Survey on Robust Carrier Tracking Techniques

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***Abstract*—In most wired and wireless systems, carrier tracking is an essential task that allows the receiver to precisely synchronize with the carrier of the incoming signal. Stringent carrier tracking requirements are imposed in systems that are sensitive to carrier mismatches, such as orthogonal frequency division multiplexing (OFDM), digital communication receivers employing high-order constellations, and terrestrial- or satellite-based positioning systems, just to mention a few. In the recent years, even more critical requirements are being imposed due to the emergence of new applications and services that are pushing traditional systems to operate in much more challenging conditions than the ones for which they were originally designed. The presence of severe fading, signal outages, abrupt phase changes and high user dynamics, are currently compromising the validity of well-known and long-established traditional carrier tracking techniques, thus calling for the development of new *robust* carrier tracking algorithms. In this paper, we provide a detailed survey on the five main strategies that can be adopted to cope with the technical challenges of robust carrier tracking. These strategies range from some basic optimizations of current tracking loops, to the use of Kalman filter-based architectures, or the application of innovative carrier tracking techniques based on particle filters or compressive sensing. We will also review some open-loop techniques, which are widely adopted in burst-mode communications receivers, as an alternative and potential candidate solution for robust carrier tracking in harsh conditions.**

***Index Terms*—Frequency locked loops, phase locked loops, Kalman filters, phase estimation, tracking loops.**

I. INTRODUCTION

COHERENT reception of continuous-wave signals is a century-old technique indispensable for the operation of most wired and wireless systems deployed nowadays [1], [2]. This is indeed the case of continuous-mode transmission systems, such as radio or television broadcasting, as well as global positioning satellite systems (GNSS), just to mention a few. For these systems, carrier tracking is of paramount importance to precisely synchronize the receiver local oscillator to that of the transmitter, as well as to follow any possible time-variation of the carrier due to propagation effects, or to user clock dynamics (either at the transmitter or the receiver side). Such a precise alignment is required in order to recover the embedded information-bearing message that will be delivered to the user. Otherwise, residual carrier errors lead to unacceptable performance degradations, particularly in digital communication systems resorting to higher-order constellations [3], orthogonal frequency division multiplexing (OFDM) modulation [4] or in positioning systems [5].

The need for precise synchronization between transmit and receive oscillators dates back to the origins of radio transmission, with some early references appearing in [6] and [7]. Although the need was already present, it was not until the 70s when the problem of carrier tracking was fully addressed under a systematic approach, influenced by the recent advances in electronics and the advent of integrated circuits (IC). This approach, widely adopted nowadays in a myriad of applications, is based on a closed-loop architecture referred to as *phase-locked loop* (PLL), whose aim is to compare the input carrier phase values with a local replica, and to drive the resulting error to zero by properly adjusting the phase of the local oscillator [8]. Significant efforts have been devoted to the study of PLL architectures in the last decades, and this is reflected in the large amount of existing contributions in the literature, with extensive surveys being conducted, such as the one in [9] addressing the connections between digital PLLs and maximum a-posterior (MAP) estimation, the special issue in [10] regarding the PLL performance analysis, the contribution in [11] focusing on the PLL constituent blocks and related ICs, or even some widely-referenced books devoted to this topic, e.g. [12] and [13], just to mention some examples.

Nevertheless, and despite its apparent maturity, new challenges are being faced in order to extend carrier tracking techniques beyond the limits of their original designs. The motivation behind this need is two-fold. On the one hand, there is an increasing interest in providing ubiquitous communications and positioning capabilities to user mobile terminals [14], [15]. This forces carrier tracking to operate in much more challenging conditions than the ones for which it was originally conceived, and this involves having to cope with severe fading, blocking and multipath degradation, as typically found in urban canyons or indoor scenarios [16], [17]. On the other hand, there is also an increasing interest in extending carrier tracking techniques to a wide range of innovative and emerging applications, such as distributed power generation [18], real-time motion tracking [19], GNSS precise point positioning (PPP) [20], ionosphere scintillation monitoring [21] or space navigation [22], where new constraints and performance requirements must be met. This is also the case of clock synchronization in Ethernet networks using the syncE protocol [23], where intermediate network nodes implement PLLs to accurately track the primary clock reference. Carrier tracking becomes challenging in the presence of packet buffering between these nodes and the master station, or when aggregating traffic in 3G or 4G networks through an Ethernet-based mobile backhaul. Note that the latter is becom-

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ing particularly relevant due to the widespread deployment of Ethernet technology in substitution of traditional time-division multiplexing (TDM) transport networks [24]. As a consequence of all these emerging applications, significant research efforts are currently being directed towards the goal of solving the technical challenges imposed by these new carrier tracking scenarios and applications [25]. The result is a very active field of research, which focuses on the design of the so-called *robust* carrier tracking techniques.

Robustness, in its broadest sense, can be defined as the degree to which a system operates correctly in the presence of exceptional inputs or stressful environmental conditions. For the case under study, robust carrier tracking can be understood as the ability to perform carrier tracking in non-nominal conditions, such as signal attenuation due to partial or complete masking of the line-of-sight, rapid fading events and user dynamics, shadowing, or other deleterious effects related to abnormal signal propagation. Operation under these conditions requires a paradigm shift in the way traditional carrier tracking architectures are implemented, in particular with respect to the fact of coping with weak signal levels. For instance, the sensitivity or tracking threshold of traditional receivers typically accounts for a fade margin on the order of $10 - 15$ dB. This range is well-dimensioned for static and outdoor scenarios, but neither for soft-indoors, dynamic scenarios, nor applications sensitive to strong scintillation caused by high solar activity, where more than 30 dB can easily be lost due to fading [26], [27]. An additional problem is that combating signal fading typically leads to receiver architectures that implement a tight tracking of the input signal, which can intuitively be understood in terms of adopting a very narrow loop bandwidth, or equivalently, a very long filtering memory. This strategy, however, enters in contradiction with the requirements for tracking high user dynamics, which involve adopting a loose tracking (i.e. a wide loop bandwidth, and thus, a shorter filtering memory) in order to provide the necessary vigorousness to track the time-varying input carrier. Such a trade-off becomes the critical point and the main limitation of robust carrier tracking, since both noise rejection (or equivalently, recovery of the lost signal power) and agile carrier tracking must be appropriately balanced to avoid penalizing the performance criteria of the specific application under analysis. Different approaches are being proposed to circumvent this limitation, although most of them, are to some extent more or less complex variations of traditional receivers.

In this sense, a fresh look into the problem of robust carrier tracking is needed, trying to go beyond the limitations of conventional architectures and focusing on the use of advanced and innovative signal processing techniques. This is indeed the motivation of the present survey, where an exhaustive review is provided on the different approaches that may be envisaged in order to cope with the demands of emerging robust carrier tracking applications. This review provides a detailed overview of the current state-of-the-art and future research directions, in order to stimulate the interest and research onto this topic within the communications community.

To do so, this survey is structured as follows. The fundamentals of carrier tracking and a brief summary of the strategies beyond traditional architectures, is provided in Section II. As a first step to achieve robust carrier tracking, Section III discusses possible optimizations of traditional constant loop bandwidth architectures, while Section IV focuses on variable loop bandwidth techniques. Later on, in Section V, Kalman filter-based techniques are presented as a more rigorous approach for implementing variable bandwidth carrier tracking. Innovative proposals for robust carrier tracking are discussed in Section VI, and potential open-loop techniques are introduced in Section VII. Finally, a qualitative comparison of all techniques is presented in Section VIII and conclusions are drawn in Section IX.

II. Fundamentals of Traditional Carrier Tracking and Strategies Beyond

A. Carrier tracking signal model

The purpose of carrier tracking is to precisely synchronize the receiver local oscillator so as to minimize the residual phase errors between the incoming carrier and the local replica. For systems operating in continuous-mode, synchronization is typically carried out following a two-steps approach: first, a coarse estimate of the synchronization parameters is obtained (i.e. the so-called *acquisition* stage); second, these estimates are further refined in order to filter-out noise and track any possible time-variation (i.e. the so-called *tracking* stage). Assuming that time-delay and coarse carrier errors have already been compensated at the acquisition stage, the discrete-time complex baseband signal for carrier tracking can be described, at time k, by the following model[1]:

$$y(k) = a(k)e^{j\theta(k)} + \eta(k) \tag{1}$$

where $a(k)$ is the envelope of the received signal affected by attenuation and time-varying fading, $\theta(k)$ is the time-varying carrier phase to be tracked and $\eta(k)$ encompasses the effects of thermal noise and residual disturbances. Note that the signal model in (1) is rather general, being valid for the matched filter output of any linearly modulated signal. Based on this signal model, the problem under consideration is that of tracking the residual carrier variations $\theta(k)$, in order to keep the local oscillator synchronized with the input signal. These variations are mainly caused by the mismatch between transmit and receive oscillators, but also because of the Doppler effect due to the relative movement between transmitter and receiver, propagation effects such as scintillation, and even random disturbances (i.e. phase noise) due to the local oscillator instabilities.

B. Architecture of traditional carrier tracking techniques

The fundamentals of traditional carrier tracking architectures were established in the 70's, and they are currently very well-known thanks to the widespread use of PLLs in communications and navigation receivers. In order to track the time-variations of $\theta(k)$ in (1), a traditional PLL is composed of three basic constituent blocks [8]: a phase detector, which is

[1] Alternatively, and without loss of generality, the equivalent continuous-time, real-valued and bandpass signal model could also be used. That is, the signal model where the carrier is typically represented by $\cos(\omega_0 t + \theta(t))$, with ω_0 the carrier frequency.

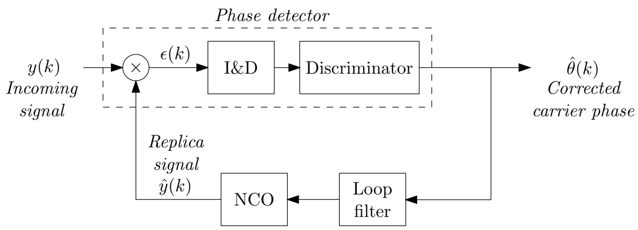

Fig. 1. Architecture of a traditional PLL with its basic constituent blocks.

in charge of providing output measurements that, on average, are proportional to the carrier error to be compensated; a loop filter, which is nothing but a very narrow low-pass filter that smoothes the variability caused by thermal noise at the phase detector output; and finally, a numerically-controlled oscillator (NCO), in digital implementations, or a voltage-controlled oscillator (VCO), in analog ones, for generating the local carrier replica based on the corrections imposed by the loop filter output.

An schematic representation of this basic PLL is depicted in Fig. 1, where the closed-loop architecture inherent to any tracking scheme can be clearly observed. In this figure, the phase detector is further decomposed into its constituent blocks. First, a correlator plus an integer-and-dump (I&D) accumulator, whose goal is to compute the inner product between the received signal and the local signal replica. Second, a discriminator, which provides an output signal that is proportional to the error incurred by the local replica. Finally, the error signal at the discriminator output is smoothed by the loop filter, and the result is fed back to the NCO for generating an updated signal replica, thus closing the loop.

C. Strategies beyond traditional carrier tracking

The traditional carrier tracking architecture introduced in Section II-B is unable to fulfill the stringent requirements imposed by robust carrier tracking applications. The main reason is that the capabilities of this architecture to filter out noise and to track high dynamics, are at odds one with each other. Both requirements are tightly coupled in traditional architectures, and thus, it is very difficult to provide solutions to problems that are demanding in one of these two directions (i.e. noise rejection or agile tracking) without incurring in a dramatic degradation in the other one. For instance, designs focusing on high-dynamics are prone to suffer from severe jitter in their carrier phase estimates, as well as frequent cycle slips, which introduce discontinuities of several cycles into the estimated carrier phase. On the opposite side, designs focusing on noise rejection are able to minimize the output phase jitter, but at the expense of suffering from dynamic stress errors (i.e. when the tracking loop is unable to follow the higher order of the input dynamics). In these circumstances, the ultimate consequence may be the loss of lock of the tracking loop, assuming that the receiver was already locked, or the impossibility to lock in, assuming that the receiver is first switched on.

In order to circumvent these limitations, four main approaches or strategies are being proposed for providing carrier tracking with the necessary flexibility that emerging applications demand. From the most simple and conservative, to the most complex and innovative one, the following approaches can be distinguished for closed-loop robust carrier tracking:

1) *Optimization of constant bandwidth carrier tracking techniques*. It involves an incremental step with respect to traditional schemes, by means of introducing minor modifications to the architecture in Fig. 1, while keeping the loop bandwidth constant. This approach will be discussed in Section III.
2) *Variable bandwidth standard carrier tracking techniques.* Since one of the challenges of robust carrier tracking is to cope with time-varying working conditions, this approach focuses on the use of adaptive filtering techniques, in which a set of relevant signal parameters is monitored and the loop filter bandwidth is adjusted accordingly. This approach will be introduced in Section IV.
3) *Kalman filter-based carrier tracking techniques*. While techniques in the previous approach are able to provide flexible carrier tracking, concerns are often raised regarding the optimality on the way the loop bandwidth is adjusted, and the ability to follow complex dynamics. It is at this point where Kalman filter-based schemes are typically preferred, due to their systematic and optimal approach for estimating time-varying parameters. These schemes will be presented in Section V.
4) *Innovative carrier tracking techniques*. The nonlinear nature or the non-Gaussianity of some propagation effects often poses significant obstacles to the derivation of accurate and feasible dynamic models. In the absence of such reliable models, the optimality of Kalman filters is no longer valid and their benefits in terms of carrier tracking robustness vanish. In this case, innovative techniques are being proposed by re-engineering the problem of carrier tracking and applying advanced signal processing tools from the fields of particle filtering, interactive models or compressive sensing, just to mention a few. A discussion on the use of innovative techniques will be provided in Section VI.

It is interesting to note that the above-mentioned approaches are strongly influenced by the traditional closed-loop implementation of tracking techniques. This implementation is the natural choice, since closed-loop architectures are tightly related to adaptive systems and control theory, and tracking is nothing but controlling a given magnitude of interest. Nevertheless, and in the seek of a much wider view of the problem, some contributions are being proposed for the potential implementation of robust carrier tracking by means of open-loop architectures, which stands for the fifth category of techniques to be reviewed in this survey:

5) *Open-loop carrier tracking techniques.* The loss of lock of closed-loop techniques under severe stress and abnormal working conditions, motivates the proposal of open-loop techniques for conducting robust carrier tracking. Open-loop schemes are widely adopted in burst-mode communications receivers, and they rely on a feedforward estimation of the signal parameters by

processing at a time, a batch of input signal samples. The application of these techniques to robust carrier tracking will be explored in Section VII.

The five approaches introduced above cover the full spectrum of techniques currently considered for robust carrier tracking applications. A summary of these techniques is shown in Table I, which serves as an outline of the present survey.

III. Optimization of Constant Bandwidth Carrier Tracking Techniques

This approach for robust carrier tracking involves an incremental step with respect to traditional techniques, in the sense that some minor modifications and optimizations are introduced while keeping the loop bandwidth constant. These adjustments are typically carried out at three different levels of the traditional PLL architecture depicted in Fig. 1:

- At the integration stage within the phase detector, by extending the overall correlation interval in order to combat the severe attenuation due to fading effects (either terrestrial-based, caused by signal blockage, or atmospheric-based caused by scintillation). Since this modification implies a rate reduction at the discriminator output, the loop filter has to be adjusted accordingly to reflect the apparently higher input dynamics.
- At the discriminator stage, by choosing the proper phase discriminator to be used for each specific application. This can be either nonlinear or linear, coherent or non-coherent, or we can even consider the adoption of frequency discriminators in order to alleviate some of the stress of phase discriminators in the presence of high user dynamics.
- At the loop filter, by increasing the order of the filter with the aim of capturing the presence of higher-order dynamics in the time-varying carrier evolution.

In all these three categories of possible adjustments, the carrier tracking loop bandwidth is kept constant during the whole operation. Therefore, these approaches are also referred to as constant bandwidth PLL (CB-PLL) techniques. In the following subsections, we will describe in more detail these optimization approches and we will provide specific examples from the current literature.

A. Optimization of the phase detector integration stage

In most standard applications, the matched filter output is directly fed to the phase discriminator in order to obtain the error signal that is needed for tracking. However, when fading occurs, the matched filter output becomes too noisy and there is a risk of causing the discriminator to enter its saturation region or to abandon its pull-in range [11]. This would introduce some bias at the tracking loop and would lead to a possible loss of lock. In order to circumvent this situation, it is customary to perform an extended accumulation of the matched filter or correlator output samples before they are fed to the discriminator. Such an accumulation is often referred to as a pre-detection integration (PDI), and it helps the receiver to further increase the signal-to-noise ratio (SNR) at the discriminator output [8], [9], [11]

The number of samples to be accumulated, K, must be mainly determined on the basis of the maximum residual carrier frequency that the loop may experience. This is a function of the residual carrier frequency error left by the coarse frequency estimate at the acquisition stage, and also a function of the user dynamics. Moreover, it has to be taken into account that the pre-detection integration is a block whose output rate is K samples lower than its input rate. As a result, the subsequent tracking blocks, and in particular, the loop filter, will have to cope with an apparent phase dynamic evolution that is K times faster than the one actually being experienced by the received signal. This implies that some adjustments are also required at the loop filter to avoid losing track and to improve the loop filter stability [28].

B. Optimization of the phase discriminator

The type of discriminator has a direct impact onto the tracking performance, especially when data-modulation or propagation impairments are present. Regarding the latter, we should highlight the case of *canonical* fading, a special type of severe fading accompanied by abrupt phase changes, which often occurs in satellite links as a result of ionospheric scintillation [21]. Even though canonical fading can be compensated by increasing the pre-detection integration length, abrupt phase changes may produce a slip of one or several phase cycles, resulting in the well-known phenomenon of *cycle slips*, which may lead to a loss of lock [29]. In these circumstances, certain types of discriminators may reduce the sensitivity to large phase deviations, thus ameliorating the tough working conditions that tracking loops must cope with. This example illustrates the interest in selecting the most appropriate discriminator depending on the specific working conditions. The following classification can help in this selection process:

- *Coherent vs. non-coherent phase discriminators.* A typical classification of PLL discriminators is based on whether the discriminator is sensitive or not to the presence of data modulating bits. The former are known as *coherent* PLL discriminators, and they assume that no data bits are present in the input signal. Assuming an additive white Gaussian noise channel, this means that $a(k) = 1$ in (1). In that case, the variance exhibited by estimates of $\theta(k)$ at the output of the four-quadrant arctangent coherent PLL (i.e. see Table II) can be approximated by [13, p. 131],

$$\sigma^2_{\theta,\mathrm{coh}} = B_n \left(\frac{C}{N_0}\right)^{-1}, \tag{2}$$

where B_n is the equivalent loop bandwidth and C/N_0 is the carrier-to-noise spectral density ratio. Nevertheless, modulated data symbols are present in communications signals, and thus countermeasures must be adopted in order to prevent abrupt phase changes due to symbol transitions (e.g. when $a(k) = \{-1, +1\}$, as in binary phase shift keying modulations). The most common approach is to use a so-called *non-coherent* or Costas discriminator, which is a discriminator that becomes insensitive to the presence of data modulation. This is done either by introducing some squaring or cross-product with the

TABLE I
SUMMARY OF TECHNIQUES FOR ROBUST CARRIER TRACKING ADDRESSED IN THIS SURVEY.

Optimization of constant bandwidth (CB) techniques		(Section III)
◇ Optimization of the phase detector integration stage		
◇ Selection of phase discriminators		
– Coherent (Coh) vs. noncoherent (NC)	– Frequency- vs. phase-based	
– Nonlinear (NL) vs. cross-product (xP)	– Frequency-assisted vs. stand-alone	
◇ Optimization of the loop filter		
Variable bandwidth standard carrier tracking techniques		(Section IV)
◇ Fast adaptive bandwidth PLL (FAB-PLL)	◇ Fuzzy logic PLL (FL-PLL)	
◇ Projected loop bandwidth PLL (PLB-PLL)	◇ Wavelet denoising PLL (WD-PLL)	
Kalman filter-based carrier tracking techniques		(Section V)
◇ Linear Kalman filter (KF)	◇ Adaptive variable Kalman filter (AKF)	
◇ Extended Kalman filter (EKF)	◇ Variable gain adaptive Kalman filter (VG-AKF)	
◇ Unscented Kalman filter (UKF)	◇ Multi-lag FLL-based Kalman filter (MFLL-KF)	
◇ Cubature Kalman filter (CKF)	◇ Levenberg-Marquardt (LM)-based tracking	
◇ Quadrature Kalman filter (QKF)		
Innovative carrier tracking techniques		(Section VI)
◇ Particle filtering (PF)	◇ Adaptive linear prediction	
◇ Interactive multiple model (IMM)	◇ Compressive-sensing	
◇ Per-survisor processing (PSP)		
Open-loop techniques		(Section VII)
◇ Snapshot/batch-processing implementations	◇ Maximum likelihood estimator (MLE)	
◇ Quasi-open loop architectures	◇ Frequency estimators (e.g. Fitz, Kay, L&R)	

TABLE II
SUMMARY OF TYPICAL CARRIER PHASE DISCRIMINATORS.

Type of discriminator	Discriminator output (e_k)
Coherent	
Q-normalized	$Q_k/\text{mean}\left(\sqrt{I_k^2+Q_k^2}\right)$
Four-quadrant arctangent	$\text{atan2}\left(Q_k, I_k\right)$
Non-coherent or Costas	
Conventional	$Q_k \cdot I_k$
Decision directed	$Q_k \cdot \text{sign}\left(I_k\right)$
Two-quadrant arctangent	$\text{atan}\left(Q_k/I_k\right)$
Decision directed four-quadrant arctangent	$\text{atan2}\left(Q_k\text{sign}(I_k), I_k\text{sign}(I_k)\right)$

in-phase (I_k) and quadrature (Q_k) components of the correlator output. Unfortunately, such a robust behavior in front of data modulation comes at the expense of a performance degradation. Indeed, for a conventional Costas PLL discriminator (i.e. see Table II) with a pre-detection bandwidth of $1/T_i$, the variance of the output phase error can be approximated by [30],

$$\sigma^2_{\theta,\text{ncoh}} = \sigma^2_{\theta,\text{coh}} \left(1 + \frac{1}{2T_i}\left(\frac{C}{N_0}\right)^{-1}\right). \qquad (3)$$

As can be seen, a penalty term is incurred in (3) with respect to the output performance of a coherent PLL discriminator in (2). This penalty, which is caused by the narrower dynamic range of non-coherent discriminators compared to coherent ones, may introduce a degradation of up to 6 dB in terms of tracking threshold [31, Sec. 5.3.1], thus compromising the receiver phase lock when signal fading is experienced. In order to circumvent this limitation, the current data bit could be inferred and then removed from the tracked signal [31, Sec. 5.3.1], [32]. This approach is known as decision directed (DD) tracking, but it only gets close to the ideal coherent performance when the decision-error probability is relatively low (i.e. when operating at moderate to high C/N_0).

Table II shows a list of common coherent and non-coherent PLL discriminators [31, Sec. 5.3.1].

- *Nonlinear vs. cross-product phase discriminators.* Depending on the type of processing carried out with the in-phase and quadrature components of the correlator output, we can distinguish between those phase discriminators relying on the use of nonlinear functions (e.g. arctangent-based discriminators in Table II), and those relying on cross-products (e.g. the conventional Costas discriminator in Table II). The performance analyses reported for instance in [21], [26], [33], conclude that nonlinear discriminators are prone to suffer from a significant degradation in the presence of fading, due to the noise amplification effect caused by the arctangent operation. In these circumstances, cross-product discriminators are found to offer more robust performance.

  The results of these performance analyses have been extended later on to the case of fading accompanied by abrupt phase changes (as it occurs in ionospheric scintillation with canonical fades, for instance), since most previous studies typically focused on fading only, thus ignoring the effects on the carrier phase. When both effects are taken into account, the results in [21] show a reversed trend, in the sense that nonlinear discriminators provide a more robust performance in terms of mean time

TABLE III
SUMMARY OF TYPICAL CARRIER FREQUENCY DISCRIMINATORS.

Type of discriminator	Discriminator output (e_k)
Crossed	c_k
Decision directed crossed	$c_k d_k$
Four-quadrant arctangent	$\text{atan2}\,(d_k, c_k)$
where $c_k \doteq Q_k I_{k-1} + I_k Q_{k-1}$, $d_k \doteq I_k I_{k-1} + Q_k Q_{k-1}$	

between cycle slips than that exhibited by cross-product discriminators. Interestingly, these results provide some hints on how to proceed for the investigation of novel nonlinear functions that may be suitable for combating propagation effects including both fading and abrupt phase changes.

- *Frequency vs. phase discriminators.* Carrier tracking under both severe fading and high dynamics is a technical challenge because the potential techniques to combat each of these two effects are at odds with each other. On the one hand, combating fades involves increasing the pre-detection integration length, which leads to a very narrow loop bandwidth. But on the other hand, high dynamics require the loop bandwidth to be wide enough so that the tracking stage is able to keep up with the variability of the input phase samples. This contradictory situation can be circumvented by performing tracking, not on the input phase samples, but on the input residual carrier frequency. These techniques are referred to as frequency-lock loops (FLL) or automatic frequency control (AFC) [34], and they share the same architecture as a PLL except for the type of discriminator being used [35]. In Table III, a list of common FLL discriminators is shown [31, Sec. 5.3.3].

  Interestingly, at usual RF frequencies and propagation conditions, changes in carrier frequency errors are orders of magnitude lower than changes in residual phase errors, thus allowing FLL techniques to further extend the pre-detection integration length without risk of incurring in phase wrapping within the integration interval. This provides a more robust performance in front of fading and high users dynamics than traditional PLL-based architectures [36], [37]. Moreover, it has to be taken into account that, since the ultimate magnitude to be tracked is often the input phase and not the frequency (because the local sinusoidal replicas are generated in the basis of phase samples), an additional mechanism must be implemented in order to obtain a reconstruction of the actual phase by means of accumulating the frequency corrections provided by the FLL, and to solve possible phase ambiguities. Such accumulation typically leads to a noise amplification on the reconstructed phase, an additional degradation to the inherent high noise level of FLL discriminators, which results from the cross-products of input noisy samples. This overall noise amplification may be one of the reasons why FLL-based architectures are sometimes discarded despite of their advantage over PLL-based schemes in terms of dynamic tolerance.

- *Frequency-assisted vs. standalone phase discriminators.* Instead of directly using an FLL discriminator in substitution of a PLL one, both discriminators can be jointly adopted. In this way, the FLL is in charge of tracking and coarsely removing the input carrier dynamics, and the PLL can operate with much less dynamic stress (i.e. with a narrower loop filter bandwidth). This cooperative strategy can be implemented in either a parallel or a sequential manner. In the former, both FLL and PLL operate simultaneously, and the FLL actually assists the PLL in reducing its dynamic stress. This approach is known as FLL-assisted-PLL [35], [38] or dynamic-reduced PLL (DR-PLL) [39], whose architecture is illustrated in Fig. 2.

  Alternatively, a Kalman filter can be used instead of the FLL for providing the frequency assistance, as proposed in [40]. In the sequential case, the FLL and PLL operate in an alternated manner [41]. That is, in normal operation, a PLL is used to track the input signal. However, when the signal power suddenly drops, the receiver switches to an FLL in order to increase the PDI and keep track of the input frequency while avoiding loss of lock. When the power raises to medium or high levels, the receiver switches back to the PLL operation and turns off the FLL. Finally, frequency assistance can also be used to implement a new and more robust phase discriminator. This is the approach proposed in [42] leading to the so-called Unambiguous Frequency-Aided (UFA) phase discriminators, which can be understood as a modified arctangent function with an extended output range [43].

C. Optimization of the loop filter

The remaining element to be potentially optimized is the loop filter. Two main features can be adjusted, namely, the filter order and the corresponding coefficients. Regarding the former, the order of the filter determines its capability to track input phase dynamics. Many receivers use first-order loop filters, which allow tracking of input phase values affected by constant frequency offsets. More advanced receivers typically implement second-order loop filters to track frequency drifts. Higher-order filters have also been reported to facilitate carrier tracking with abrupt phase changes, and thus they are potential candidates to be incorporated in robust carrier tracking architectures affected by high dynamics [44].

Once the order of the loop filter has been set, the optimal coefficients directly follow by using the standard results in [31, Sec. 5.5], [45, Ch. 8], which have been derived using Wiener filtering theory for the case of small phase error and additive white Gaussian noise [46]. For the case of digital implementations, the coefficients are typically derived from the discrete-time approximation of continuous-time designs [47]. This is done by assuming that the product $B_n T_i$, between the equivalent loop bandwidth B_n and the pre-detection integration time T_i, is close to zero. Such assumption, however, enters into conflict with robust tracking architectures where the PDI time T_i has been extended to cope with fading. In this case, the increase of the product $B_n T_i$ causes a loop instability that may lead to loss of lock. In order to avoid this problem, an optimization of the discrete-time loop filter coefficients is

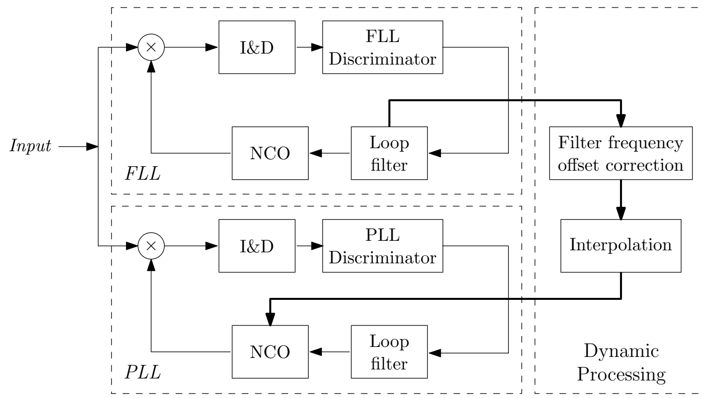

Fig. 2. Architecture of a dynamic-reduced PLL (DR-PLL) where an FLL-assisted approach is adopted in order to provide robust carrier tracking at the PLL [39].

proposed in [48], [49]. The analysis takes into account that the NCO does not need to perform and instantaneous update, but it can make a gradual correction during the PDI interval. As a result, the product B_nT_i initially limited to 0.4 in third-order loops can be made greater than 3 while preserving the loop convergence.

Finally, and despite the wide range of different optimizations being proposed in this Section, it should be remarked that all of them lead to constant bandwidth loop filters, which assume that the working conditions remain stationary. This is not typically the scenario found in robust carrier tracking applications, thus confirming once again the unsuitability of traditional architectures for robust carrier tracking applications. In that sense, the bulk of current research efforts is being directed towards the development of variable bandwidth carrier tracking architectures, which better suit the challenges imposed by robust carrier tracking, and whose details will be introduced next in Section IV.

IV. Variable Bandwidth Standard Carrier Tracking Techniques

One of the main limitations of traditional carrier tracking architectures is the constant bandwidth of their tracking loops, which is in contrast with the time-varying nature of the input working conditions. In practice, a trade-off must be established. That is, either implementing a narrow bandwidth loop filter to accurately track the input phase and reject as much noise as possible, or a wide bandwidth loop filter in order to track the fast phase variations caused by high dynamics. Intuition suggests that a variable loop bandwidth should be adopted instead, in order to adapt the tracking bandwidth to the actual conditions. In this Section, we will review the most important contributions and we will shed some light on the advantages and disadvantages of variable bandwidth architectures.

A. Fast adaptive bandwidth PLL (FAB-PLL)

An alternative approach to the dynamic reduction PLL (DR-PLL) depicted in Fig. 2 is to automatically adjust the loop bandwidth according to the actual working conditions, as schematically shown in the block diagram of Fig. 3. Following this approach, the contributions in [50] and [51]

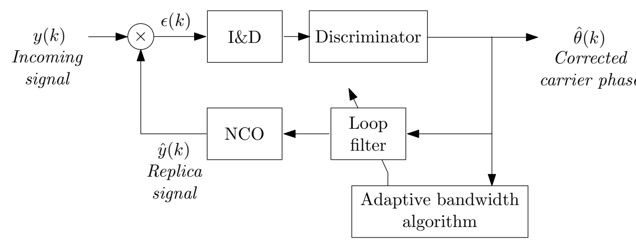

Fig. 3. Architecture of a fast-adaptive bandwidth PLL (FAB-PLL).

propose the adoption of the so-called fast adaptive bandwidth PLL (FAB-PLL), where the phase errors at the discriminator output are compared to a pre-defined threshold. Based on this comparison, on the estimate of the actual received power, and also using an accurate model to account for the impact of thermal noise, phase noise and dynamic stress, the system is able to automatically calculate the optimal loop bandwidth for the actual conditions. In experiments with severe fading and abrupt phase changes, FAB-PLL architectures are able to move from an initial loop bandwidth of 15 Hz, to less than 5 Hz, providing a 5 dB increase in SNR compared to traditional PLL architectures with a fixed 10 Hz loop bandwidth [51].

B. Projected loop bandwidth PLL (PLB-PLL)

One of the disadvantages of adaptive bandwidth PLL tracking techniques is that they need to permanently estimate some of the input signal parameters, and then use this information as part of an adaptive algorithm that ultimately determines the loop bandwidth to be used at that time. As a result, the overall computational burden can be quite high. In order to avoid this problem, a low-complexity variation was proposed in [52] while still providing fairly the same performance as truly adaptive techniques. The proposed method, which is known as projected loop bandwidth PLL (PLB-PLL), relies on three key facts: first, it only requires rough C/N_0 estimates of the input signal; second, it avoids the need to estimate user dynamics; third, instead of using a costly adaptive algorithm, it simply uses a simple look-up table (LUT), as illustrated in Fig. 4. The values stored in this LUT are the specific loop bandwidths that should be used at each particular time according to the input C/N_0 and some pre-defined user dynamics. Interestingly,

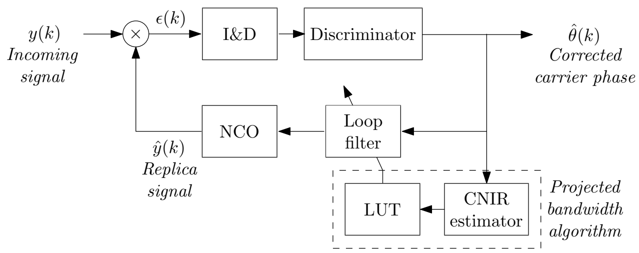

Fig. 4. Architecture of a projected loop bandwidth PLL (PLB-PLL).

these bandwidths are pre-computed offline, and this avoids the complexity of implementing an online adaptive algorithm. For the user dynamics, a specific value is chosen so that it becomes representative of the whole dynamic stress range (e.g. jerk dynamic stress ranging from 0.1 g/s to 1 g/s [52]), and for the C/N_0, the whole range of possible values is mapped onto just a finite set (e.g. low, medium and high). Because of this discretized mapping, a slight performance degradation is unavoidably incurred in practice. Nevertheless, by properly designing this mapping, the effect of such mismatch is found to be very small, thus confirming the validity of this projected approach.

C. Fuzzy logic PLL (FL-PLL)

Fuzzy logic has been proposed as a possible way to provide intelligence to the loops and to improve their robustness. The main idea is to use the fuzzy logic automatic control in order to adapt the loop bandwidth to the actual receiver conditions. Contributions on the use of fuzzy logic to carrier tracking can be found in [53], where a so-called fuzzy loop filter is proposed. In this case, however, the tracking model needs an a-priori known trajectory for the fuzzy PLL to be trained, and thus it poses some practical difficulties to its applicability in real conditions. This limitation has been overcome in [54] and [55], where the authors present an intelligent carrier loop able to track dynamic variations. The algorithm, which outperforms the conventional PLL, uses both a phase discriminator and a frequency discriminator as inputs for the fuzzy logic controller (FLC), as shown in Fig. 5.

D. Wavelet denoising techniques

The use of the wavelet transform has been shown in [56] to be a useful tool for reducing the noise fed to the loop filter. Since the noise is mitigated, the loop filter can concentrate on tracking the input dynamics with a wide loop bandwidth, without suffering from an increased phase error jitter due to thermal noise. The so-called wavelet denoising (WD) technique involves a two-step approach. First, the input signal is decomposed using an octave-band filterbank implementing a wavelet transform. Second, the wavelet coefficients are compared to a threshold in order to retain just the most significant ones, thus performing a kind of rank-reduction approach to suppress noisy wavelet dimensions. With the subset of selected wavelet coefficients, the denoised signal is reconstructed and fed to the loop filter, as shown in Fig. 6. Note that because of the rank-reduction carried out during the denoising process, there is the risk of incurring in an excessive removal of wavelet components, which may result in some bias onto the reconstructed signal thus increasing the PLL lock-in time.

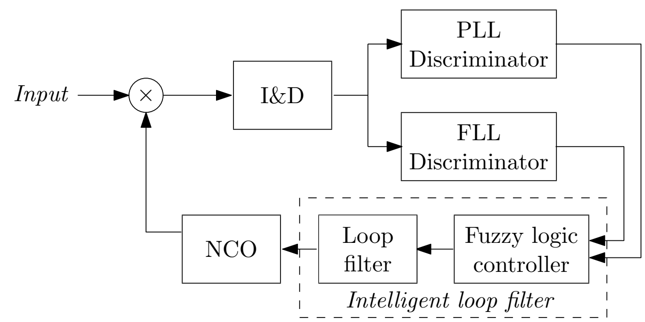

Fig. 5. Architecture of a fuzzy-logic PLL.

V. Kalman Filter-Based Carrier Tracking Techniques

The capability of dynamically adjusting the loop bandwidth is definitely the answer for the provision of robust carrier tracking in practical working conditions. In that sense, the techniques already introduced in Section IV constitute a first step towards this goal, since variable loop bandwidths are implemented but in a somehow heuristic manner. The question that remains to be answered is whether an optimal bandwidth adaptation does exist. The answer can be found by noticing that traditional carrier tracking loops are nothing but a particular case of Kalman filters, in which the filtering coefficients are all set to be constant [57], [58]. Interestingly, Kalman filters provide a much more general framework for the optimal estimation of signal parameters, which evolve according to a given dynamical model. As a result, Kalman filters are able to provide, in a natural way, a closed-loop architecture where the filtering coefficients are automatically adjusted so as to minimize the mean square error between the input signal (i.e. the observation) and the local replica (i.e. the prediction), under the assumption of additive white Gaussian noise [59].

This adaptive behavior is achieved by the Kalman filter through the use of state-space dynamical models for predicting and correcting the estimated parameters. Moreover, and unlike traditional tracking techniques, the estimates are updated taking into account the actual measurement noise and the accuracy of the model being assumed. Regarding the latter, the Kalman filter is able to keep on with the estimation process even when the actual dynamics do not coincide exactly with the ones initially assumed in the model. Such tolerance is indeed one of the most valuable features being sought by robust techniques, and it is actually provided by Kalman filters in a natural manner. The systematic combination of optimality and robustness is certainly the reason why Kalman filter architectures are widely being proposed for robust carrier tracking in the existing literature [60]–[66].

In this section, we will introduce first the fundamentals of linear Kalman filtering, which is the simplest and probably the mostly adopted Kalman filter implementation in practice. The purpose is not to thoroughly elaborate on the Kalman filter, but just to provide a minimum background to understand

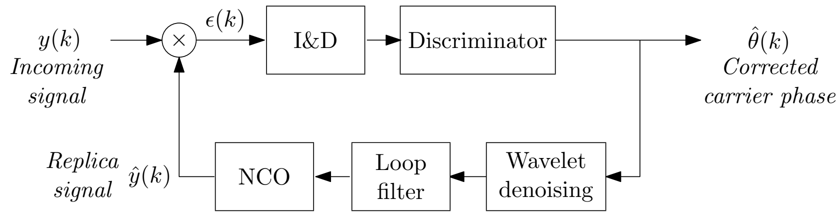

Fig. 6. Architecture of a wavelet denoising PLL (WD-PLL) for robust carrier tracking.

the use of Kalman filtering in the literature of robust carrier tracking. Later on, we will consider nonlinear Kalman filter implementations by focusing on the Extended Kalman filter (EKF) and also some recent proposals based on sigma-point implementations, such as the Unscented Kalman filter (UKF), the Cubature Kalman filter (CKF) or the Quadrature Kalman filter (QKF). Note that these nonlinear implementations are of interest in robust carrier tracking applications, in order to cope with the presence of nonlinear effects such abrupt phase changes or signal outages, which are typically caused by abnormal propagation events.

A. Fundamentals of linear Kalman filtering

As already highlighted in the seminal work by Kalman in [67], the fundamental concept to describe the time-varying evolution of a dynamic system is the notion of *state*, which can be understood as the minimum amount of data that is required to know about the past and the future behavior of the system. The values that form such amount of data are typically stacked in the form of a $(N \times 1)$ vector, referred herein to as the Kalman state vector, and denoted in discrete-time notation by $\mathbf{x}_k$, at time-instant k. Based on this state vector $\mathbf{x}_k$, the dynamics of the system under study can be described by the so-called *transition* equation shown in (4), which specifies how the state vector evolves with time.

$$\mathbf{x}_k = \mathbf{F}\mathbf{x}_{k-1} + \mathbf{G}\mathbf{v}_{k-1} \tag{4}$$

For the linear Kalman filter, a linear time-varying evolution is considered through the so-called *transition* matrix $\mathbf{F}$. Note that for the case of carrier tracking, such a linear behavior is consistent with the fact that the carrier phase (i.e. the magnitude of interest) evolves linearly with respect to its first and second derivatives (i.e. the carrier frequency and the carrier drift, respectively), which are typically contained within the same Kalman state vector. Finally, in order to account for the effect of higher-order terms that may have been ignored in the model, a colored noise term is added to (4) by projecting a zero-mean white Gaussian noise vector $\mathbf{v}_{k-1} \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}_{k-1})$ through the so-called process noise matrix $\mathbf{G}$.

So far, the focus has been placed on the Kalman state vector $\mathbf{x}_k$, which is indeed an internal variable of the system being modeled. A link must now be establish with the outer part of the system, which involves the set of K measurements that we observe at its output and that will actually be processed by the Kalman filter. Stacking these measurements at time instant k into the $(K \times 1)$ vector $\mathbf{z}_k$, such a link is provided by the so-called *measurement* equation, which for the linear Kalman filter becomes:

$$\mathbf{z}_k = \mathbf{H}^H\mathbf{x}_k + \mathbf{w}_k \tag{5}$$

where $\mathbf{H}$ is the so-called *measurement* matrix, and $\mathbf{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R}_k)$ the measurement noise. Based on the linear models introduced in (4)-(5), the linear Kalman filter operates following a three-step approach, whereby a prediction of the input measurement is implemented first, the resulting prediction error is used to update the Kalman state vector, and finally, the updated Kalman state vector is propagated forward in time in order to obtain the estimate of the Kalman state vector at time $k+1$, denoted by $\hat{\mathbf{x}}_{k+1}$. For simplicity, these filtering steps can be summarized into a single and compact equation as shown below:

$$\hat{\mathbf{x}}_{k+1} = \hat{\mathbf{x}}_{k+1|k} + \mathbf{K}_{k+1}\left(\mathbf{z}_{k+1} - \hat{\mathbf{z}}_{k+1}\right) \tag{6}$$

where $\hat{\mathbf{x}}_{k+1|k} \doteq \mathbf{F}\hat{\mathbf{x}}_k$ is the propagation of the estimated state vector from time sample k to $k+1$, and $\hat{\mathbf{z}}_{k+1} \doteq \mathbf{H}^H\hat{\mathbf{x}}_{k+1|k}$ is the prediction of the corresponding input measurement. The $(N \times K)$ matrix $\mathbf{K}_k$ is known as the Kalman gains matrix, and it contains the filtering coefficients that are required to optimally weight the error between the input measurement and the predicted one. Interestingly, the value of the Kalman gains $\mathbf{K}_k$ is time-varying, as indicated by the subindex $_k$, and gradually becomes smaller in order to reflect the learning process of the Kalman filter as the time goes on. If the model in (4) matches perfectly with the actual system dynamics (i.e. and thus, $\mathbf{G} = \mathbf{0}$), it can be verified that $\lim_{k\to\infty} \mathbf{K}_k = \mathbf{0}$. Otherwise, if some higher-order moments are missing in the model, then $\lim_{k\to\infty} \mathbf{K}_k = \mathbf{K}_\infty$ for some constant $\mathbf{K}_\infty \neq \mathbf{0}$, thus leaving the filter permanently vigilant in front of possible unexpected input signal variations. This sort of robustness is the one that we already mentioned as being a significant advantage of Kalman filters in front of traditional approaches.

The above description briefly summarizes the tasks to carried out by a linear Kalman filter. The details on how to calculate the Kalman gains, or how to statistically characterize the Kalman state vector are out of the scope of the present survey. The interested reader will find detailed information in Kalman's seminal work [67], in [59], [68], [69] where a rigorous mathematical study is provided, in [70] for a historical perspective, or in some other more general references such as [71, Ch. 13], [72]. However, it is interesting herein to elaborate a bit further on some implementation aspects, in order to understand some of the techniques that have recently been proposed for robust carrier tracking in the literature. An example is shown in Fig. 7, where the input measurements are the complex samples of the baseband received signal, and not carrier phase observables, as one would expect. Similarly, the Kalman predictions are samples of the complex local replica, which are generated by processing the Kalman state vector through a nonlinear function $h(\cdot)$. This nonlinear function would play the role of an NCO in traditional carrier tracking architectures.

The key point in Fig. 7 is that this configuration perfectly matches the architecture of traditional receivers, in which the received signal is correlated with a local replica and an error metric is obtained at the output of a carrier phase or carrier frequency discriminator. This discriminator output would now be the input to the Kalman filter, and since it represents an error in terms of carrier phase or carrier frequency magnitudes, it has a linear dependence with the carrier-based Kalman state vector, thus preserving the linear formulation of the Kalman filter despite the use of the nonlinear function $h(\cdot)$. This approach has received significant attention in the literature, particularly for its application to the robust carrier tracking of spread-spectrum signals, such as those in GNSS systems [66], [73]–[75]. In that sense, the architecture in Fig. 7 can be understood as a generalization of the techniques already proposed in Section III and IV, where an optimal variable loop bandwidth is introduced through the time-varying Kalman gains. Such optimality however, is only guaranteed for the case in which linear discriminators are used. When nonlinear discriminators are adopted (e.g. as when data-modulated bits are present) the Kalman input statistics are not Gaussian anymore, and optimality cannot be guaranteed. In spite of this, a near-optimal performance can still be achieved when operating in the medium- to high-SNR regime.

B. Extended Kalman filter

The extended Kalman filter (EKF) is a variant of Kalman filtering that allows the input measurements to be nonlinearly related to the state vector, and the dynamics of the latter to be nonlinear in nature. That would be case, for instance, when the complex received samples are directly provided to the Kalman filter, instead of using the discriminator output signal, as in Fig. 7. In general, the presence of nonlinearities can be expressed by the following model, which corresponds to the nonlinear extension of the transition and measurement equations already presented in (4)-(5):

$$\mathbf{x}_k = f(\mathbf{x}_{k-1}) + \mathbf{v}_{k-1} \quad (7)$$

$$\mathbf{z}_k = h(\mathbf{x}_{k-1}) + \mathbf{w}_{k-1} \quad (8)$$

where $f(\cdot)$ and $h(\cdot)$ are continuous and differentiable nonlinear functions. In order to circumvent the drawbacks of nonlinearities, these functions are linearized at each time instant k around the estimated value of the Kalman state vector $\mathbf{x}_k$. In particular, we can define the linearized and time-variant versions of the transition and measurement matrices as follows, $\mathbf{F}_k \doteq \{\nabla_{\mathbf{x}} f(\mathbf{x})\}_{|\mathbf{x}=\mathbf{x}_k}$ and $\mathbf{H}_k \doteq \{\nabla_{\mathbf{x}} h(\mathbf{x})\}_{|\mathbf{x}=\mathbf{x}_k}$, with $\nabla_{\mathbf{x}}$ the gradient with respect to the Kalman state variables. This has the advantage of allowing a linearized formulation similar to that in (4)-(5), at the expense of being a valid approximation within the neighborhood of $\mathbf{x}_k$, only. As a result, convergence of EKF implementations cannot always be guaranteed, particularly when abrupt changes do occur in the variables being tracked [76].

In spite of this limitation, EKF implementations have been widely adopted in the literature of carrier tracking. The reasons are mainly two-fold. On the one hand, the EKF is typically adopted as a way to cope with nonlinear effects in the dynamic model of the variables being tracked [77]–[80]. On the other hand, it is adopted as a way to operate directly on the received signal samples, and thus avoid the saturation, bias and noise enhancement that may occur with traditional discriminators or phase extractors when operating under severe noise conditions [81]–[83].

C. Unscented Kalman filter

The unscented Kalman filter (UKF) was originally proposed in [84] as a way to overcome the instabilities and divergence problems experienced by the EKF when mild nonlinear conditions do not hold anymore. In particular, the key point that differentiates the EKF and UKF implementations is the computation of the first- and second-order moments of the Kalman state vector, which are the two required moments for computing the Kalman gains and then implementing the filtering recursion. In the EKF, these moments are obtained by assuming that the current propagated Kalman state vector is approximately linearly related to the previous one. Thanks to this linear assumption, the first two moments of the propagated state vector can easily be computed from the moments already available for the past vector. Unfortunately, the relationship between both state vectors is often highly nonlinear, and thus, this linear approximation of the EKF poses many practical concerns. The main difference in the UKF is that the Kalman state propagation is the exact nonlinear one. Then, this nonlinear transformation is simultaneously applied to the current state vector and to a set of carefully selected neighboring vectors. These vectors, also known as *sigma points*, are such that their nonlinear transformation can be used to calculate the first- and second-order moments of the propagated Kalman state vector by just using linear manipulations [85]. In summary, a linear approximation is not applied to the nonlinear dynamic model, but instead, a specific set of points is chosen to facilitate the computation of first- and second-order moments of the propagated state vector, once the nonlinear transformation is applied to this set of points.

The UKF filter is a relatively new approach that is increasingly receiving attention from different disciplines. For the case of carrier tracking applications, some contributions have already been published for the joint carrier and channel tracking in mobile communications [86], for robust carrier tracking in high dynamics scenarios [87] or in the presence of severe noise [88].

D. Cubature and Quadrature Kalman filters

Similar to the UKF, the cubature Kalman filter (CKF) is another sigma-point approximate nonlinear Bayesian filter, but with the key feature of using a completely different set of points. The criterion adopted by the CKF for the sigma-points selection is based on the cubature rule, which is a numerical method for efficiently solving the problem of how

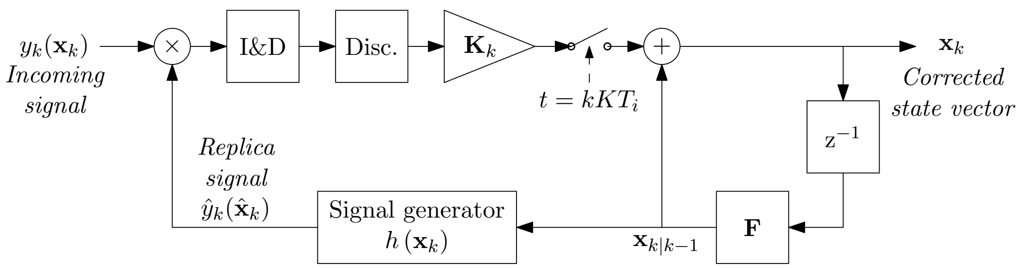

Fig. 7. Kalman filter-based architecture for robust carrier tracking [66].

to compute integrals whose integrands are all of the form of a nonlinear function multiplied by a Gaussian distribution [89], [90]. These integrals are indeed the ones required to compute the first- and second-order moments of the Kalman state vector, as discussed above, and therefore, they are of paramount importance for the Kalman filter implementation. Other numerical methods can be applied to solve these type of integrals, such as the Gauss-Hermite quadrature rule, which leads to the so-called quadrature Kalman filter (QKF) [91], and the square-root QKF (SQKF). Indeed, the latter propagates the square root of the Kalman state vector covariance matrix instead of the covariance itself, and is considered a robust implementation of the QKF in front of numerical inaccuracies and limited precision [92].

In summary, both the CKF and the QKF are sigma-point based implementations whose goal is not to approximate the nonlinear functions involved in the Kalman filtering process, but rather, to numerically approximate those integrals where a nonlinear function is multiplied by a Gaussian distribution. Although these numerical rules are well-known in the mathematical literature, little attention had been paid so far to their application on Kalman filtering, thus constituting an emerging field of research. Indeed, the potential application of these techniques to the case robust carrier tracking is currently one their most attractive future research lines.

E. Adaptive Kalman filtering

Adaptive Kalman filtering (AKF) is one of the approaches that have been proposed in order to counteract for the possible inaccuracies in the a-priori information initially provided to the Kalman filter. This mismatch may occur in certain time-varying conditions, which cause the dynamical and statistical models to change unexpectedly. Because of this mismatch, the Kalman filter deviates from its optimal performance. One of the most widely adopted countermeasures for this effect leads to the concept of AKF, in which an adaptive mechanism is implemented to permanently estimate the variance of the prediction error. This estimate is then used to correct both the noise covariance and the process noise matrices, thus keeping the Kalman filter aligned with the actual working conditions.

AKF implementations have been proposed in [93] for tracking carrier phase measurements in the context of vehicle navigation, where a significant improvement is observed with respect to conventional Kalman filters. In [94], a variation is proposed based on the concept of adaptive two-stage Kalman filter (ATKF), developed in the context of estimating the dynamic states of a linear system in the presence of an unknown bias [95]. The contribution in [94] is able to monitor sudden changes in the input Doppler, and then adapt the Kalman filter parameters in order to match the filter to the new scenario.

F. Variable gain adaptive Kalman filter

Within the very same context of adaptive Kalman filtering, the contribution in [96] focuses on two modifications that lead to the so-called variable gain adaptive Kalman filter (VG-AKF). The main idea is to provide additional robustness to Kalman filters by reducing the impact that large errors or outliers may have onto the overall estimation process. These errors typically occur when severe fading and abrupt phase changes do occur, introducing large and inconsistent deviations that may compromise the overall tracking convergence. This is indeed what happens in the presence of canonical fading caused by ionospheric scintillation, as already mentioned above. In that sense, the motivation in [96] is to provide an additional degree of robustness by introducing limiting or thresholding functions to the prediction errors, in a similar manner as it is done with influence functions in the field of robust statistics [97]. In order to determine when these functions need to be applied, the system permanently monitors the input SNR level and three regions of operation are defined. The first region lies above an upper threshold on the input SNR, and within this region, the Kalman filter operates in normal mode. The second region lies in-between an upper and a lower threshold, and within this region, a penalty function is applied to the prediction error to reflect its lower reliability. Finally, the third region lies below a lower threshold, and here the predictions are discarded to avoid propagating large deviations to the estimated variables. According to this approach, the overall effect is equivalent to modifying the actual Kalman gains almost instantaneously, in a faster and more determinant manner than the Kalman filter would do by itself if its noise covariance matrix was updated accordingly.

G. Multi-lag FLL-based Kalman filter

In Section III-B, we have already pointed out the advantages of FLL discriminators for robust carrier tracking in the presence of high dynamics. These advantages can further be extended to the field of Kalman filter-based tracking, where traditional phase discriminators can be substituted by frequency ones. This approach leads to the so-called *FLL-based* Kalman filter-based tracking, where the Kalman filter is in charge of tracking the phase and frequency of the input signal while taking as observations the output of a frequency discriminator. Since the observations are not phase but frequency measurements, the technique is able to track the carrier phase of the input signal except for some constant ambiguity (i.e. typically half-cycle, when data bits are present and the discriminator operates in noncoherent mode). The compensation of this ambiguity is left to the subsequent data demodulation stage, where bit polarity resolution has to be addressed anyway by making use of a parity check process or unique-word detection.

One of the traditional problems of FLL discriminators is the noise amplification exhibited at its output, as a consequence of the nonlinear operations that are required to obtain the frequency magnitude from the complex input samples (i.e. typically due to the conjugate product between two consecutive noisy complex samples). In order to circumvent this limitation, the contribution in [98] proposes the use of a so-called *multi-lag* FLL discriminator for providing the input measurements to a carrier tracking Kalman filter. This FLL discriminator is inspired on the structure of open-loop frequency estimators typically adopted in the field of digital communications, such as the Fitz or the Luise & Reggiannini (L&R) methods [99, pp. 88-89]. The key idea is to combine multiple correlation lags of the input signal with the aim of producing a single and more robust frequency estimate than traditional FLLs. In this way, traditional FLL discriminators can be understood as a particular case of multi-lag FLL discriminators, where just one correlation lag is considered. The resulting architecture, referred to as multi-lag FLL-based Kalman filter-based tracking, is found to clearly outperform traditional FLL-based tracking architectures, providing a robust behavior in harsh working conditions.

H. Levenberg-Marquardt (LM)-based tracking

The previous technique of multi-lag FLL-based tracking can be understood as a KF-based tracking where the traditional frequency discriminator has been replaced by an improved estimator of the carrier frequency. A similar but more complex approach is proposed in [100], where the carrier discriminator is replaced by a joint nonlinear estimation process that is solved via the Levenberg-Marquardt (LM) algorithm [101], [102]. The set of parameters that are jointly estimated are the carrier phase, carrier frequency, carrier amplitude and code phase error, the latter being of interest in spread-spectrum systems. The input to the LM algorithm is a bank of correlators that provides a bi-dimensional grid on the code phase and carrier frequency dimensions. The span of the bi-dimensional grid is such that it allows detecting any variation of the input signal dynamics within a specified uncertainty region. The estimates provided by the LM algorithm are later on fed to a Kalman filter that is in charge of extrapolating these estimates in time, and adjusting their value to the actual dynamical model. The output of the Kalman filter is used to implement the required tracking corrections, thus closing the loop. This technique has been applied to rising satellite limb scanning applications, with LEO satellites carrying a GPS receiver. No comparisons have been provided yet with existing advanced tracking techniques, so it remains to be assessed the actual convenience of this technique, taking into account the significant complexity of the LM algorithm.

VI. Innovative Carrier Tracking Techniques

Despite the advantages of Kalman filter-based techniques, the nonlinear nature of strong fading, abrupt phase changes and high user dynamics, often poses significant obstacles to the derivation of accurate and feasible dynamic models to be incorporated as a part of a Kalman filter. Moreover, in the presence of nonlinear effects, correlated measurements or non-Gaussian disturbances, the Kalman filter is no longer optimal and approximations must be adopted. This is the case of the well-known and widely adopted EKF, although the price to be paid for this approximation is the lack of a guaranteed convergence, in contrast to the linear Kalman filter. In these circumstances, it is therefore convenient to explore new ways that allow us to circumvent these limitations by implementing new and advanced signal processing techniques. Research efforts are currently being directed towards the exploitation of nonlinear filtering, iterative techniques or compressive sensing, just to mention a few. In the present section, we will present the most relevant of these new approaches, and we will discuss how they address the challenges imposed by robust carrier tracking.

A. Particle filter-based tracking

Particle filtering has become an important alternative to approximate Bayesian methods such as the EKF. The rationale behind particle filtering is to approximate continuous distributions by random measures, which are composed of the so-called *particles*. These particles are nothing else but sample values of the parameters to be estimated within the state-space, which are appropriately weighted according to probability masses computed by using Bayes theory [103]. The advantage of particle filtering over traditional Bayesian methods is that the approximation carried out does not involve any linearization of the dynamic model (i.e. as the EKF does) but rather, the continuous statistical distributions are approximated by discrete ones. As the number of samples becomes very large, this discrete-time approximation becomes a faithful representation of the continuous distribution, and the filtering process being conducted approaches the optimal Bayesian estimate.

Particle filters have recently been applied to the carrier tracking of OFDM signals [104], whose performance is very sensitive to carrier frequency mismatches, and in satellite links subject to impulsive noise [105]; applications are also found in robust carrier tracking for Global Navigation Satellite Systems (GNSS) signals in the presence of ionospheric scintillation, thus combating rapid phase changes and amplitude perturbations [106]. In this case, since ionospheric effects can be fairly modeled as a nonlinear distortion in the received signal, particle filters have been shown in [106] to clearly outperform existing methods. A detailed performance analysis of particle filters for carrier tracking is also provided in [107] for a wide range of different dynamic models.

B. Interactive Multiple Model (IMM) estimator

Another approach to cope with the drawbacks of traditional Kalman filters, particularly when the actual propagation or dynamic model is unknown, is to implement an Interactive Multiple Model (IMM) estimator. The IMM algorithm allows combining different Kalman-based filters, each of which is configured to a different propagation or dynamic model [108]. Based on this set of possible models, the algorithm adaptively determines some weights that represent the probability that, at a given instant, the current measurements are being generated by any linear combination of these models. When it comes to the implementation level, IMM methods can be built on the basis of several Kalman filters, each of them using a model that is accurately designed for a particular scenario (e.g. scenarios characterized by low dynamics and high C/N_0, or high dynamics and low C/N_0, or presence of fading and abrupt phase changes). In that case, once the IMM identifies the scenario that is active at the present time, it switches to the appropriate Kalman filter, which is in charge of providing the corresponding carrier estimates. Since the selected Kalman filter is specially designed for that scenario, it provides very accurate estimates in contrast to other estimation approaches in which just a single Kalman filter is adopted, and it is configured for the worst case scenario, even when this scenario has a low probability of occurring. As a consequence, the capability of this single filter to eliminate noise and track the carrier evolution is very limited, because it is most the time operating with inappropriate assumptions. In that sense, IMM algorithms provide a versatile and improved performance, while keeping a reduced complexity, and they have successfully been tested for carrier tracking in spread-spectrum ranging receivers [109], [110].

C. Per-survivor processing for joint carrier tracking and data detection

It is well-known that traditional carrier tracking techniques are unable to operate when extremely weak signals are being received. This situation may occur in the presence of signal blockage, but it is also found in communications systems where powerful error correcting codes are adopted. In that case, the problem of detecting the sequence of transmitted symbols is typically coupled with the problem of estimating or tracking the synchronization parameters. This is because data detection requires the receiver to be synchronized, but synchronization of extremely weak signals requires very long integration intervals, and this requires knowing the data bits in advance. Recovery of the data sequence involves searching along a trellis, which is typically implemented with the Viterbi algorithm. In per-survivor processing (PSP) techniques, each survivor data sequence in the trellis produces its own estimate of the synchronization parameters [111]. Therefore, in the case of carrier tracking, there would be as many PLLs as survivor paths in the trellis running in parallel. In this coupled way, if the correct data sequence is present among the survivors, one of the PLL will provide the best performance without experiencing the usual delays incurred in decoupled implementations [112].

The use of PSP techniques in the presence of carrier mismatches can be found for instance in [113], where the complex carrier samples are tracked, instead of just the carrier phase or frequency arguments. Joint data decoding and carrier tracking was also proposed in [114] for satellite link with time-varying channel conditions. PSP-based carrier tracking is also proposed in [115], where the UFA discriminator discussed in Section III-B is adopted.

D. Adaptive linear prediction-based tracking

Linear prediction can be defined as the signal processing problem whereby a linear combination of the past M received samples is used to predict the value of the actual received sample. To do so, linear prediction methods use a finite impulse response (FIR) filter to process the input samples, and the problem aims at finding the optimal filter coefficients so as to minimize the mean square prediction error [116]. As it can be observed, there is close parallelism between prediction and tracking, since both approaches aim at minimizing the error between the input signal and a generated local replica.

For the particular problem of carrier tracking, linear prediction methods have been used as a low-complexity and suboptimal alternative to optimal carrier estimation methods, which typically involve a nonlinear optimization process. This application of linear prediction has been known for several decades, but the practical application of these methods has been typically put aside in practice because of their bias and suboptimality, particular at high SNR conditions. Interestingly, their potential advantages with respect to traditional techniques do appear when operating in very low SNR and highly nonstationary conditions, there where their robustness and learning ability compensates their bias and suboptimality [117]. With just few contributions focusing on the application to carrier tracking [118], [119], linear prediction methods are currently receiving an increasing interest for their adoption in emerging applications with stringent requirements. This is the case of the contribution in [120], where adaptive linear prediction methods have been proposed for carrier tracking in space missions, which are subject to severe Doppler, time-varying attenuation and noise.

E. Compressive sensing PLL (CS-PLL) tracking

Compressive sensing is an emerging field in signal processing that enables the acquisition and recovery of sparse signals without loss of information, while sampling at a rate significantly below the Nyquist rate. To do so, compressed sensing uses a randomized measurement matrix to collect combinations of the input samples, and then typically recovers the signal by solving a convex optimization problem. Despite the significant computational burden that compressive sensing algorithms involve, low-complexity implementations are possible for the special case of carrier tracking, as shown in [121]. This work proposes a technique based on the observation that traditional PLL architectures can be modeled by using low-rate sampling blocks (e.g. the output of the I&D block in Fig. 1 has a significant lower rate that its input). Because of this parallelism, the theoretical framework of compressive sensing is well suited for the problem of carrier tracking.

Moreover, in the same manner as the goal of a PLL is to keep the local carrier tightly aligned with the input signal, the goal of a compressive sensing PLL is to keep the (lower rate) compressive samples of the local carrier tightly aligned with the (lower rate) compressive samples of the input signal. It should be remarked that even though low rate samples are being processed, the randomized measurement matrix is designed to fulfill the so-called restricted isometry property (RIP), which guarantees that the correlation between compressive samples is very close to the correlation between Nyquist rate samples [122]. Thus, operating on the low rate domain not only can save a significant computational burden, but it also preserves most of the optimality properties of algorithms operating on the Nyquist rate domain. Indeed, it is shown in [121] that a CS-PLL provides the maximum likelihood estimates of the input signal phase and frequency. These results suggest that, although still very preliminary, the application of compressive sensing theory to the field of robust carrier tracking is envisaged as a novel and promising approach to be explored in the near future.

VII. Potential Open Loop Techniques

From an architectural point of view, synchronization of digital receivers can be carried out either in a closed-loop or open-loop manner. The former is the natural choice for systems operating in continuous-mode, in which the signal transmission is permanent and uninterrupted. This allows the receiver to accurately synchronize the local replica with the incoming signal by gradually driving an error signal to zero. In contrast, open-loop techniques are well-suited for burst-mode systems, in which the received signal is present just for a limited period of time. In this case, synchronization must be performed by processing a batch of received signal samples at a time. So far, both approaches have remained apart due to their different fields of applications, with closed-loop techniques being widely adopted in code-division multiple access (CDMA) systems, such as GNSS while open-loop techniques being widely adopted in time-division multiple access (TDMA) systems. This trend, however, started to change with the advent, for instance, of high-sensitivity GNSS (HS-GNSS) receivers, which are based on open-loop architectures specifically tailored to allow operation in harsh working conditions where traditional closed-loop GNSS receivers fail [17], [123].

For the particular case of robust carrier tracking, the need for open-loop architectures is motivated by the long observation intervals that are required to filter out noise, and thus compensate part of the attenuation undergone by the received signal. Note that the filtered output rate may be orders of magnitude below the input rate, thus making it very difficult to provide a timely feedback to the incoming signal. In that case, it is preferable not to close the loop and focus instead on the open-loop estimation of the synchronization parameters by independently processing pieces of input received samples. This leads to the so-called *snapshot* or *batch processing* implementation, and it is a convenient approach to provide robustness to continuous-mode receivers by inheriting many of the existing open-loop techniques already developed for burst-mode receivers. An example of the resulting architecture is schematically depicted in Fig. 8.

As an example of open-loop carrier tracking, the contribution in [124] proposes an iterative frequency estimator by re-using some previous results on the optimal maximum likelihood (ML) frequency estimator used in open-loop communication receivers. This contribution is based on a two-step approach: first, a bank of parallel correlators implemented through the fast-Fourier transform (FFT) provides a three-dimensional time-frequency-energy representation of the input signal; second, the carrier frequency is further refined by using a second FFT processor, thus resembling the double-FFT algorithm proposed in [123]. A simpler single-step approach is proposed in [125] based on a frequency estimator and a smoothing filter, which allows partial feedback in the form of a quasi-open-loop architecture. Different frequency estimators can be used for this purpose, mainly inherited from the communications domain. This is the case of Fitz's frequency estimator [126], Kay's method [127] and its generalized version [128] or the Luise & Reggiannini frequency estimator [129].

The advantages of open-loop architectures have also been reported in [130], showing that the tracking margin can be improved by 8 dB as compared to that provided by traditional closed-loop tracking techniques, particularly when external aiding from inertial sensors is considered in both of them. Such a gain paves the way for the potential adoption of open-loop architectures for the robust carrier tracking in harsh working conditions. In that case, the improved signal observability of open-loop implementations (i.e. the wider span due to the availability of a batch of samples at a time), provides a more robust carrier phase performance. In particular, such a wider span helps the receiver to immediately recover after a temporary signal loss and boost re-acquisition, as well as to cope with high-dynamics such as those experienced in radio occultation applications [131], [132].

VIII. Qualitative Comparison of Robust Carrier Tracking Techniques

In previous sections, we have concentrated on the high-level description of different carrier tracking techniques, on the discussion of their advantages and disadvantages, as well as on their potential target application. As far as performance is concerned, it is actually difficult to fairly compare all these techniques, since there is not a single technique that performs the best in all possible working conditions. Instead, some techniques do perform better than others for certain scenarios, but this trend is often reversed when the working conditions change. It is therefore not possible to make a decision on the best technique to be used anytime, for a given target application.

Nevertheless, it is actually possible to provide some guidelines regarding the technique, or family of techniques, that should be considered for a specific problem at hand. In that sense, there are three main problems that we may face in carrier tracking applications: dynamics (e.g. the presence of Doppler effect in moving vehicles), stationary random disturbances (e.g. severe thermal noise) and non-stationary random disturbances (e.g. scintillation events due to abnormal solar activity in satellite receivers, or just signal outages). These three threats are the ones graphically represented by the three

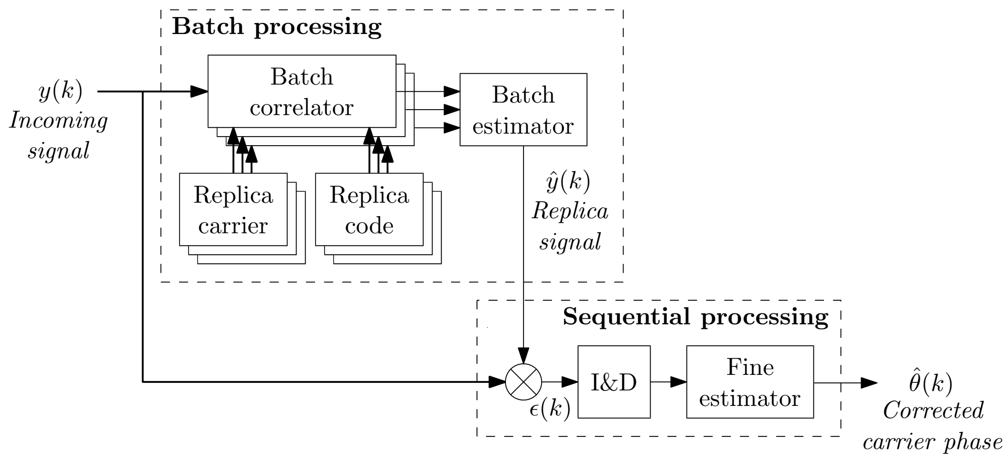

Fig. 8. Architecture of a generic open-loop carrier tracking techniques.

vertices of the triangle in Fig. 9. This pictorial representation visually maps the capability of each carrier tracking technique to cope with each of the three main impairments. For instance, constant bandwidth PLL techniques are specialized in dealing with stationary effects, and so they appear on the upper part of the stationarity axis, close to its vertex. Similarly, they are also close to the dynamics axis, indicating their suitability for this type of effect. However, they are far apart from the non-stationarity axis, due to their lack of adaptability to time-varying effects. Following this rationale, techniques lying in the central part of the triangle in Fig. 9 possess the virtue of being equally capable of coping with any of the three impairments represented by each vertex. This region is thus, the one where the most versatile techniques can be found. We believe that this representation provides a clear picture of how different techniques behave, and it may be helpful for potential users or designers in order to choose the best candidate technique for a given application, according to the three main impairments considered herein.

IX. Conclusions

In this survey, we have presented a detailed and comprehensive overview of the different existing approaches to cope with the problem of robust carrier tracking in non-nominal working conditions. This is a challenging problem with implications in a myriad of different applications, ranging from synchronization of communication receivers, provision of accurate phase measurements in positioning receivers, monitoring of ionospheric scintillation in the presence of solar flares or storms, or control of loads in distributed electrical power generation. In all these applications, carrier tracking becomes the most vulnerable stage at the receiver side, particularly when severe fading, blocking, or other abnormal propagation effects do appear. The solution to this problem has attracted the interest of the research community for several decades, and a plethora of techniques as well as small improvements over already existing implementations, have been proposed in the existing literature.

In that sense, the motivation of the present survey was two-fold. First, to bring together most of the contributions on robust carrier tracking disseminated over the last decades in different publications and research fora. These techniques range from simple modifications of traditional tracking loops to the use of variable loop bandwidth architectures through Kalman filter-based schemes. Second, to provide a new and fresh look onto this problem, by providing future directions based on innovative concepts and tools that are just being considered in other applications and disciplines. This is the case of compressive-sensing, particle filters or interactive multiple models, whose application to robust carrier tracking would provide significant advantages. Therefore, we believe that the present survey will help the reader to have a detailed overview of the existing robust carrier tracking techniques available in the literature, while at the same time, it will foster research onto this topic thanks to the challenges and future directions that have been highlighted herein, and for which significant research efforts are still required.

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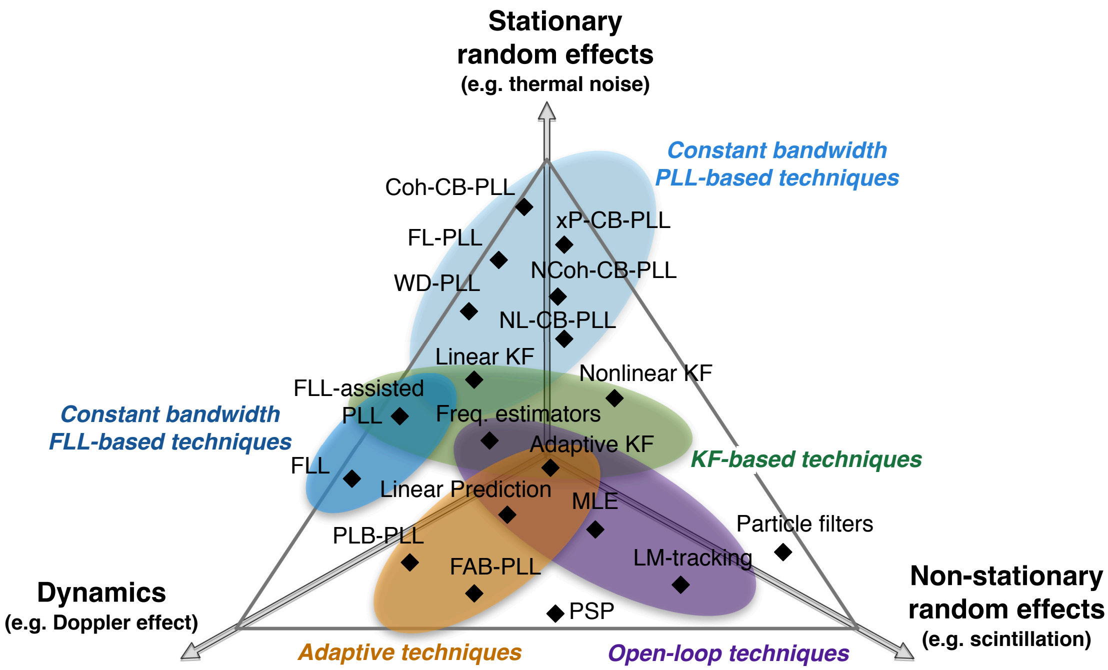

Fig. 9. Suitability of the most representative robust carrier tracking techniques in front of the three main impairments typically challenging carrier tracking applications.

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