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LI Cancellation and Power Allocation for Multipair FD Relay Systems with Massive Antenna Arrays

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***Abstract*—Massive antenna arrays are capable of cancelling out the loop interference (LI) at the relay station in multipair full-duplex (FD) relay networks even without LI channel knowledge if the number of antennas is allowed to grow without a bound. For large but finite number of antennas, however, channel estimation based LI cancellation is required. In this paper, we propose a pilot protocol for LI channel estimation by exploiting the channel coherence time difference between static and moving transceivers in a multipair FD relay system. To maximize the end-to-end achievable rate, we also design a novel power allocation scheme to adjust the transmit power of each link at the relay. The analytical and numerical results show that the proposed novel pilot protocol and power allocation scheme jointly improve spectral and energy efficiency significantly with realistic coherence time differences.**

***Index Terms*—full-duplex relaying, pilot protocol, power allocation, interference mitigation, hardware impairments.**

I. Introduction

Full-duplex (FD) relaying has been intensively studied recently, since it can ideally double the achievable rate of half-duplex (HD) relaying [1]–[7]. The main obstacle for FD relaying to achieve this improvement is powerful loop interference (LI), that is caused by signals transmitted and received using the same time and frequency resources [4]. Passive isolation of antennas and analog circuit domain cancellation can be used to mitigate LI without instantaneous channel state information (CSI), before digital LI cancellation that does requires CSI [2], [4]. Furthermore, smart power allocation at the relay station has been shown to reduce the impact of LI and improve the end-to-end (E2E) rate in single-pair relay systems [1], [7].

Relay stations with ideal hardware and massive antenna arrays are known to have the ability to asymptotically cancel LI without LI CSI when the number of antenna elements grows without bound [3]. With non-ideal hardware and large but finite number of antennas, however, the residual interference [5], [8] is strong enough to have severe impact on the E2E data rate. On the other hand, due to the limited coherence time of the mobile wireless channels, obtaining LI CSI in massive FD relay systems is often considered infeasible and has lead to unrealistic assumptions on the level of passive and analog cancellation in the literature (see e.g. [3], [5]). However, this assumption neglects the fact that the coherence time of a channel between static transceivers, i.e. the LI channel, tends to be several times of that between the relay station and the moving terminals, as confirmed by the measurements in [9].

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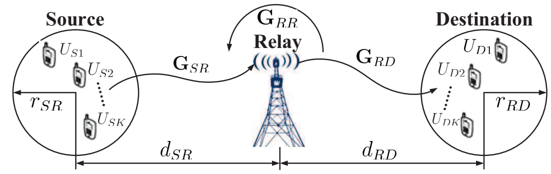


Fig. 1. Multipair full-duplex relaying system.

In this letter, LI cancellation and power allocation schemes for multipair FD relaying systems suffering from hardware impairments and strong residual LI after passive and analog cancellation are investigated. A new pilot protocol that utilizes the coherence time difference of the LI channel and the channels between the relay station and the moving terminals is proposed. Furthermore, a novel statistics-based low complexity power allocation scheme that adjusts the power for each link at the relay by using a simple iterative algorithm is presented.

II. System Model

The system model is depicted in Fig. 1, where K source terminals, $U_{S1}, U_{S2}, ..., U_{SK}$, each with one antenna, transmit signals to K single-antenna destination terminals $U_{D1}, U_{D2}, ..., U_{DK}$, using the same frequency and time resources. The direct links between the source and destination terminals are assumed to be blocked. A decode-and-forward relay station with M_t transmit and M_r receive antennas is used to establish the connections between the terminals. We assume that all the source (destination) terminals are located inside a circle of radius r_{SR} (r_{RD}), which is d_{SR} (d_{RD}) meters away from the relay station. Note that the relay station works in FD mode, while all the terminals operate in HD mode.

At time instant i, the source terminals and the relay station transmit signals $\mathbf{x}_S[i] \in \mathbb{C}^K$ and $\mathbf{x}_R[i] \in \mathbb{C}^{M_t}$ over the channels $\mathbf{G}_{SR}$ and $\mathbf{G}_{RD}^T$, respectively. Due to FD operation, the received and transmitted signals at the relay are coupled through the LI channel $\mathbf{G}_{RR}$. The received signals at the relay station and the destinations are respectively [3], [5], [8]

$$\mathbf{y}_R = \mathbf{G}_{SR}\mathbf{x}_S[i] + \mathbf{G}_{RR}\mathbf{x}_R[i] + \overbrace{\mathbf{G}_{RR}\mathbf{u}_t + \mathbf{u}_r + \mathbf{n}'_R}^{\triangleq \mathbf{n}_R}, \quad (1)$$

$$\mathbf{y}_D = \mathbf{G}_{RD}^T(\mathbf{x}_R[i] + \mathbf{u}_t) + \mathbf{n}_D, \quad (2)$$

where the source-to-relay (S→R) channel matrix $\mathbf{G}_{SR}$ and relay-to-destination (R→D) channel matrix $\mathbf{G}_{RD}^T$ are decomposed as[1] $\mathbf{G}_* = \mathbf{H}_*\mathbf{D}_*^{1/2}$, where the entries of $\mathbf{H}_*$ are

[1]Whenever $*$ is used, the actual subscript can be inferred from the context.

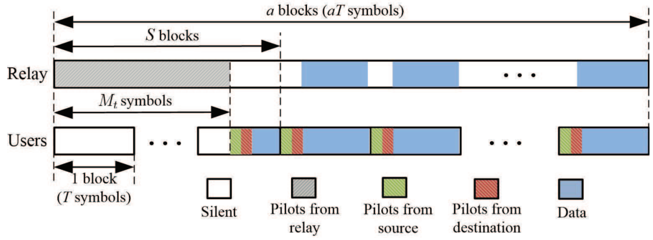


Fig. 2. Pilot protocol (As $ST - M_t > 2K$).

i.i.d. standard circularly symmetric complex Gaussian (CSCG) random variables and model small scale fading. The diagonal matrix $\mathbf{D}_{SR}$ ($\mathbf{D}_{RD}$) with kth diagonal entries $\beta_{SR,k}$ ($\beta_{RD,k}$) represents the large scale attenuation. Assuming the relay station is located at the origin, $\beta_{SR,k}$ ($\beta_{RD,k}$) is modeled as $\beta_{SR,k} = \kappa_{SR,k}\|\mathbf{z}_{S,k}\|^{-\alpha}$ ($\beta_{RD,k} = \kappa_{RD,k}\|\mathbf{z}_{D,k}\|^{-\alpha}$), where α is the path loss exponent, vector $\mathbf{z}_{S,k}$ ($\mathbf{z}_{D,k}$) defines the location of the kth source (destination) terminal and $\kappa_{SR,k}$ ($\kappa_{RD,k}$) represents shadow fading between the relay and the kth source (destination) terminal. Since $\beta_{SR,k}$ ($\beta_{RD,k}$) is changing slowly, it is assumed to be known at the kth source (destination) terminal and the relay station. The elements of the LI channel $\mathbf{G}_{RR} \in \mathbb{C}^{M_r \times M_t}$ are assumed to be i.i.d. CSCG with equal variances β_R since the antennas are closely spaced and the passive and analog cancellation schemes can effectively mitigate the direct path[2] of LI, so that the residual LI is mostly coming from the rich scattering environment [2].

To reduce cost, massive FD relay is likely built with cheap hardware that suffers from various impairments (e.g. amplifier non-linearities and I/Q imbalance) that cause distortions to both the received and transmitted signals [5], [8]. The system model in (1) takes into account the combined effects of such hardware impairments at the relay station via the additive CSCG distributed transmit- and receive-side noise vectors $\mathbf{u}_t \sim \mathcal{CN}(\mathbf{0}, \mu_t \mathsf{diag}(\mathbb{E}\{\mathbf{x}_R\mathbf{x}_R^H\}))$ and $\mathbf{u}_r \sim \mathcal{CN}(\mathbf{0}, \mu_r \mathsf{diag}(\mathbb{E}\{\mathbf{y}_R\mathbf{y}_R^H\}))$ [5], [8], respectively. The coefficients $\mu_t > 0$ and $\mu_r > 0$ indicate the level of hardware impairments and are related to the error vector magnitude (EVM) requirements of the system. In the following, the transmit-side noise vector $\mathbf{u}_t$ is omitted from the R→D link since it has negligible impact on the rate. The elements of the thermal noise vectors $\mathbf{n}'_R$ and $\mathbf{n}_D$ are i.i.d. $\mathcal{CN}(0, \sigma_w^2)$ and we denote the combined noise and distortion terms at the relay station by $\mathbf{n}_R$. Note that $\mathbf{n}_R$ neither is Gaussian distributed nor has i.i.d. elements in general.

A. Novel Pilot Protocol and Channel Estimation

As the relay station is static while the terminals are moving, the coherence time of the LI channel is typically several times longer than that of the S→R and R→D channels. We model this by considering a block fading channel with coherence time of T symbols (one block) for S→R and R→D channels, and aT symbols (a blocks) for the LI channel, where $a > 1$ in realistic scenarios [9, Table I]. Based on this observation, we propose a pilot protocol depicted in Fig. 2 to facilitate CSI-based LI cancellation at the relay station.

[2]Ricean fading LI channel leads only to a minor modification in the residual LI term. Rayleigh fading is considered herein for notational simplicity.

In $S = \lceil M_t/T \rceil$ consecutive blocks, where $\lceil x \rceil$ denotes the smallest integer which is not less than x, first M_t symbols are used by the relay station to transmit pilot matrix $\mathbf{\Phi}_R \in \mathbb{C}^{M_t \times M_t}$ for estimating the LI channel. If the number of remaining symbols in the Sth block is greater than $2K$, i.e. $ST - M_t > 2K$, the terminals transmit pilots as described below, followed by data transmission from the source and the relay station. Otherwise, all nodes keep radio silence for the rest of the block. From the $(S+1)$th block onwards, pilot matrices $\mathbf{\Phi}_S \in \mathbb{C}^{K \times K}$ and $\mathbf{\Phi}_D \in \mathbb{C}^{K \times K}$ are transmitted by the terminals at the beginning of each block.

1) Channel estimation for LI cancellation: We require $\mathbf{\Phi}_R\mathbf{\Phi}_R^H = \mathbf{I}_{M_t}$ to satisfy pilot orthogonality and power constraint. The received pilot matrix at the receive-side antennas of the relay station is given by

$$\mathbf{Y}_{RR} = \sqrt{\rho_{LI}}\mathbf{G}_{RR}\mathbf{\Phi}_R + \mathbf{N}_{RR},$$

where ρ_{LI} is the transmit power of one pilot symbol during the training phase. $\mathbf{N}_{RR}$ is a combination of transmit- and receive-side noise terms and is in general not Gaussian. It is, however, uncorrelated with the LI channel $\mathbf{G}_{RR}$ and a pessimistic prediction of the channel estimator performance can be obtained by treating the elements of $\mathbf{N}_{RR}$ as being independent with equal variance $\sigma_{RR}^2 = (\mu_t + \mu_r)\rho_{LI}\beta_R + \sigma_w^2(1 + \mu_r)$.

2) Channel estimation for detection and precoding: We assume that all terminals know their own channel statistics. To satisfy pilot orthogonality, we require $\mathbf{\Phi}_S\mathbf{\Phi}_S^H$ and $\mathbf{\Phi}_D\mathbf{\Phi}_D^H$ to be diagonal matrices with $K\rho_{pS,k}$ and $K\rho_{pD,k}$ on their kth diagonal. The received pilots at the relay station are given by

$$\mathbf{Y}_{SR} = \mathbf{G}_{SR}\mathbf{\Phi}_S + \mathbf{N}_{SR},$$
$$\mathbf{Y}_{DR} = \mathbf{G}_{RD}\mathbf{\Phi}_D + \mathbf{N}_{DR},$$

where the entries of the noise matrices $\mathbf{N}_{SR}$ and $\mathbf{N}_{DR}$ are i.i.d. complex Gaussian random variables $\mathcal{CN}(0, \sigma_w^2)$.

After receiving all pilots, the relay uses linear minimum mean squared error (LMMSE) estimator to obtain the instantaneous channel estimates $\hat{\mathbf{G}}_{SR}$, $\hat{\mathbf{G}}_{RD}$ and $\hat{\mathbf{G}}_{RR}$. We denote $\tilde{\mathbf{G}}_* = \mathbf{G}_* - \hat{\mathbf{G}}_*$ for the error matrix, which is uncorrelated with the estimate [10]. Note that for the LI channel, the LMMSE estimator does not yield optimal MMSE, which leads to a lower bound on the E2E spectral efficiency [8]. The per-element variance $\tilde{\beta}_*$ of the estimation error can be obtained from the knowledge of pilot sequence energy E_p, noise power σ_*^2 and channel gain β_* [10], as $\tilde{\beta}_* = \frac{\beta_*}{E_p\beta_*/\sigma_*^2+1}$. Thus, the entries of $\tilde{\mathbf{G}}_{RR}$ have the same variance $\tilde{\beta}_R = \frac{\beta_R}{\rho_{LI}\beta_R/\sigma_{RR}^2+1}$, while the error matrices $\tilde{\mathbf{G}}_{SR}$ and $\tilde{\mathbf{G}}_{RD}$ have independent CSCG elements, the variance of the entries in the kth column being $\tilde{\beta}_{SR,k} = \frac{\beta_{SR,k}}{K\rho_{pS,k}\beta_{SR,k}/\sigma_w^2+1}$ and $\tilde{\beta}_{RD,k} = \frac{\beta_{RD,k}}{K\rho_{pD,k}\beta_{RD,k}/\sigma_w^2+1}$ respectively. The properties of the estimator also guarantee that $\hat{\beta}_* = \beta_* - \tilde{\beta}_*$ holds for all channels.

B. Data Transmission

At time instant i, the source terminals transmit information vector $\mathbf{x}_S[i] = \mathrm{diag}(\sqrt{\rho_{S,1}}, \sqrt{\rho_{S,2}}, \ldots, \sqrt{\rho_{S,K}})\mathbf{m}[i]$ directly to the relay station. For all time instants i, the entries of $\mathbf{m}[i]$ are assumed to be i.i.d. standard CSCG. After subtracting the known part of the LI by using the knowledge of $\hat{\mathbf{G}}_{RR}$ and $\mathbf{x}_R[i]$, the received signal at the relay station reads $\mathbf{y}_R[i] =$

$\mathbf{G}_{SR}\mathbf{x}_S[i]+\boldsymbol{\xi}+\mathbf{n}_R$, where we denoted $\boldsymbol{\xi}=\tilde{\mathbf{G}}_{RR}\mathbf{x}_R[i]$ for the residual LI due to imperfect CSI of the LI channel. Assuming the system employs linear detection and precoding by using matrices $\mathbf{W}$ and $\mathbf{V}$, which are functions of $\hat{\mathbf{G}}_{SR}$ and $\hat{\mathbf{G}}_{RD}$, respectively, the kth estimated signal stream at the relay reads

$$y_{R,k}[i]=\mathbf{w}_k^H\mathbf{g}_{SR,k}x_{S,k}[i]+\sum_{j\neq k}\mathbf{w}_k^H\mathbf{g}_{SR,j}x_{S,j}[i]+\mathbf{w}_k^H(\boldsymbol{\xi}+\mathbf{n}_R) \tag{3}$$

where $\mathbf{g}_{SR,k}$, $\mathbf{g}_{RR,k}$ and $\mathbf{w}_k$ are the kth columns of $\mathbf{G}_{SR}$, $\mathbf{G}_{RR}$ and $\mathbf{W}$, respectively, and $x_{S,k}[i]$ is the kth element of $\mathbf{x}_S[i]$. Following the common assumption in decode-and-forward relaying, there is a processing delay of $d\geq 1$ symbols at the relay, $\mathbf{x}_R[i]=\mathbf{V}\mathbf{m}[i-d]$, and thus the transmit signal at the relay station is uncorrelated with the received signal [1]. Finally, the received signal at kth destination terminal reads

$$y_{D,k}[i]=\mathbf{g}_{RD,k}^T\mathbf{v}_k m_k[i-d]+\sum_{j\neq k}\mathbf{g}_{RD,k}^T\mathbf{v}_j m_j[i-d]+n_{D,k},$$

where $\mathbf{g}_{RD,k}$, $\mathbf{v}_k$, $m_k[i-d]$ and $n_{D,k}$ denote the kth columns (or elements) of $\mathbf{G}_{RD}$, $\mathbf{V}$, $\mathbf{m}[i-d]$ and $\mathbf{n}_D$, respectively.

III. Performance Analysis And Novel Power Allocation Scheme

A. Achievable Rate Analysis

While the residual LI and noise + distortion term $\boldsymbol{\xi}+\mathbf{n}_R$ is uncorrelated with the desired signal, it is not Gaussian. We thus consider an auxiliary system to find a lower bound on the achievable rate. More precisely, we treat the sum of inter-pair interference, residual LI and noise in (3) as additive Gaussian noise of the same variance [11], which is independent of the desired signal. For the kth S$\rightarrow$R and R$\rightarrow$D links, the lower bounds on the achievable rates[3] are then given as in (4) and (5) at the top of the next page, where we denoted with some abuse of notation $\boldsymbol{\xi}$ and $\mathbf{n}_R$ for CSCG vectors that are independent of the desired signal and have i.i.d. entries of variance (provided later) LI and σ_R^2.

Since the ergodic achievable rate depends on the weaker link, the lower bound of E2E rate of the kth terminal pair reads $R_k=\min\{R_{SR,k},R_{RD,k}\}$ [3]. Due to the space constraint, we analyze here only zero-forcing (ZF) processing

$$\mathbf{W}^H=(\hat{\mathbf{G}}_{SR}^H\hat{\mathbf{G}}_{SR})^{-1}\hat{\mathbf{G}}_{SR}^H,$$
$$\mathbf{V}=\mathbf{B}\mathbf{P}=\hat{\mathbf{G}}_{RD}^*(\hat{\mathbf{G}}_{RD}^T\hat{\mathbf{G}}_{RD}^*)^{-1}\mathbf{P},$$

where $\mathbf{P}\in\mathbb{C}^{K\times K}$ is a power allocation matrix to be designed in the next subsection. The kth diagonal entry of $\mathbf{P}$ is

$$p_k=\sqrt{\frac{q_k}{\mathbb{E}\{\|\mathbf{b}_k^T\|^2\}}}=\sqrt{(M_t-K)\hat{\beta}_{RD,k}q_k},$$

where $\mathbf{b}_k$ is the kth column of the matrix $\mathbf{B}$ and q_k denotes the relay's transmit power for the kth link. Using similar techniques as in [3], a lower bound for the E2E achievable rate of kth terminal pair with ZF processing reads

$$R_k=\log_2\left(1+\min\left(\frac{\rho_{S,k}(M_r-K)\hat{\beta}_{SR,k}}{\sum_{j=1}^K\rho_{S,j}\tilde{\beta}_{SR,j}+LI+\sigma_R^2},\frac{(M_t-K)\hat{\beta}_{RD,k}q_k}{\tilde{\beta}_{RD,k}q_{tot}+\sigma_w^2}\right)\right), \tag{6}$$

where $q_{tot}=\sum_k q_k$ is the total transmit power of the relay and $LI=\tilde{\beta}_R(1-\frac{K}{M_t})q_{tot}$ is the power of the residual LI. The power of noise + distortion is $\sigma_R^2=(\mu_t+\mu_r)\beta_R q_{tot}+\mu_r(\sum_K\rho_{S,k}\beta_{SR,k}+\mu_t\beta_R q_{tot})+\sigma_w^2(1+\mu_r)$.

B. Novel Power Allocation Scheme

For the kth terminal pair, increasing transmit power at the relay station yields a higher rate for the R$\rightarrow$D link but increases the LI and hence decreases the rate of the S$\rightarrow$R link. As the E2E rate depends on the weaker link, we propose adjusting $(q_1,...,q_K)$ so that the achievable rates of two links are equal, i.e., $R_{SR,k}=R_{RD,k},\forall k$. This can be achieved via a simple iterative algorithm given for ZF processing by

$$q_k^{(l)}=\frac{\frac{M_r-K}{M_t-K}\rho_{S,k}\hat{\beta}_{SR,k}(\tilde{\beta}_{RD,k}q_{tot}^{(l-1)}+\sigma_w^2)}{\hat{\beta}_{RD,k}(\sum_{j=1}^K\rho_{S,j}\tilde{\beta}_{SR,j}+\tilde{\beta}_R(1-\frac{K}{M_t})q_{tot}^{(l-1)}+\sigma_R^2)}, \tag{7}$$

where l is the iteration index and $q_{tot}^{(l-1)}$ is the total transmit power of the relay station in the $l-1$th iteration. The initial point of the iteration can be found by treating the large scale fading factors of all terminals the same and assuming $q_1^{(0)}=q_2^{(0)}=...=q_K^{(0)}$. Then (7) becomes a quadratic equation that has only one real positive solution, which can be used as the initial point of the iteration. Note that instantaneous CSI is not required for the proposed power allocation scheme, which makes the complexity very low. The same power allocation scheme at the relay station can also be used for the case when LI is not canceled, by simply replacing $\tilde{\beta}_R$ by β_R in (7).

C. Spectral Efficiency and Energy Efficiency

Given the E2E achievable rate for the kth terminal pair in (6), the average sum spectral efficiency for FD relaying reads

$$SE=\begin{cases}\frac{aT-ST-2K(a-S)}{aT}\mathbb{E}\big\{\sum_{k=1}^K R_k\big\}, & ST-M_t\leq 2K\\ \frac{aT-M_t-2K(a-S+1)}{aT}\mathbb{E}\big\{\sum_{k=1}^K R_k\big\}, & ST-M_t>2K\end{cases}$$

where the expectation is over the terminal locations and shadow fading. Energy efficiency is defined as $EE=\frac{SE}{E_{tot}}aT$, where E_{tot} denotes the average total energy consumption of the whole system during data and pilot transmission (a blocks). In numerical examples, the energy consumption is based on the power consumed by the amplifiers and baseband circuit power consumption is omitted from the analysis.

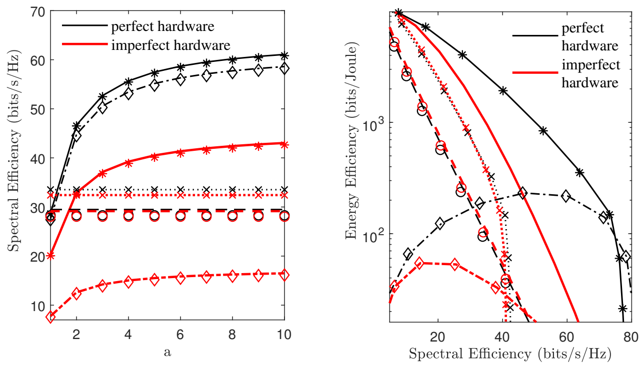
IV. Numerical Results

Unless otherwise specified, the system parameters used in the numerical results are $T=200$, $K=10$, $M_r=M_t=100$, $\sigma_w^2=-101$ dBm and $\beta_R=-90$ dB, corresponding to a slightly optimistic but realistic level of passive and analog LI mitigation [2], [4]. The parameters of the geometric model are

[3] Although the relay station has the instantaneous channel estimate, $\hat{\mathbf{g}}_{RD,k}$, as in [3], [5], we assume that it always uses statistical channel estimates $\mathbb{E}_{\{\mathbf{g}\}}\{\mathbf{w}_k^H\hat{\mathbf{g}}_{SR,k}\}$ for decoding. This provides a lower bound on the achievable rate of the S$\rightarrow$R link.

$$R_{SR,k} = \log_2 \left(1 + \frac{\rho_{Sk} |\mathbb{E}_{\{\mathbf{g}\}}\{\mathbf{w}_k^H \mathbf{g}_{SR,k}\}|^2}{\rho_{Sk} \mathbf{Var}_{\{\mathbf{g}\}} \left(\mathbf{w}_k^H \mathbf{g}_{SR,k} \right) + \sum_{j=1, j\neq k}^{K} \rho_{Sj} \mathbb{E}_{\{\mathbf{g}\}}\{|\mathbf{w}_k^H \mathbf{g}_{SR,j}|^2\} + \mathbb{E}_{\{\mathbf{g},\boldsymbol{\xi},\mathbf{n}_R\}}\{\|\mathbf{w}_k^H(\boldsymbol{\xi} + \mathbf{n}_R)\|^2\}} \right) \quad (4)$$

$$R_{RD,k} = \log_2 \left(1 + \frac{|\mathbb{E}_{\{\mathbf{g}\}}\{\mathbf{g}_{RD,k}^T \mathbf{v}_k\}|^2}{\mathbf{Var}_{\{\mathbf{g}\}} \left(\mathbf{g}_{RD,k}^T \mathbf{v}_k \right) + \sum_{j=1, j\neq k}^{K} \mathbb{E}_{\{\mathbf{g}\}}\{|\mathbf{g}_{RD,k}^T \mathbf{v}_j|^2\} + \sigma_w^2} \right) \quad (5)$$



(a) Spectral efficiency vs. the ratio of coherence time difference.

(b) Energy efficiency of the whole system vs. sum spectral efficiency.

Fig. 3. Performance of the proposed pilot protocol and power allocation scheme, analytical results of FD w/ LI cancellation (solid), FD w/o LI cancellation (dashed), FD w/ LI cancellation and fixed relay power q_{tot} = 23 dBm (dash-dotted) and HD (dotted) presented with curves and Monte Carlo simulations with markers (stars, circles, diamonds and crosses, respectively).

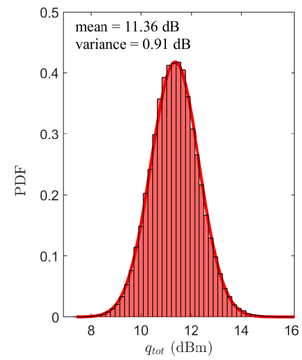


Fig. 4. Empirical PDF of total power consumption at relay with proposed power allocation scheme.

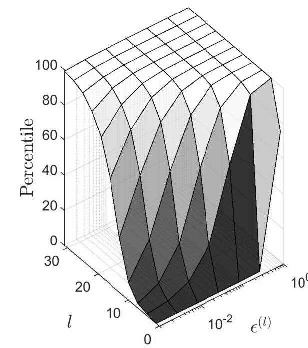


Fig. 5. Convergence of the proposed power allocation scheme at the relay station as in (7).

$d_{SR} = d_{RD} = 400$ m and $r_{SR} = r_{RD} = 100$ m with path loss exponent $\alpha = 4$ and log-normal shadowing with zero mean and 6 dB variance. Strict power constraint of 23 dBm is enforced at the relay station. Pilots used for estimating the LI channel at the relay are transmitted at the maximum power, i.e. $\rho_{LI} = 23$ dBm. With hardware impairments, the distortion coefficients are chosen as $\mu_t = \mu_r = 0.1^2$ that corresponds to EVM $= 0.1$, and is within the EVM range $[0.08, 0.175]$ of the LTE standard. We apply statistics-based power control at the source terminals $\rho_{S,k} = \frac{\gamma}{\beta_{SR,k}}$, where γ is a design parameter, and denote the average transmit power (over β's) of the source terminals $\overline{\rho}_S$. In pilot transmission phase, we set $\rho_{pS,k} = \gamma_p/\beta_{SR,k}$ and $\rho_{pD,k} = \gamma_p/\beta_{RD,k}$, where γ_p is a design parameter. In numerical results $\gamma = \gamma_p$ is assumed and ZF processing is used both for precoding and detection.

Fig. 3 demonstrates the performance of the considered schemes with perfect and imperfect hardware, where Fig. 3(a) plots the SE versus the coherence time ratio a for $\overline{\rho}_S = 11.57$ dBm ($\gamma = -95$ dBm). The curves for HD relaying (with relay power optimized so that $R_{SR,k} = R_{RD,k}$) and FD relaying without LI cancellation (as in [3], [5]) are horizontal since the relay does not transmit any pilots. Due to severe pilot overhead, the SE of the proposed pilot protocol is relatively low when $a = 1$. However, already for $a = 2$, the proposed power allocation strategy with LI cancellation offers the highest SE. In Fig. 3(b), SE and EE tradeoff is investigated for $a = 8$, that is a very conservative choice according to [9, Table I]. Here the FD system with the proposed power allocation scheme outperforms the fixed FD relay power case with significant margin since the latter wastes part of the transmit power at the relay station as increased LI.

The relay power variation in the proposed scheme is illustrated in Fig. 4 that plots the empirical probability density function (PDF) of q_{tot} for the case $\overline{\rho}_S = 11.57$ dBm. The PDF is well approximated by a Gaussian distribution (the solid line) implying that the variations around the mean decay exponentially. It is also clear that the proposed algorithm does not cause violation of the relay power constraint 23 dBm.

Fig. 5 shows the percentile of power allocation instances that converge to a normalized difference $\epsilon^{(l)} = ||\mathbf{q}^{(l)} - \mathbf{q}^{(l-1)}||_1/||\mathbf{q}^{(l-1)}||_1$ after l iterations when $\overline{\rho}_S = 11.57$ dBm. Clearly the proposed power allocation scheme converges very fast, typically within 30 iterations.

V. Conclusion

In this letter, we proposed pilot-based LI cancellation and power allocation schemes for multipair FD relaying systems with hardware impairments and large but finite number of antennas. The low-complexity iterative power allocation scheme requires only channel statistic and converges very fast. The combination of both schemes improves the SE and EE of the FD relaying with fixed relay power or the HD relaying significantly under practical system parameters.

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