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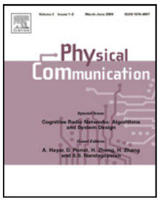

Full length article

Reduced complexity Kalman filtering for phase recovery in XPIC systems

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ABSTRACT

Reduced-complexity Kalman-based algorithms are proposed to recover the phase of cross-polar interference cancellation (XPIC) receivers in microwave radio relay links. In particular, two completely independent radio frequency (RF) transceiver chains are considered for the two different polarizations, in order to have the maximum flexibility to connect different single carrier transceivers to dual-polarized antennas. A one-state Kalman model is proposed, which is of low complexity and thus suitable for a modern higher data rates M-ary quadrature amplitude modulation (M-QAM) receiver. Moreover, a further reduced complexity version is developed that uses a lower amount of information to recover the phase at the receiver, as well as a downsampling procedure to speed up the Kalman algorithm, and an alternative error computation that is essential to ease the Kalman implementation. It is worth noting that the three last simplifications are general and can be applied not only to a one-state Kalman model. Simulation results compare the proposed simplified Kalman solutions to typical phase-locked loop (PLL) algorithms proving their comparable performance with the benefit of lower complexity. Finally, the relationships between the Extended Kalman and the PLL approaches are investigated. The obtained relation is essential for the cross-polar phase recovery, since, as far as the authors know, there are not closed-form solutions for the PLL parameter optimization in cross schemes.

1. Introduction

The recent spread of smart applications has led to the growth of data traffic in the last years. As a result, the development of fifth-generation (5G) communications technology is required to fulfill the increasing users' traffic demand. For this purpose, operators and carriers are claimed to improve the user experience and, in general, the overall network performance. In this sense, there are notable market interests on the development of innovative backhaul solutions to accommodate the increased wireless traffic and the resulting higher bandwidth demand [1].

Cross polarization interference cancellation (XPIC) technology represents the enabler for dual-polarized transmissions over the same radio frequency (RF) channel, so that the link capacity is doubled by using two orthogonal polarizations channels over the same link [2].

In order to have the maximum flexibility from an installation and maintenance point of view, some XPIC architectures are based on two independent and unsynchronized transceiver paths for backhaul links, with completely independent transmitter and receiver local oscillators (LOs) [3].

Differently from multiple input multiple output (MIMO) solutions that work with a carrier-over-interference ratio (C/I) almost equal to 0 dB, XPIC operating conditions have cross polarization discrimination (XPD) around $20 - 25$ dB. Despite the fact that such XPD value could be considered almost error free for low order modulations, higher order QAM schemes still could represent a challenge [4,5], for example they highly suffer from phase noise even in line of sight (LoS) environments.

Carrier frequency and phase synchronization are also challenging for higher order M-QAM single polarization receivers, and may be accomplished by a Kalman algorithm, as described in [6,7].

In [8], we proposed a cross-polarized Kalman based phase recovery scheme for an XPIC architecture that jointly recovers the phase of both the received signal and the interfering one at the input of the cross-polar interference canceller. In particular, a four-state extended Kalman filter (EKF) algorithm for an XPIC receiver was derived, along with a modified version that exploits two simpler two-state EKFs, one for the main polarization path and the other for tracking the interference signal phase.

In this paper, starting from the two-state Kalman model for a XPIC receiver [8], we focus on studying the computational complexity of such schemes in order to develop practical architectures

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that could be efficiently implemented in modern digital hardware for high data rate microwave backhaul links. We think that computational aspects are crucial to make the Kalman based architecture more attractive with respect to the simpler one based on two phase-locked loops (PLLs), especially from a hardware feasibility point of view. Moreover, we think that a comprehensive study of the performance-complexity trade off is crucial in order to help the interested technical community in developing real hardware prototypes of the scheme proposed in [8].

The main contributions of the paper are listed in the following:

- a low-complexity Kalman filter scheme is proposed for phase recovery in XPIC systems, based on two one-state EKFs. Although such solution shows a lower computational burden with respect to the scheme in [8], it provides similar or anyway acceptable performance.
- the performance of the presented scheme is also evaluated by studying the effects of the following complexity reduction algorithm implementations:
    - The computational burden needed for computing the covariance matrix inverse may be reduced. Specifically, since the phase noise variations are slow respect to the symbol timing, the covariance matrix computation update may be kept constant during several Kalman iterations without affecting the overall algorithm performance. This is equivalent to downsampling only inside the covariance matrix computation loop;
    - the phase-error computation is modified in order to avoid two phase counter-rotations in the Kalman state update equations. In this way the hardware design is more feasible, since phase rotation are computationally expensive;
    - complexity reduction is also achieved by considering in the phase error computation only the in-phase or in-quadrature component of the signals.
- the relation between the -EKF based approach and the commonly used PLL parameters is extensively studied. While [9] probes the relation between Kalman and PLL gains, we investigate the connection between the Extended Kalman version and the PLL. This relation is important for the cross-polar phase recovery, since, as far as the authors know, while there are closed form solutions for PLL parameters in single polarization receivers, they do not exist for the cross PLL parameter optimization. Indeed, such EKF–PLL relation could be useful to optimize cross PLL parameters through EKF simulations. In particular, being the PLL implementation easier than a Kalman scheme, we envisage a final practical solution where a typical cross PLL scheme with fixed gains is replaced by a cross PLL with variable gains, which are calculated through Kalman simulation, resulting in a solution more robust to channel variations.

The paper is organized as follows: Section 2 describes the system model, Section 3 briefly reviews the EKF models described in [8], while Section 4 analyzes the proposed reduced complexity Kalman schemes and the relation between the EKF parameters and the PLL filter gains. Section 5 shows some interesting simulation results, and, finally, concluding remarks wrap up and close the paper in Section 6.

2. System model

We consider a backhaul link with two distinct receiver paths and unsynchronized local oscillators (LO), as in [3,8]. Fig. 1 depicts the considered XPIC architecture, highlighting the two distinct receiver paths, with unsynchronized local oscillators (LO) for a backhaul link [3]. Since our focus is a typical microwave backhaul application, we model the channel with only AWGN without multipath fading as in [8].

Let us consider the signal $r_0(n)$, received at one polarization path:

$$r_0(n) = t_0(n)e^{j\theta(n)} + gt_1(n)e^{j\phi(n)} + w(n) \tag{1}$$

where $t_0(n)$ is the nth complex QAM transmitted symbol of the main polarization component with phase $\theta(n)$, g is the cross-polar attenuation factor, $t_1(n)$ is the nth complex QAM symbol transmitted on the interference path with phase $\phi(n)$, and $w(n)$ represents the additive white Gaussian noise (AWGN) at the receiver.

The aim of both the Kalman and PLL algorithms is to estimate the phases $\theta(n)$ and $\phi(n)$, along with the corresponding frequencies $\dot{\theta}(n)$ and $\dot{\phi}(n)$, by using the input of the main polarization slicer:

$$u_0(n) = \left(r_0(n) - gt_1(n)e^{-j\hat{\phi}(n)}\right) e^{-j\hat{\theta}(n)} \tag{2}$$

where $\hat{\phi}(n)$ and $\hat{\theta}(n)$ represent the estimated phases of the main and cross polar signals at the receiver. The cross-polar attenuation factor g is assumed to be known, since, in high-order M-QAM receivers for microwave backhaul links, a linear filter interference canceller/equalizer is able to converge in presence of both baseband phase and frequency errors, providing a good initial guess for the PLL or the Kalman algorithms. Usually, during the acquisition phase, the adaptive linear filter works in a blind mode, typically by a constant modulus algorithm (CMA), and switches to a minimum mean square error (MMSE) algorithm once the normal operating condition is reached. Once the equalizer switches to MMSE, all other recovery algorithms, like Kalman phase recovery, start using the decisions at the output of the slicer.

In the following Section 3, we give a short outline of the phase recovery using the two-state Kalman models [8], and then, in Section 4, we describe the proposed solutions, which include (i) a one-state Kalman model, (ii) a further simplified one-state version that uses a lower amount of information to recover the phase, and (iii) a downsampling of the covariance matrix computations to speed up the Kalman algorithm. All the proposed schemes aim at reducing the complexity of a Kalman-based solution in a smart way in order to not degrade the performance. An alternative error computation that can decrease the computational load of Kalman implementation is also included, as well as some interesting relations between the Kalman and PLL parameters, useful for cross PLL parameters optimization, which is still missing.

3. XPIC phase recovery based on Kalman filtering

Since our purpose is to estimate the phase and the frequency of the signals in an XPIC scheme, such variables are considered in the Kalman state vectors. We also define the observation vectors and the error to be minimized through the Kalman approach in order to obtain the estimates of the signal frequency and phase discrete values.

Specifically, we consider a two-state XPIC Kalman algorithm for the main path and another one for the cross polar interference, so that the two-state vectors of the main and cross polar signals are expressed [8]:

$$\mathbf{x}_0(n) = \begin{bmatrix} \theta(n) \\ \dot{\theta}(n) \end{bmatrix} \tag{3}$$

$$\mathbf{x}_1(n) = \begin{bmatrix} \phi(n) \\ \dot{\phi}(n) \end{bmatrix} \tag{4}$$