Improving the tuning of First-Order Autoregressive Model for the estimation of Amplify and Forward Relay channel

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***Abstract*—This paper deals with the estimation of the Amplify-and-Forward channel. Considering two widely accepted Rayleigh links with Jakes' spectrum, a first-order autoregressive model AR(1) is used to approximate the cascade of both links. A standard estimation algorithm is the Kalman filter. In this paper, we keep the choice of the AR(1)-Kalman filter, but we show that the method usually exploited in the literature to calculate the AR(1)-model parameter presents some disappointing results. We propose other values of the AR(1)-model parameter to improve the channel estimation, based on an off-line minimization of the asymptotic mean square error MSE for a given Doppler and signal to noise ratio. The simulation results show a considerable gain in terms of MSE of the well-tuned Kalman-based channel estimator, especially for the most common scenario of slow-fading channel.**

Index Terms - Amplify-and-Forward Relay, Channel estimation, Autoregressive model, Kalman Filter, Jakes' spectrum, Bessel function, Auto-correlation, Doppler Frequency.

I. Introduction

Recently, engineers switched to cooperative communications. The principal cause of this switching is the need to exploit spatial diversity at low cost or sometimes in small space. When we talk about cooperative communication, we have to mention the Multiple Input Multiple Output systems due to the relation between them. After the revolution of the MIMO systems, the engineers and researchers proposed a new way to benefit from the MIMO systems, without need of multiple antennas at the source and/or destination. The simplest way to do this is to use one relay, and to send one version of the signal from the unique antenna placed at the source, but to receive at the destination two versions of the signal, from the direct path and the via-relay path.

The cooperative communication is then summarized by a network composed of a source, a destination, and one or more relays. There are many types of relays, and the widely used types are the Amplify-and-Forward relay (AF) which amplifies the received signal and retransmits it, and the decode-and-Forward relay (DF) which decodes the received signal, then re-encodes and retransmits it. We cite the Estimate-and-Forward relay (EF) [6] and Compress-and-Forward relay (CF) too [7]. The source-relay-destination and source-destination links should be independent, since their dependency expels the diversity benefits. Moreover, the source-relay and relay-destination links are supposed independent too [1], [2], [3], [4].

Each of the Source-Relay and Relay-Destination links is modeled by a Rayleigh fading channel model with Jakes' Doppler spectrum. This is the most accepted random model that represents temporal variations of the equivalent baseband channel complex gain (CG) [4], [5], [8], [11].

To estimate or equalize this channel, it is difficult to use directly this model, because it is not convenient for implementation and for computer simulation. In the literature, the authors of [9] demonstrate that the autoregressive model with order one AR(1) is convenient enough for such correlated fading channel, especially in case of narrowband Doppler fading processes. So usually, the AR(1) model, accompanied with the assumption of zero-mean additive white circular complex Gaussian noise (CAWGN), is used to approach the one-link channel and facilitate its manipulation [8], [10], [11], [13].

Up to now, the appropriateness of AR(1) model for the Amplify-and-Forward channel is not demonstrated. Although, the AR(1) model has been used in the literature to model the Amplify-and-Forward channel [2], [4]. This approximation has been used to track the true channel by a Kalman Filter (KF) in various wireless communication systems [2], [10], [11], [13], and sometimes by other particle filters [4], linear MMSE estimator [1], [3], or least square estimator [3]. In this work, we keep using the Kalman filter like in our previous work dealing with one-link channel in [11].

The use of an AR(1) model requires a good choice of the AR(1) coefficient. In many papers [2], [4], [13], the AR(1) coefficient calculation for a given normalized Doppler frequency is based on a same criterion, called Correlation Matching (CM) in this paper. However, the problem of poorly tuned coefficient by Correlation Matching criterion has just recently been pointed out and analyzed in [10], [11] for the case of one-link flat fading Rayleigh channel with Jakes' spectrum.

In this paper, we extend our previous one-link work in [11] to the case of cooperative communications and more specifically for Amplify-and-Forward channel. This channel is the product of two Rayleigh channels approached with an AR(1) model. The filter used for estimation is the Kalman Filter (KF) and the goal is to minimize the asymptotic variance of estimation error (MAV). So we find numerically the optimal AR(1) coefficient under the MAV criterion, without the CM constraint and compare the performances for both cases. The paper is organized as follows: we first write the mathematical model used to represent the channel in section II. We then find numerically the value of optimal coefficient for the criterion of

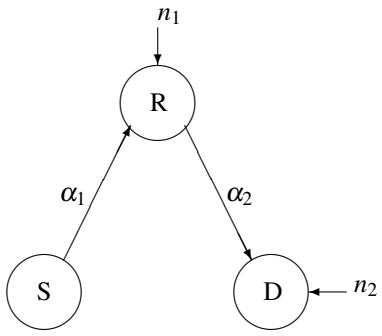

Figure 1. *Relay-channel system model*

minimizing the estimation error variance in section III.A. We also emphasize in section III.B and III.C the poor performance with the CM-based method, compared to the proposed method. Moreover, we study the behavior of the optimal MSE for a given Doppler and SNR scenario.

II. Mathematical Model

A. Real Transmission

We consider the estimation of the channel shown in figure 1. It consists of a source S, a destination D, and a relay R placed between them. We suppose that the direct link from source to destination is too poor, and we consider only the via-relay link. We divide our channel into two links, the Source-Relay link and the Relay-Destination link. Each of those links may be subject to be:

- A link where both extremities are mobile
- A link where one extremity is fixed while the other one is mobile
- A link where both of them are fixed

From the different scenarios that derivate, we focus on the mobile-fixed-mobile scenario. The source is moving at a speed of v_S, and the destination is moving at a speed of v_D. The relay is fixed. We can assume in this case that each link ($S-R$ and $R-D$) is a flat fading Rayleigh channel with Jakes' spectrum (Clarkes' model [12]), characterized by a complex gain CG α_1 and α_2 respectively, varying from one symbol to another, but we assume that the CG variation can be neglected during one symbol period. The variance of those gains are $\sigma^2_{\alpha_1}$ and $\sigma^2_{\alpha_2}$ respectively. For a sampling rate of T, the normalized Doppler frequency of the $S-R$ link is $f_{d1}T$, where $f_{d1}=\frac{v_S}{\lambda}$, and the normalized Doppler frequency of the $R-D$ link is $f_{d2}T$, where $f_{d2}=\frac{v_D}{\lambda}$. λ is the wavelength of the analog emitted signal. A Jakes' Doppler spectrum is assumed for the $S-R$ link (the same will be for the $R-D$ link by replacing f_{d1} by f_{d2} and $\sigma^2_{\alpha_1}$ by $\sigma^2_{\alpha_2}$):

$$\Gamma_{\alpha_1}(f)=\begin{cases}\frac{\sigma^2_{\alpha_1}}{\pi f_{d1}\sqrt{1-\left(\frac{f}{f_{d1}}\right)^2}} & \text{if } |f|<f_{d1}\\ 0 & \text{if } |f|>f_{d1}\end{cases} \quad (1)$$

The autocorrelation coefficient for the k^{th} tap of S-R link is given by:

$$R_{\alpha_1}[k]=\sigma^2_{\alpha_1}J_0(2\pi f_{d1}Tk) \quad (2)$$

where J_0 is the zeroth-order Bessel function of the first kind. The same holds for the $R-D$ link.

The source sends the signal s_k. The relay receives the signal r_k, amplifies it with a factor of A called relay gain, and retransmits the amplified signal $A.r_k$ to the destination. The destination receives the signal y_k at the end. Since the gain of both links is constant during the period of the symbol, we observe a sampled and noised signal (sampling at rate T).

$$r_k=s_k\alpha_{1k}+n_{1k} \quad (3)$$

$$y_k=Ar_k\alpha_{2k}+n_{2k} \quad (4)$$

where n_{1k} and n_{2k}, $k=1,2,...$ are Complex Additive White Gaussian Noises (CAWGN), with variances ${\sigma_{n_1}}^2$ and ${\sigma_{n_2}}^2$ respectively.
The observation equation will be then

$$y_k=s_k\alpha_k+n_k \quad (5)$$

where $\alpha_k=A\alpha_{1k}\alpha_{2k}$ and $n_k=A\alpha_{2k}n_{1k}+n_{2k}$, leading to

$${\sigma_\alpha}^2=A^2{\sigma_{\alpha_1}}^2{\sigma_{\alpha_2}}^2 \quad (6)$$

and

$${\sigma_n}^2=A^2{\sigma_{\alpha_2}}^2{\sigma_{n_1}}^2+{\sigma_{n_2}}^2 \quad (7)$$

The Gain A is implicitly determined from the desired/required signal-to-noise ratio in the second link (SNR_2) defined below, which is related to the energy of symbols emitted given $\sigma^2_{\alpha_1}$, $\sigma^2_{\alpha_2}$, $\sigma^2_{n_1}$ and $\sigma^2_{n_2}$. The signal s_k is transmitted from the source with energy E_1. The energy E_2 of the signal Ar_k transmitted from relay is then

$$E_2=A^2(E_1{\sigma_{\alpha_1}}^2+{\sigma_{n_1}}^2) \quad (8)$$

The signal-to-noise ratio for the S-R link, R-D link, and all the channel are respectively given by :

$$\gamma_1=\frac{E_1{\sigma_{\alpha_1}}^2}{{\sigma_{n_1}}^2} \quad (9)$$

$$\gamma_2=\frac{E_2{\sigma_{\alpha_2}}^2}{{\sigma_{n_2}}^2} \quad (10)$$

$$\gamma=\frac{E_1{\sigma_\alpha}^2}{{\sigma_n}^2}=\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1} \quad (11)$$

And the corresponding values in (dB) are:

$$SNR_{1,2}=10log_{10}\gamma_{1,2} \quad (dB)$$

$$SNR=10log_{10}\gamma \quad (dB)$$

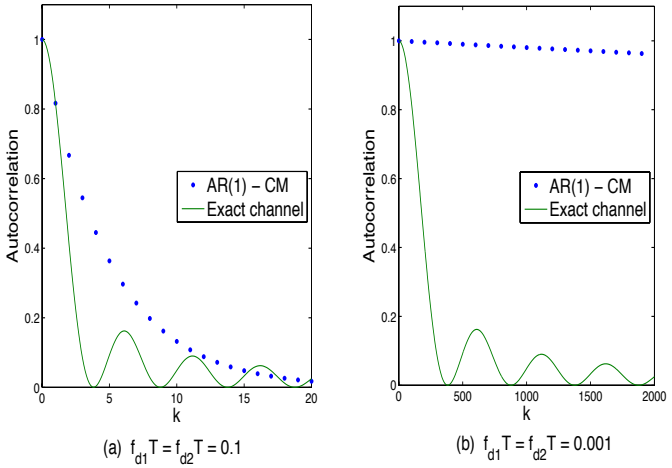

Figure 2. *Comparison of the auto-correlation functions of the true process α (continuous line) and the approached AR(1) process $\tilde{\alpha}$ for high and low Doppler frequencies (respectively left and right figures)*

Both links are supposed independent. This leads to a total Doppler spectrum and total autocorrelation function [12], [4]:

$$\Gamma_\alpha(f) = A\Gamma_{\alpha_1}(f) * \Gamma_{\alpha_2}(f) \tag{12}$$

$$\begin{aligned} R_\alpha[k] &= A^2 R_{\alpha_1}[k] R_{\alpha_2}[k] \\ &= A^2 \sigma_{\alpha_1}^2 \sigma_{\alpha_2}^2 J_0(2\pi f_{d1} T k) J_0(2\pi f_{d2} T k) \end{aligned} \tag{13}$$

We design by $*$ the convolution product.

B. First-order autoregressive dynamical model

In the literature, the time-varying CG α_k is often approached by a first-order autoregressive (AR(1)) model $\tilde{\alpha}_k$:

$$\tilde{\alpha}_k = a.\tilde{\alpha}_{k-1} + e_k \tag{14}$$

where e_k is a white circular complex Gaussian noise with variance $\sigma_e^2 = (1-a^2)\sigma_\alpha^2$. The observation equation (5) is then approximated by:

$$y_k = s_k \tilde{\alpha}_k + n_k \tag{15}$$

The AR(1) coefficient verifies

$$a = \frac{R_{\tilde{\alpha}}[1]}{R_{\tilde{\alpha}}[0]} \tag{16}$$

In the literature, the correlation matching (CM) criterion is usually imposed [2], [4]. It means that the autocorrelation of the exact channel gain α and the AR(1) approached process $\tilde{\alpha}$ coincide for the first two coefficients (i.e., $R_{\tilde{\alpha}}[0] = R_\alpha[0] = A^2\sigma_{\alpha_1}^2\sigma_{\alpha_2}^2$, and $R_{\tilde{\alpha}}[1] = R_\alpha[1]$), and using equation (16) and (13) the AR(1) coefficient a noted a_{CM} becomes

$$a_{CM} = J_0(2\pi f_{d1} T) J_0(2\pi f_{d2} T) \tag{17}$$

The figure 2 shows the autocorrelation functions for both dual Rayleigh link and AR(1)-CM cases, at two values of Doppler frequencies. When the channel is varying slowly, that means when we have low Doppler frequencies (right figure, with $f_{d1}T = f_{d2}T = 10^{-3}$), we see that the AR(1)-CM autocorellation function seems to stay constant, since the AR(1) coefficient $a_{CM} \approx 1$ (see eq. (17), with $J_0(\varepsilon) \approx 1$ when $0 \leq \varepsilon << 1$). Then, the matching is less convincing in case of low frequencies, contrary to the situation with high frequencies where the autocorrelation function is less out of tune (left figure, with $f_{d1}T = f_{d2}T = 10^{-1}$). Based on this observation, we will not consider the CM criterion to compute the AR(1) parameter in the present study but a variance criterion, as already proposed for the one-link channel in [10] and [11]. The choice of the AR(1) parameter a will then be based on minimizing the asymptotic estimation error variance (MAV) as developed in the section III.A, and we will call it a_{MAV}.

C. Kalman filter (KF)

Given the model and observation equations (14) and (15), we use a KF to get an on-line unbiased estimate, $\hat{\alpha}_k$, of the true α_k. The error is $\varepsilon_k = \alpha_k - \hat{\alpha}_k$, with variance $MSE = E\{|\varepsilon_k|^2\}$.
In this work, we concentrate of the performance of the channel estimator. So we treat a simplified case assuming the symbols are known (pilot-aided scenario) or perfectly decided (decision-directed scenario), thus we assume $s_k = 1$. Note that in practice, our channel estimator can be easily coupled with a detector in order to perform joint channel estimation and decision tasks, for example via the Expectation-Maximization algorithm framework (see [13]).

The KF for this simplified case is given by (see p. 436 in [14]):

Prediction	$\hat{\alpha}_{k\|k-1}$	=	$a\ \hat{\alpha}_{k-1}$	(i)
Prediction MSE	$P_{k\|k-1}$	=	$a^2 P_{k-1} + \sigma_e^2$	(ii)
Kalman Gain	K_k	=	$\frac{P_{k\|k-1}}{\sigma_n^2 + P_{k\|k-1}}$	(iii)
Correction	$\hat{\alpha}_k$	=	$\hat{\alpha}_{k\|k-1} + K_k(y_k - \hat{\alpha}_{k\|k-1})$	(iv)
MSE	P_k	=	$(1-K_k)P_{k\|k-1}$	(v)

Replacing (ii) in (iii), (v) in (ii), and (i) in (iv), we obtain the simplified system:

$$K_k = [a^2 P_{k-1} + \sigma_e^2]/[a^2 P_{k-1} + \sigma_e^2 + \sigma_n^2] \tag{18}$$

$$P_k = (1-K_k)(a^2 P_{k-1} + \sigma_e^2) \tag{19}$$

$$\hat{\alpha}_k = a\ \hat{\alpha}_{k-1} + K_k(y_k - a\ \hat{\alpha}_{k-1}) \tag{20}$$

where K_k is the Kalman gain at iteration k and P_k is the estimation error variance.
Without loss of generality, we assume $E_1 = 1$ and $\sigma_{\alpha_1}^2 = \sigma_{\alpha_2}^2 = 1$. Given (6),

$$\sigma_\alpha{}^2 = A^2$$

For the special case where $\sigma_{n_1}^2 = \sigma_{n_2}^2$, given (7)

$$\sigma_n^2 = A^2\sigma_{n_1}^2 + \sigma_{n_2}^2 = \sigma_{n_1}^2(A^2+1)$$

So for this case, and given (11), we have

$$\gamma = \frac{A^2}{\sigma_{n_1}^2(A^2+1)} = \gamma_1 \frac{A^2}{A^2+1} \tag{21}$$

We clearly see that $\gamma < \gamma_1$.

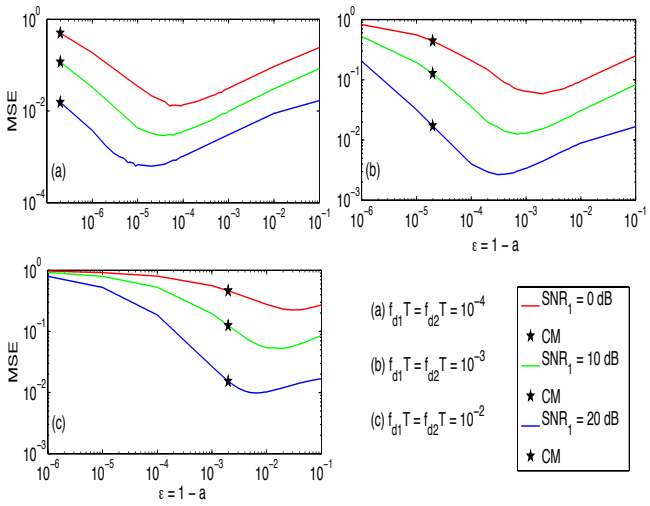

Figure 3. *MSE in function of $\varepsilon = 1-a$ for different Doppler frequencies $f_{d1}T = f_{d2}T = f_dT$. The $\star$ indicates the position of MSE_{CM} and the corresponding $1-a_{CM}$.*

III. Simulation and results

We present Monte Carlo simulations to demonstrate the channel estimation error variance of AF relaying. We apply the Kalman filter for the CM case where $a = a_{CM}$, and calculate the corresponding error variance MSE_{CM} as first step. As a second step, we apply the AR(1) Kalman filter for many other cases where a is taken manually, and found the MSE for each case. At the end, we choose the optimal value of a, denoted a_{MAV}[1], that minimizes the MSE.

In our simulations, we are in the special case of $\sigma^2_{n_1} = \sigma^2_{n_2}$, and we take $A = 1$. Then $\sigma^2_n = 2\sigma^2_{n_1}$ and $\gamma = \frac{\gamma_1}{2}$, similarly to say $SNR = SNR_1 - 3dB$ where SNR_1 is the signal to noise ratio for the S-R link.

A. Tuning of the AR(1)-parameter

The figure 3 shows the error variance in function of $\varepsilon = 1-a$. We see that at low frequencies, the minimum value of MSE is attended for $\varepsilon_{MAV} >> \varepsilon_{CM}$, i.e, for $a_{MAV} < a_{CM}$ while we can see that this difference is more reduced when the Doppler frequency and/or the SNR increase. Comparing the values of the MSE in the "valley" (*i.e.* in the minimum region) and the one obtained with CM criterion, MSE_{CM}, we observe that the CM criterion is far from optimal, leading to a strong loss in performance in terms of MSE. The strict minimum is noted MSE_{MAV}, from which we can measure the related AR(1)-parameter, a_{MAV}.

[1]Note that once the values of a_{MAV} for different values of SNR and Doppler frequencies are stored in tables, we can use them for the on-line estimation.

$\frac{a_{CM}}{a_{MAV}}$	$f_{d1}T = 1e-4$	$f_{d1}T = 1e-3$	$f_{d1}T = 1e-2$
$f_{d2}T = 1e-4$	0.9999998 0.9999500	0.9999900 0.9991000	0.9990131 0.9800000
$f_{d2}T = 1e-3$	0.9999900 0.9991000	0.9999802 0.9980000	0.9990034 0.9800000
$f_{d2}T = 1e-2$	0.9990131 0.9800000	0.9990034 0.9800000	0.9980275 0.9700000

Table I
COMPARISON BETWEEN a_{CM} AND a_{MAV} FOR DIFFERENT DOPPLER FREQUENCIES AT $SNR = 0\ \ dB$

$\frac{a_{CM}}{a_{MAV}}$	$f_{d1}T = 1e-4$	$f_{d1}T = 1e-3$	$f_{d1}T = 1e-2$
$f_{d2}T = 1e-4$	0.9999998 0.9999800	0.9999900 0.9998000	0.9990131 0.9960000
$f_{d2}T = 1e-3$	0.9999900 0.9998000	0.9999802 0.9997000	0.9990034 0.9950000
$f_{d2}T = 1e-2$	0.9990131 0.9960000	0.9990034 0.9960000	0.9980275 0.9930000

Table II
COMPARISON BETWEEN a_{CM} AND a_{MAV} FOR DIFFERENT DOPPLER FREQUENCIES AT $SNR = 20\ dB$

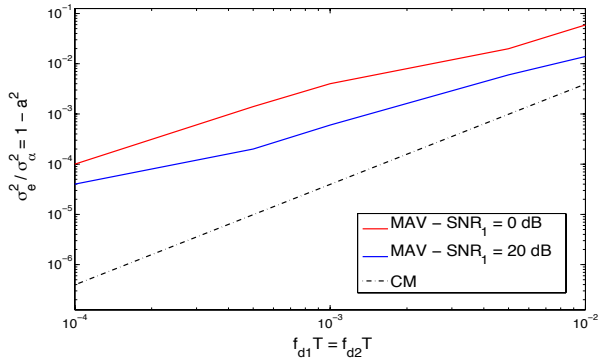

Figure 4. *State noise variance $\sigma^2_e/\sigma^2_\alpha = 1-a^2$ used in the AR(1)-model in function of Doppler frequency for MAV and CM cases*

In tables I and II, we can compare the values of a_{MAV} and a_{CM}. It is clear, especially for low Doppler frequencies, that the CM coefficient is higher than the optimal coefficient. Thus, when we are in the optimal case, the AR(1)-based autocorrelation curve decreases more rapidly to zero and approaches better the values of the Bessel-based autocorrelation function (13) than it was in figure 2 for the CM case.

In figure 4, we have plotted the state noise variance σ^2_e used in the Kalman filter as a function of f_dT. We recall that the state noise variance is related to the AR(1)-parameter a by $\sigma^2_e = (1-a^2)\sigma^2_\alpha$. We can measure by this figure how much the state noise variance of the CM criterion is too weak compared to the optimal value (MAV criterion), leading about a factor 100 for $f_dT = 10^{-4}$, and about a factor 10 for $f_dT = 10^{-2}$.

It should be noted that the variation of $\sigma^2_{e\,CM}$ versus f_dT in a log/log scale is linear with a slope of 2 (*i.e.* 20 dB/decade). It can be explained analytically by an approximation of

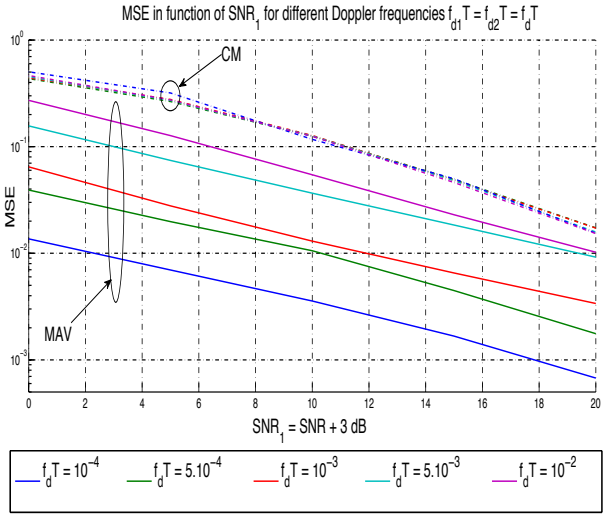

Figure 5. *Comparison between MSE_{CM} and MSE_{MAV} in function of signal-to-noise ratio for different Doppler frequencies*

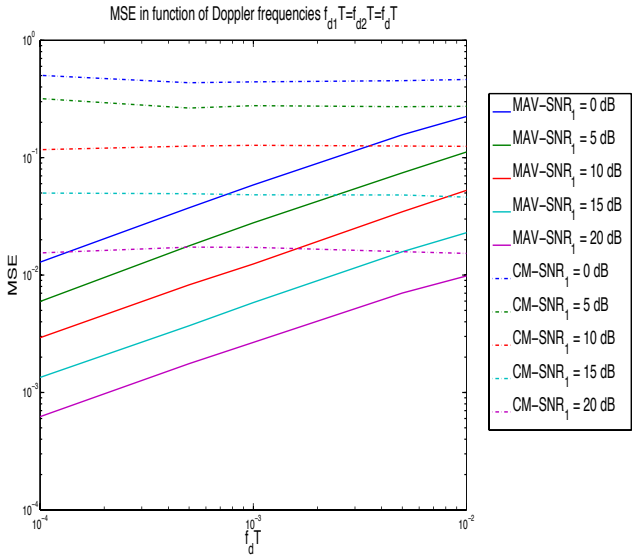

Figure 6. *Comparison between MSE_{CM} and MSE_{MAV} in function of Doppler frequency for different signal-to-noise ratio*

the Bessel function : $[J_0(2\pi f_d T)]^2 \approx 1-(2\pi f_d T)^2/2$ when $2\pi f_d T << 1$, leading to $\frac{\sigma^2_{\hat{e}\,CM}}{\sigma^2_{\hat{\alpha}}} = 1 - a^2_{CM} \approx (2\pi f_d T)^2$.

B. Same Doppler frequencies

In this case, we suppose the source and the destination moving at the same speed. We note $f_{d1}T = f_{d2}T = f_dT$.
In figure 5, we plot the error variance for Correlation Matching case (MSE_{CM}) in function of SNR, and compare it to the minimum error variance we reached (MSE_{MAV}). The plots are dressed for different Doppler frequencies f_dT.
We see that $MSE_{CM}dB$ and $MSE_{MAV}dB$ varies linearly with SNR_1 dB. We deduce then that $MSE_{MAV} = K.\gamma^{\beta}$. Graphically, we can calculate the coefficient β

$$\beta = \frac{\Delta[log_{10}(MSE_{MAV})]}{\Delta[log_{10}(\gamma)]} = 10\frac{\Delta[log_{10}(MSE_{MAV})]}{\Delta[SNR]}$$

We obtain $\beta \approx -0.67 \approx -\frac{2}{3}$

In figure 6, we plot the error variance for Correlation Matching case (MSE_{CM}) in function of f_dT, and compare it to the minimum error variance we reached (MSE_{MAV}). The plots are dressed for different SNR. We see too that $MSE_{MAV}dB$ vary linearly with $log_{10}(f_{d1}T) = log_{10}(f_{d2}T) = log_{10}(f_dT)$, while MSE_{CM} seems constant with respect to f_dT. In the same way, we can say that $MSE_{MAV} = K'.(f_dT)^{\zeta}$ and we calculate graphically the coefficient ζ. We obtain

$$\zeta = \frac{\Delta[log_{10}(MSE_{MAV})]}{\Delta[log_{10}(f_dT)]}$$

We obtain $\zeta \approx 0.69 \approx \frac{2}{3}$.

Finally, and given $\gamma = \frac{1}{\sigma^2_n}$ in our simulations, we can say that

$$MSE_{MAV} = C.(f_dT \times \sigma^2_n)^{\frac{2}{3}}$$

where C is a constant value.
It is noteworthy that this optimal MSE for the AR(1) Kalman-based estimation of the mobile-fixed-mobile relay channel (with two Clarkes' models) seems to take the same form than the one obtained for the one-link Clarkes'model channel established in [11], eq. (25) (*i.e.* with the same $(2/3)$ power of $f_dT \times \sigma^2_n$).

C. Different Doppler frequencies

In this case, we suppose the source and the destination moving at different speeds. The same reasoning persists. The minimum error variance MSE_{MAV} increases with $f_{d1}T$ and $f_{d2}T$, and with SNR, as can be observed in figure 6.

D. BER performances

Until now, all the performances are dressed in terms of MSE. Finally, we have a look at the consequences in terms of Bit Error Rate (BER) in figure 8. This figure refers to a binary PSK (BPSK) transmitted over an Amplify-and-Forward dual Rayleigh fading channel with $f_{d1}T = f_{d2}T = 10^{-3}$. In order to ensure convergence of the iterative detection and decoding algorithm, 10 pilot symbols (known at the receiver) every 100 code symbols is placed in the transmitted codeword[2]. So we

[2]To use the KF equations in (18), (19) and (20), which are given for known symbols case, *i.e.* for $s_k = 1$ in (15), and since we have $s_k \in \{-1;+1\}$, the KF equations are modified by substituting y_k with $y_k \times \hat{s}^*_{k|k-1}$ where $\hat{s}_{k|k-1} = s_k$ if s_k is known (pilot) or $\hat{s}_{k|k-1} = sgn\{\Re(\hat{\alpha}^*_{k-1} \times y_k)\}$ if s_k is unknown (data). In this case, $\hat{s}_{k|k-1}$ represents the *a priori* decision, and the *final* decision will be $\hat{s}_k = sgn\{\Re(\hat{\alpha}^*_k \times y_k)\}$.

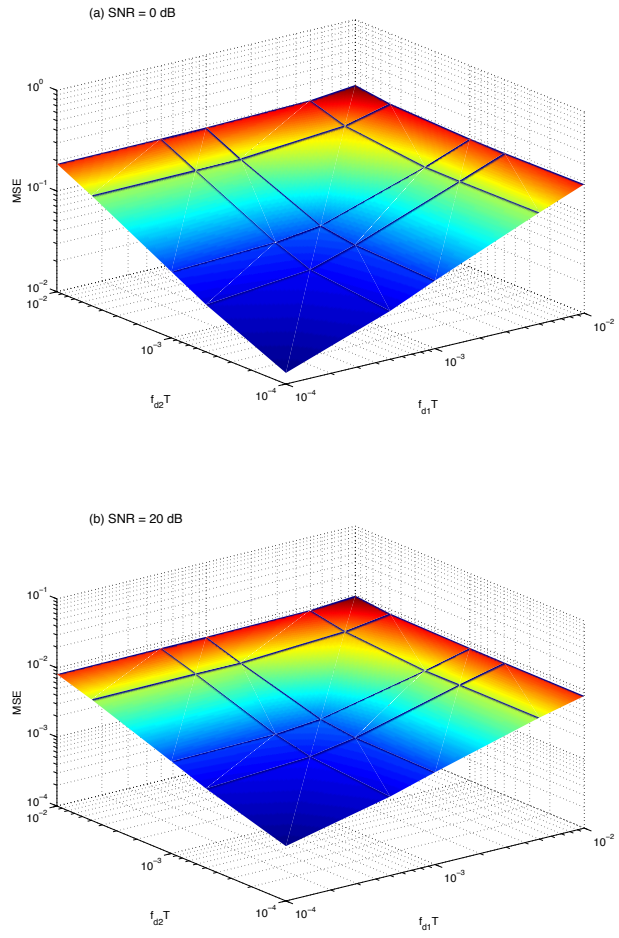

Figure 7. *MSE_{MAV} in function of Doppler frequencies for high and low signal-to-noise ratios SNR*

use a semi-blind pilot-assisted channel estimation. We show a significant improvement in BER performance after channel estimation with MAV-KF versus the CM-KF, especially in low SNR region.

IV. Conclusion

This paper addresses the problem of estimating an Amplify-and-Forward channel using a first-order AR(1) model. Simulations show that the most widely used choice for the AR(1) pole estimation (the CM criterion) is not accurate for low SNR and low Doppler f_dT. Therefore, varying the value of the AR(1) coefficient, we carry out the optimization of the AR(1) model. It is demonstrated graphically that the MSE_{MAV} of the AR(1) KF is proportional to the $(2/3)$ power of the product $(f_dT \times \sigma_n^2)$, where σ_n^2 is the observation noise variance.

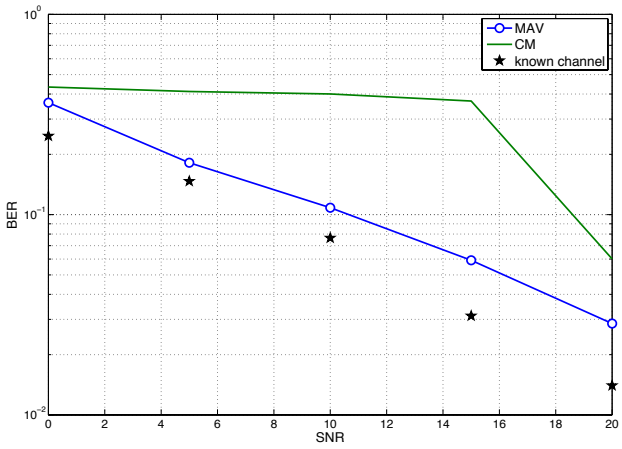

Figure 8. *BER in function of SNR for $f_dT = 10^{-3}$*

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