An Iterative Pilot-Data Aided Estimator for OFDM-Based Relay-Assisted Systems

Neves, D.[1], Ribeiro, C.[1, 2], Silva, A.[1] and Gameiro, A.[1]
[1]Instituto de Telecomunicações, Universidade de Aveiro, Aveiro, Portugal
[2]Instituto Politécnico de Leiria, Leiria, Portugal
darlene@av.it.pt, cribeiro@estg.ipleiria.pt, asilva@av.it.pt, amg@ua.pt

Abstract — **We propose and assess a pilot-data aided channel estimation scheme for realistic relay-assisted scenarios designed for the downlink SFBC OFDM-based systems. We consider that both the base station and the relay node are equipped with an antenna array whereas the user terminal is a single antenna device. The relay protocol considered is equalise-and-forward. The channel estimation method iteratively uses the information carried by the pilots and data to improve the estimate of the equivalent channels for the path Base Station – Relay Node – User Terminal. The MMSE criterion is used in the design of the estimator for both the pilot-based and data-aided iterations. The results show the benefits of cooperation in terms of MSE and also show that the proposed scheme allows, with a single data iteration, a reduction of the number of pilots when compared with non-data-aided schemes.**

I. INTRODUCTION

The use of cooperation techniques can be achieved through the use of dedicated relays or user terminals with relay capabilities. In both cases it is possible to generate virtual antenna arrays (VAA) even if the relaying devices are limited in the number of antenna elements. Such techniques are promising solutions to improve capacity and fairness in the future cellular wireless systems.

Most works on cooperative/relaying communications have assumed perfect channel estimation at both relay and receivers terminals [1]-[3], and some have only evaluated the impact of imperfect channel estimates on the performance of cooperative schemes [4]-[8]. However, accurate channel estimation schemes are needed in order to ensure good link performance. With the decode-and-forward (DF) protocol channel estimation algorithms developed for point-to-point links can be used without modifications. The situation is different when employing amplify-and-forward (AF) or techniques performing linear filtering at the relay node (RN) because the overall channel from the base station (BS) to the user terminal (UT) is a composite one with additional source of noise degrading the performance of point-to-point techniques.

This motivated research on channel estimation considering AF and different schemes have been reported in [9-16]. A criterion for the choice of the Wiener filter length, pilot spacing and power has been presented in [9]. A permutation pilot matrix to eliminate inter-relay interference has been discussed in [10]. Such approach allows the use of the least square estimator in the presence of frequency off-sets. An approach based on pilot amplifying matrix sequence has been developed in [11] in order to improve the compound channel estimate by taking into account the interim channels estimate. Transceiver schemes that jointly design the relay forward matrix and the destination equaliser have been proposed in [12]. Concerning the two-way relay, [13] proposed an estimator based on new training strategy to jointly estimate the channels and frequency offset. For MIMO relay channels, [14] derived the linear mean square error estimator and optimal training sequences to minimise the MSE.

The estimation algorithms of the previously referred papers were based on pilots or training sequences. However the channels present in a cooperative scenario can also be estimated or aided using the energy of the transmitted data. As such in [15] the authors proposed an iterative channel estimator based on the expectation and maximisation (EM) algorithm to separately estimate the channels B→R (BS – RN) and R→U (RN – UT). Although not using directly the regenerated data, in [16] superposition of pilots and data was considered and based on the non-Gaussian nature of the dual-hop relay link, the authors proposed a first-order autoregressive channel model and derived an estimator based on Kalman filter.

In this paper we consider the scenario of [17], and propose a pilot-data based estimator for the equivalent channel B→R→U (BS – RN – UT). The scenario considers the use of space frequency block coding (SFBC) at both BS and RN, which uses the equalise-and-forward (EF) protocol. Such scenario is of practical importance in the downlink of cellular systems since the BS and RNs (if dedicated) have fewer constraints than the user terminals and can be equipped with antenna arrays allowing space diversity. However since we obtain an equivalent channel with additional sources of noise and distortion it requires improved channel estimation schemes.

In order to overcome the penalty imposed by the channel B→R→U, the estimation method at the UT consists of two iterations. In the first, only pilots are used to estimate the channels and the data symbols are regenerated. Then, in the next iteration, these symbols are used as virtual pilots. The MMSE criterion is used in the design of the estimator for both the pilot-based and data-aided iterations. The results show that mean square error (MSE) and the system spectral efficiency can be improved with only a single data iteration.

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The remaining of the paper is organised as follows. Section II presents the system model with the description of the scenario and the cooperative scheme. Section III presents the proposed pilot-data based estimator method and then in Section IV the system performance is evaluated in terms of MSE of the channel estimates. Finally, Section V points out the conclusions of this work.

II. SYSTEM MODEL

In this paper the index n and k denote time and frequency domain variables, respectively. $\mathrm{E}\{\cdot\}$ is the expected value, $(\circ)$, $(\cdot)^T$ and $(\cdot)^*$ are the point-wise, transpose and conjugate operations, respectively. $\operatorname{diag}(\cdot)$ stands for a diagonal matrix. Variables, vectors or matrices in time domain (TD) are denoted by $(\sim)$. All estimates are denoted by $(\wedge)$.

A. Channel Model

We consider an OFDM based system with K subcarriers and time-variant channels with discrete impulse response of the type

$$\tilde{h}_{(n)} = \sum_{g=1}^{G} \beta_{g(n)} \delta\left(n - \tau_g\right), \qquad (1)$$

where n is the instant when the channel impulse response (CIR) is evaluated, G is total number of paths and β_g, τ_g the complex amplitude and delay of the path g. β_g is modelled as a zero mean complex Gaussian variable with variance σ_g^2 determined by the power delay profile and satisfying $\sum_{g=1}^{G} \sigma_g^2 = 1$. Although the channel is time-variant we assume it quasi-static, i.e. constant during one OFDM symbol interval. In the frequency domain the channel gains, $h_{(k)}$, $k = 0, \cdots, K-1$, are therefore also zero mean complex Gaussian variables with unit variance. We also assume $\mathrm{E}\left\{\left|h_{(k)}\right|^2\right\} = 1$.

B. Relay Assisted (RA) / Cooperative Scheme

The scenario we consider is for the downlink and the BS transmits information to the UT using both the direct link and a relay. The BS and RN are equipped with two antennas whereas the UT is a single antenna device. Therefore the signals at the transmitters are mapped according to SFBC Alamouti presented in Table 1.

TABLE 1 - SFBC MAPPING FOR TWO TRANSMITTING ANTENNAS

Subcarrier	Antenna 1	Antenna 2
k	$d_{(k)} \big/ \sqrt{2}$	$-d_{(k+1)}^* \big/ \sqrt{2}$
$k+1$	$d_{(k+1)} \big/ \sqrt{2}$	$d_{(k)}^* \big/ \sqrt{2}$

In the following, the indices m and l, where $m = 1,\ 2$ and $l = 1,\ 2$ are related to the antennas at the BS and RN, respectively. Therefore, the channels B→U (BS – UT), B→R and R→U are represented by $h_{\mathrm{bu}m}$, $h_{\mathrm{br}ml}$ and $h_{\mathrm{ru}l}$, respectively.

We consider a half-duplex RN using the EF protocol which requires two communication phases. In phase I, the SFBC encoded data d, with unit variance, are broadcasted via B→R and B→U. This allows achieving space diversity of four in the link B→R and two in the link B→U which could not be obtained with the AF protocol. At the UT the SFBC de-mapping takes place and its result, i.e. the soft estimates, are stored. At the RN, after obtain the soft estimates an additional SFBC mapping is performed and then the outcome is normalised.

In phase II, while the BS is idle the RN forwards the signal. Therefore the received signals at the UT on subcarrier k and $k+1$ are

$$\begin{cases} y_{\mathrm{ru},(k)} = \dfrac{1}{\sqrt{2}}\left(h_{\mathrm{ru}1,(k)} \alpha_{(k)} s_{\mathrm{br},(k)} - h_{\mathrm{ru}2,(k+1)} \alpha_{(k+1)}^* s_{\mathrm{br},(k+1)}^*\right) + n_{\mathrm{ru},(k)} \\ y_{\mathrm{ru},(k+1)} = \dfrac{1}{\sqrt{2}}\left(h_{\mathrm{ru}1,(k+1)} \alpha_{(k+1)} s_{\mathrm{br},(k+1)} + h_{\mathrm{ru}2,(k)} \alpha_{(k)}^* s_{\mathrm{br},(k)}^*\right) + n_{\mathrm{ru},(k+1)} \end{cases}, \qquad (2)$$

where $n_{\mathrm{ru},(k)}$ is the additive Gaussian noise with zero mean and variance σ_{ru}^2, $\alpha_{(k)}$ is a normalisation constant that constrains the overall power at the RN to one and $s_{\mathrm{br},(k)}$ is the soft estimate, given by

$$\begin{cases} s_{\mathrm{br},(k)} = \Gamma_{\mathrm{br},(k)} d_{(k)} + q_{\mathrm{br},(k)} \\ s_{\mathrm{br},(k+1)} = \Gamma_{\mathrm{br},(k)} d_{(k+1)} + q_{\mathrm{br},(k+1)} \end{cases}, \quad \Gamma_{\mathrm{br},(k)} = \frac{1}{2} \sum_{m=1}^{2} \sum_{l=1}^{2} \left|h_{\mathrm{br}ml,(k)}\right|^2, \qquad (3)$$

$q_{\mathrm{br},(k)}$ representing the noise term that is transmitted by the RN.

Using the expressions of (3) in (2) we can verify that the data component at the UT is $h_{\mathrm{ru}l,(k)} \alpha_{(k)} \Gamma_{\mathrm{br},(k)} d_{(k)}$ and therefore $h_{\mathrm{ru}l,(k)} \alpha_{(k)} \Gamma_{\mathrm{br},(k)}$ is the equivalent channel $h_{\mathrm{eq}l,(k)}$ from the BS to the UT. Regarding (2), the corresponding soft estimates are

$$\begin{cases} s_{\mathrm{ru},(k)} = g_{\mathrm{ru}1}^* y_{\mathrm{ru},(k)} + g_{\mathrm{ru}2} y_{\mathrm{ru},(k+1)}^*, \quad g_{\mathrm{ru}1} = h_{\mathrm{eq}1,(k)} \Big/ \left(\sqrt{2}\sigma_{\mathrm{t}}^2\right) \\ s_{\mathrm{ru},(k+1)} = -g_{\mathrm{ru}2} y_{\mathrm{ru},(k)}^* + g_{\mathrm{ru}1}^* y_{\mathrm{ru},(k+1)}, \quad g_{\mathrm{ru}2} = h_{\mathrm{eq}2,(k)} \Big/ \left(\sqrt{2}\sigma_{\mathrm{t}}^2\right) \end{cases}. \qquad (4)$$

In (4) σ_{t}^2 is the variance of the total noise given by

$$\sigma_{\mathrm{t}}^2 = \alpha_{(k)}^2 \Gamma_{\mathrm{br},(k)} \Gamma_{\mathrm{ru},(k)} \sigma_{\mathrm{br}}^2 + \sigma_{\mathrm{ru}}^2, \quad \Gamma_{\mathrm{ru},(k)} = \frac{1}{2} \sum_{l=1}^{2} \left|\hat{h}_{\mathrm{ru}l,(k)}\right|^2, \qquad (5)$$

with σ_{br}^2 being the variance of the noise at the input of the RN.

After that, the next stage corresponds to combine the soft estimates variables received in both phases of the protocol in order to perform the hard decision.

As aforementioned and according to (2)-(4), the extra sources of distortion imply that the accuracies of the initial

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channel estimates present some penalties relatively to the case of a point-to-point link. Therefore, in order to improve their accuracies, data-aided estimation is carried out using the regenerated data symbols as virtual pilots.

III. PROPOSED PILOT-DATA BASED CHANNEL ESTIMATION

The iterative pilot-data based estimator is focused on phase II where the proposed estimation takes place to estimate only the relay channels. The estimation processing follows Figure 1 where superscript i indicates the number of the iteration ($i=1,\ 2$) of the estimator method. $\hat{h}_{\mathrm{ru}l}^{(i)}$ corresponds to the channels estimates, $\hat{D}^{(1)}$ are the binary decoded data and $\hat{d}^{(1)}$ represents the data symbol that are obtained after the re-modulation. In iteration #1, $\hat{h}_{\mathrm{ru}l}^{(1)}$ correspond to the initial estimates which are obtained using only pilots. $\hat{h}_{\mathrm{ru}l}^{(2)}$ correspond to the pilot-data based channel estimates. In iteration #2, the pilot-data based estimates $\hat{h}_{\mathrm{ru}l}^{(2)}$ are used to re-do the SFBC de-mapping and the output is then fed to the Joint Processing block to perform the final hard-decision.

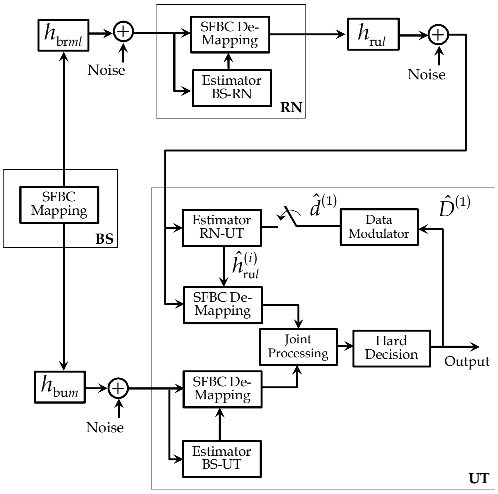

Figure 1 - Block diagram of RA OFDM system.

A. *The Initial Estimation*

The initial estimation is accomplished according to the pilot-based TD-MMSE [18] estimator which provides the LS estimation and MMSE filtering, both in time domain.

For one OFDM symbol with K subcarriers, two consecutive pilot subcarriers are spaced by N_f. According to the Nyquist theorem, summing delayed (by K/N_f) replicas of the input signal is equivalent to filtering in the frequency domain the pilot positions, and therefore the LS estimate of the point of the CIR is given by [18]

$$\hat{\hat{h}}_{(n)}^{\mathrm{LS}}=\begin{cases}\sum_{m=0}^{N_f-1}\tilde{h}_{\left(n-mK/N_f\right)}+\sum_{m=0}^{N_f-1}\tilde{w}_{\left(n-mK/N_f\right)}, & n=0,1,\cdots,\dfrac{K}{N_f}-1\\ 0,\ \text{remainig}\end{cases},\quad (6)$$

where $\tilde{w}$ is the noise samples with noise variance σ_n^2.

For one OFDM symbol the LS estimate is a vector $1\times K$ where assuming the Nyquist criterion about pilot separation is fulfilled, the last $K-K/N_f$ elements are null,

$$\hat{\hat{\mathbf{h}}}_K^{\text{LS, pilots}}=\left[\hat{\hat{\mathbf{h}}}_{K/N_f}^{\mathrm{LS}}\quad \mathbf{0}_{K-\left(K/N_f\right)}\right].\quad (7)$$

The LS estimate given by (7) is improved by performing MMSE filtering. If the channel taps are properly separated by the sampling interval, the MMSE filter in time domain corresponds to a sparse K/N_f diagonal matrix with non-null elements whose number is equal to the number of taps G occurring only in the diagonal:

$$\tilde{\mathbf{W}}_{\mathrm{MMSE}}=\operatorname{diag}\left(\frac{\sigma_1^2}{\sigma_1^2+\dfrac{\sigma_n^2}{K/N_f}},\cdots,\frac{\sigma_G^2}{\sigma_G^2+\dfrac{\sigma_n^2}{K/N_f}},0,\cdots,0\right).\quad (8)$$

Equations (7) and (8) may be simultaneously implemented, thus the final CIR estimate presents G non-null elements and zeros in the remaining. This simplifies the estimator implementation [19].

B. *Data-Based Channel Estimation*

According to our system, the OFDM symbol has K subcarriers where the subcarriers carrying pilots symbols are spaced by N_f and therefore the set of pilot subcarriers is $\mathfrak{P}=\left\{0,N_f,2N_f,\cdots,K-N_f\right\}$. If $\mathbf{d}$ and $\mathbf{p}$ correspond to data and pilot vectors and pilots are multiplexed with data symbols in different subcarriers, $\mathbf{d}$ and $\mathbf{p}$ contain non-zero values in disjoint subcarriers. Consequently, the set of data symbol subcarriers is $\mathfrak{S}=\left\{1,\cdots,N_f-1,N_f+1,\cdots,2N_f-1,\cdots,K\right\}$. Since our scenario has the BS and RN equipped with two antennas, the pilot subcarriers are arranged such that each antenna has different sub-sets of subcarriers, i.e. $\mathfrak{P}_1=\left\{0,2N_f,\cdots,K-2N_f\right\}$ and $\mathfrak{P}_2=\left\{N_f,3N_f,\cdots,K-2N_f\right\}$. Thus the pilot array for one OFDM symbol is represented by $\mathbf{p}=\left[\mathbf{p}_1\ \ \mathbf{p}_2\right]$. Similarly, the data symbol array is given by $\mathbf{s}=\left[\mathbf{s}_1\ \ \mathbf{s}_2\right]$ where the non-zero elements of $\mathbf{s}_1$ and $\mathbf{s}_2$ corresponds to the first and second column of $\mathbf{D}$ in (9), i.e. the SFBC mapped data symbol matrix. $\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{s}_1$ and $\mathbf{s}_2$ are $1\times K$.

$$\mathbf{D}=\frac{1}{\sqrt{2}}\begin{pmatrix} d_{(j)} & -d_{(j+1)}^{*}\\ d_{(j+1)} & d_{(j)}^{*}\end{pmatrix},\ j\in\mathfrak{S}.\quad (9)$$

In frequency domain the received signal at the destination corresponds to $\mathbf{y}=(\mathbf{s}+\mathbf{p})\mathbf{h}+\mathbf{n}$, where $\mathbf{h}$ represents the diagonal of the channel matrix and $\mathbf{n}$ represents the additive Gaussian noise. In the phase II, $\mathbf{y}$ follows (2), and $\mathbf{h}$ can be expressed as $\mathbf{h}_{\mathrm{ru}}=\left[\mathbf{h}_{\mathrm{ru}1}\ \ \mathbf{h}_{\mathrm{ru}2}\right]$, where $\mathbf{h}_{\mathrm{ru}1}$ and $\mathbf{h}_{\mathrm{ru}2}$ are the diagonals of the $K\times K$ matrices that represent the channel frequency responses (CFRs) of the channels between the antenna l of the RN and the UT.

Using the set of data subcarriers we perform the LS estimation. Since the SFBC is used at the RN, the LS estimation based on the regenerated data requires a matrix inversion. Considering that two data symbols are encoded in subcarriers j and $j+1$, the LS estimate for the equivalent channels is given by

$$\hat{\mathbf{h}}_{\mathrm{eq},(j)}^{\mathrm{LS}} = \sqrt{2}\left(\hat{\mathbf{D}}_{(j)}^{-1}\mathbf{y}_{\mathrm{u},(j)}^{(2)}\right), \tag{10}$$

where, $\hat{\mathbf{h}}_{\mathrm{eq},(j)}^{\mathrm{LS}} = \left[\hat{\mathbf{h}}_{\mathrm{eq1},(j)} \quad \hat{\mathbf{h}}_{\mathrm{eq2},(j)}\right]^{T}$, and $\mathbf{y}_{\mathrm{u},(j)}^{(2)}$ follows (2).

It is worth to note that although we have two subcarriers, we obtain a single estimate for each antenna, i.e. if there was noiseless, we would obtain the average of the equivalent channels at subcarriers j and $j+1$.

The MSE of the estimates in (10) for SISO channel is

$$\begin{aligned} \mathrm{E}\left\{|\varepsilon|^{2}\right\} &= \frac{1}{J}\sum_{j\in\mathfrak{S}}\mathrm{E}\left\{\left|h_{(j)}-\hat{h}_{(j)}\right|^{2}\right\} \\ &= \frac{1}{J}\sum_{j\in\mathfrak{S}}\mathrm{E}\left\{\left|\left(1-d_{(j)}\big/\hat{d}_{(j)}\right)\right|^{2}\right\}+\sigma_{n}^{2}\mathrm{E}\left\{\left|\left(1\big/\hat{d}_{(j)}\right)\right|^{2}\right\}, \end{aligned} \tag{11}$$

where $\hat{d}_{(j)}$ is the data regenerated in iteration #1, $w_{(j)}$ is the noise component at subcarrier j and J is the size of $\mathfrak{S}$.

For QPSK with unit power we obtain (12) which relates the error probability P_e and the MSE of the estimates under the assumption of the correlation involving the disposed data and noise are negligible.

$$\mathrm{E}\left\{|\varepsilon|^{2}\right\} \approx \sigma_{n}^{2}\left(1+2P_{\mathrm{e}}\mathrm{SNR}\right), \tag{12}$$

where SNR is the signal-to-noise ratio assuming that the noise power per subcarriers is σ_n^2 and the average received signal power (including pilots) is normalised to 1, i.e. $\mathrm{SNR} = 1/\sigma_n^2$ (12) shows that even for a moderate probability of symbol error (e.g. 0.01) the increase is quite small. Therefore we can conclude that even with first data iteration being very inaccurate still there is potential for improving the channel estimates using data.

Moreover in (10) we consider that the data subcarriers used in the SFBC coding are adjacent. In fact, when designing the transmitted frame, we insert pilots and therefore not all the pairs of subcarriers corresponding to one SFBC codeword will be adjacent. For example if we consider a pilot spacing of 4, i.e. $N_f = 4$, there will be pilots at subcarriers $0,\ 4,\ 8,\ \cdots$, and the first SFBC codeword will be transported in the adjacent subcarriers 1 and 2, but the second codeword will be transported in the carriers 3 and 5. In order to overcome that, after performing the LS estimation we set groups of virtual pilots uniformly spaced. This result in N_f-1 groups of LS estimates with virtual pilots equispaced of N_f-1 as well.

For one OFDM symbol, in order to obtain estimates $1\times K$ we perform the zero-padding processing in the N_f-1 CIR estimates. This results in N_f-1 estimates $1\times K$ that present K/N_f null elements. Therefore, for one OFDM symbol each CIR estimate may be represented by:

$$\hat{\hat{\mathbf{h}}}_{K}^{\mathrm{LS,\ data}} = \left[\hat{\hat{\mathbf{h}}}_{\left(K-\left(K/N_f\right)\right)/\left(N_f-1\right)}^{\mathrm{LS}} \quad \mathbf{0}_{\left(N_f-1\right)\left(K/N_f\right)}\right]. \tag{13}$$

C. Estimation Combination

The pilot-based and the data-based CIRs estimates are combined according to (14). An averaging factor guarantees that the resulting power is normalised to 1 and by design this factor results in N_f. After combining the CIRs the MMSE filtering is performed to enhance the estimate. The final CIR estimate is expressed by:

$$\hat{\hat{\mathbf{h}}}_{K} = \left\{\mathrm{diag}\left(\tilde{\mathbf{W}}_{\mathrm{MMSE}}\right)\circ\left[\left(\sum_{N_f-1}\hat{\hat{\mathbf{h}}}_{K}^{\mathrm{LS,\ data}}+\hat{\hat{\mathbf{h}}}_{K}^{\mathrm{LS,\ pilots}}\right)\Big/N_f\right]\right\}. \tag{14}$$

IV. SIMULATION RESULTS

We focus our analysis on the scenario presented in Section II.B and in the simulations we used the ITU pedestrian channel model A [20] at speed $v = 10\,\mathrm{km/h}$. The number of subcarriers (K) set to 1024 and the modulation is QPSK. The transmitted OFDM symbol carried pilot and data subcarriers with a pilot separation N_f. We used the same pilot pattern at the BS and RN and since they were double antenna arrays we allocated different sets of subcarrier pilots to perform the estimation. Therefore for both the BS and RN the pilot subcarriers were spaced by $2N_f$ for each antenna.

The simulations were performed assuming uncorrelated antenna channels, the receiver was perfectly synchronised and the insertion of a long enough cyclic prefix in the transmitter ensured that the orthogonality of the subcarriers is maintained after transmission.

In order to validate the proposed estimation method, channel estimation simulations were performed. The results are presented in terms of normalised MSE, both as function of E_b/N_0, where E_b is the received energy per bit and $N_0/2$ the bilateral power spectral density of the noise added at the BS in the direct links, i.e. B→U. The MSE is expressed according to (15) where h represents the generic CFR. Since BS and RN are double antenna arrays the resulting MSE of the direct channels B→U and the relay channels R→U is obtained by averaging the individual MSE.

$$\mathrm{MSE} = \mathrm{E}\left\{\left|\hat{h}-h\right|^{2}\right\}\Big/\mathrm{E}\left\{|h|^{2}\right\}. \tag{15}$$

In terms of BER proposed performance depends on the achieved MSE of the channel estimators. However with the proposed method, to achieve the same MSE fewer pilots are needed and therefore a higher spectrum efficiency can be achieved when the pilot-data based estimator scheme is employed since more subcarriers can be allocated to carry data. Therefore, we present results only in terms of MSE.

We evaluate the estimator performance in four scenarios which are referred in Table 2 as: #1: all links have the same statistics; # 2: the links B→R are 10 dB better than the links B→U and R→U; # 3: the overall relay links are 10 dB better than the direct ones.

TABLE 2 – ASSESSED SCENARIOS

Scenario #	**Link SNR**
1	$E_b/N_0^{B\to R} = E_b/N_0^{R\to U} = E_b/N_0^{B\to U}$
2	$E_b/N_0^{B\to R} = E_b/N_0^{B\to U} + 10\ \text{dB}$
3	$E_b/N_0^{B\to R} = E_b/N_0^{R\to U} = E_b/N_0^{B\to U} + 10\ \text{dB}$

A. *MSE Channel Estimation Performance*

Figure 2 shows the MSE of the CFR estimate of the relay (RL) and the direct links (DL), employing the pilot and the pilot-data estimators, both considering the Scenario #1. It shows that the RL presents a penalty over the DL which accounts for the extra source of noise aforementioned. It also shows that the pilot-data based estimation method can significantly overcome such penalisation and provides a performance better than the DL for all N_f considered. For high values of E_b/N_0 as N_f increases the relative gain provided by the data-aided estimator increases as well. From the figure we verify that for $E_b/N_0 = 6$ dB, the pilot-data based results provide 5 and 3 dB gain over the estimator using only pilots for values 16 and 4 of N_f, respectively. For low values of E_b/N_0 the gain is smaller but even for E_b/N_0 as low as 0 dB we still gain 2 dB over the pilot-based estimator when $N_f = 4$. The gain reduction as E_b/N_0 decreases is understandable since the probability of error in the first iteration increases and therefore several virtual pilots used for the second iteration are erroneous. Moreover, inspection of the curves of Figure 2, shows us that the MSE of the pilot-data based estimator for a given N_f is always below the one achieved considering the pilot-based estimator with pilot separation of $N_f/2$. This means that the total number of pilots can be halved leading to an improved spectral efficiency.

Figure 3 and Figure 4 present the estimators MSE performance considering the Scenarios # 2 and # 3, respectively. The choice of these scenarios for downlink derives from the fact that, in most real situations, the cooperative links have higher transmission quality conditions than the direct link. The results presented in Figure 3 and Figure 4 emphasises the benefits of cooperation in terms of MSE and the improvements that are achieved using the proposed pilot-data scheme as well.

Figure 3 shows that the RL and DL present approximately the same performance. This is due to the fact that in the case that the links between BS and RNs are highly reliable, most of the channel information is successfully detected at the RN, which has a positive impact on the relays links. In the case where $E_b/N_0 = 7$ dB the pilot-data estimation performance is approximately the same of the pilot-based one and in this case the data-aided scheme makes use only $1/4$ of the pilot subcarriers used by the pilot-based method.

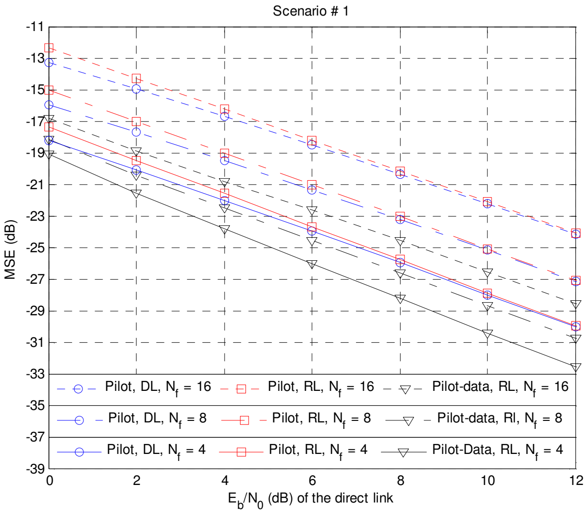

Figure 2 - MSE performance of the direct (DL) and relay links (RL) considering the Scenario # 1.

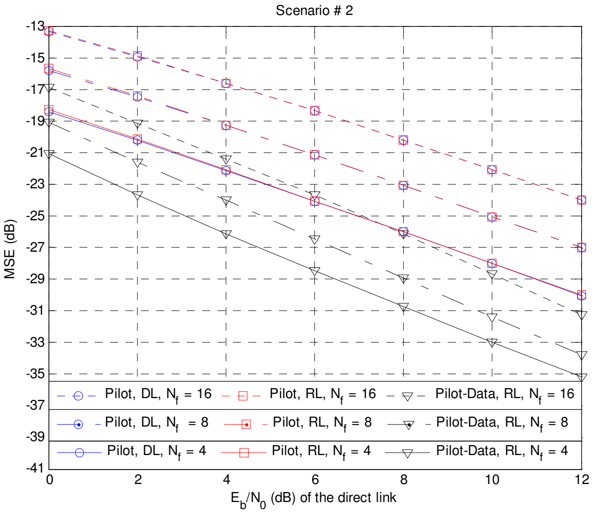

Figure 3 - MSE performance of the direct (DL) and relay links (RL) considering the Scenario # 2.

Figure 4 presents the results relative to Scenario # 3. In such scenario both links B→R and R→U have higher quality conditions over the direct one. In this case the noise variances have a minor effect on the pilot-based estimates and due that the RL performance overreaches the DL one. The proposed scheme nevertheless can improve the RL performance. For $N_f = 8$ the proposed estimator presents a performance close to the pilot-data performance considering only $1/2$ of the pilots used by the pilot-based estimator, i.e. $N_f = 4$. In this scenario, the MSE of the pilot-data based estimator for a given N_f is quite close to the one achieved considering the pilot-based estimator with pilot separation of $N_f/2$.

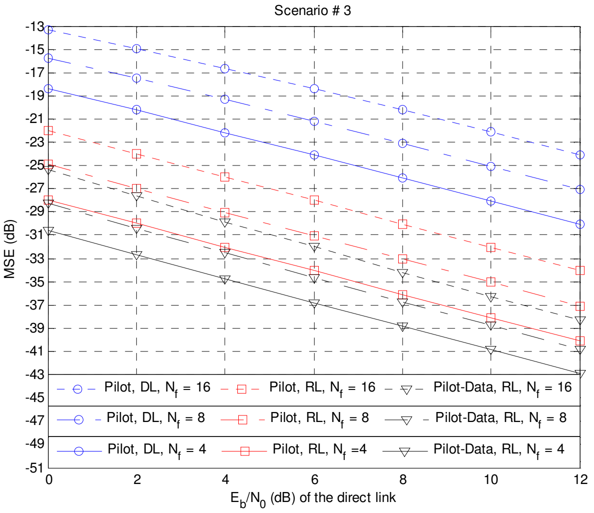

Figure 4 - MSE performance of the direct (DL) and relay links (RL) considering the Scenario # 3.

V. CONCLUSION

We proposed a pilot-data based estimation algorithm for an OFDM-based cooperative scenario where spatial diversity provided by SFBC is complemented with the use of the EF protocol. The proposed estimator consists of two iterations and uses the MMSE criterion to design the estimator for both the pilot-based and data-aided iterations. The data-aided estimation component is carried out using the regenerated data symbols as virtual pilots. The results have shown that for the same pilot density the MSE is reduced or alternatively requires less pilots to achieve the same performance therefore improving the overall system spectral efficiency with only one data iteration.

Moreover for a scenario where the links present the same statistics the results have shown, that using the same amount of pilot subcarriers, the proposed method provides at least 2 dB gain over the pilot-based estimator.

It is clear from the presented results that the proposed pilot-data based method has significant interest for application in next generation wireless networks for which cooperation is anticipated.

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