$$\mathcal{H}_{\ell_2}(x_{\ell_2}^*)(1+\delta_{\ell_2}) - \mathcal{H}_{\ell_1}(x_{\ell_1,\delta_{\ell_1}=0}^*) < 0, \tag{33}$$

which contradicts (19). □

When at least one node has inactive goodput constraint at the optimum, Lemma 2 provides the optimal value of λ and we can then optimally solve Problem 3 by solving the linear Problem 4. There actually exists a node with inactive goodput constraint iff Problem 4 is feasible with λ^* given by (28).

Case 2: $\forall \ell, \delta_\ell > 0$. This case can be solved through a conventional linesearch method for the optimal value of λ. This resolution is similar to the waterfilling solution and is thus not discussed to save space.

C. Algorithm to solve Problem 2

The optimal solution of Problem 2 is depicted in Algorithm 1 with $\mathbf{Q}^* := [Q_1^*, \cdots, Q_L^*]$ and $\boldsymbol{\gamma}^* := [\gamma_1^*, \cdots, \gamma_L^*]$.

Algorithm 1 Optimal resolution of Problem 2.

Set $\epsilon_D > 0$, $\lambda_D^{(0)} = 0$, $i = 0$, $\mathcal{C}_D = \epsilon_D + 1$
while $\mathcal{C}_D > \epsilon_D$ **do**
  Set $\lambda^* = -\min_\ell \mathcal{H}_\ell(x_{\ell,\delta_\ell=0}^*)$, where $\forall \ell$, $x_{\ell,\delta_\ell=0}^*$ is computed as indicated in Lemma 2
  If Problem 4 is feasible with λ^* **then**
    Find $(\mathbf{Q}^*, \boldsymbol{\gamma}^*)$ by solving Problem 4
  else
    Find $(\mathbf{Q}^*, \boldsymbol{\gamma}^*)$ using a linesearch method similar to the waterfilling solution (case 2 in Section III-B)
  end if
  Set $\mathcal{C}_D = \sum_{\ell=1}^{L}(\gamma_\ell^*(1-q_\ell(G_\ell Q_\ell^*/\gamma_\ell^*)) - \nu^{(i)}(A_\ell Q_\ell^* + B_\ell))$
  Update $\nu^{(i+1)} = \mathcal{G}(\mathbf{Q}^*, \boldsymbol{\gamma}^*)$
  $i = i + 1$
end while

IV. Numerical examples

We use the convolutional code with generator polynomials $[171, 133]_8$ along with the quadrature phase shift keying (QPSK) modulation. The number of link is $L = 5$ and the link distances D_ℓ are uniformly drawn in $[50 \text{ m}, 1 \text{ km}]$. We set $B = 5$ MHz, $N_0 = -170$ dBm/Hz and $\mathcal{L}_\ell = 128$. The carrier frequency is $f_c = 2400$ MHz and we put $\zeta_\ell^2 = (4\pi f_c/c)^{-2} D_\ell^{-3}$ where c is the celerity of light in vacuum. We assume that $\eta_\ell^{(0)}$ is equal for all the links. We put $\forall \ell$, $P_{ctx,\ell} = P_{crx,\ell} = 0.05$ W and $\kappa_\ell = 1/2$. To perform the RA, q_ℓ is given by the approximation of the PER under the Rician channel provided by [19].

In Fig. 1, we plot the GEE obtained for the MGEE and the minimum power (MPO) criterion obtained from [19] when two links are Rician distributed with $K_\ell = 10$, while the others are Rayleigh distributed (i.e. $K_\ell = 0$). As expected, the MGEE gives much higher GEE than the MPO. For instance, for $\eta_\ell^{(0)} = 0.1$ b/s/Hz, the MGEE yields a GEE about 90% higher than the MPO, i.e., for the same amount of bits to transmit, the energy consumed by the MPO is about 90% higher than those of MGEE. Notice that, when the goodput constraint increases, the difference between the MGEE and the MPO decreases, since maximizing the EE is equivalent to minimizing the transmit power in in the high power regime.

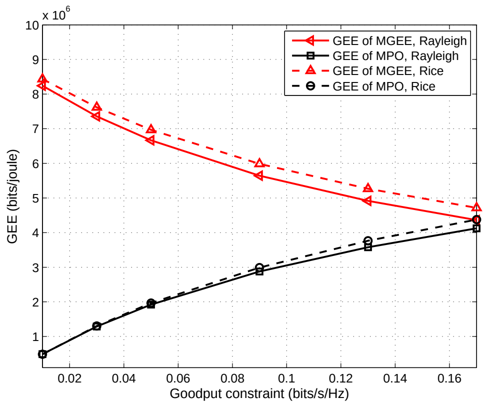

Fig. 1: GEE obtained with the MGEE and power minimization versus the minimum goodput constraint.

We now consider that the number of Rician links with $K_\ell = 10$ varies and we set $\eta_\ell^{(0)} = 0.13$ bits/s/Hz. We define $\mathbf{E}_R^*$ and $\boldsymbol{\gamma}_R^*$ as the optimal values of $\mathbf{E}$ and $\boldsymbol{\gamma}$ when the Rician channel is considered, respectively. We also define $\mathbf{E}_C^*$ and $\boldsymbol{\gamma}_C^*$ as the optimal values of $\mathbf{E}$ and $\boldsymbol{\gamma}$ when considering the Rayleigh channel, respectively. In Fig. 2, we plot the gain of considering the Rician channel instead of the Rayleigh one by computing $100 \times (\mathcal{G}(\mathbf{E}_R^*, \boldsymbol{\gamma}_R^*)/\mathcal{G}(\mathbf{E}_C^*, \boldsymbol{\gamma}_C^*) - 1)$. There is a GEE gain of about 3% when only one link is Rician, while this gain is about 18% when all the links are Rician distributed. Substantial gains can thus be achieved by taking into account the channel's distribution when performing RA.

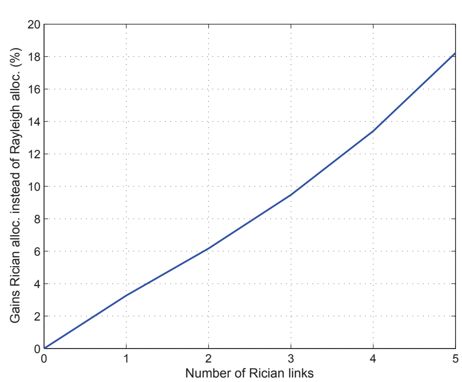

Fig. 2: Gains in GEE when considering the Rician channel instead of the Rayleigh one versus the number of Rician links.

V. Conclusion

We addressed the optimal resolution of the joint bandwidth and power allocation for type-I HARQ for the MGEE problem under the Rician channel. We provided an algorithm allowing to solve this problem using linear programming. Through simulations, we exhibited the interest of explicitly taking into account the channel's distribution during the RA process.

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