Enhanced Code Acquisition in Global Positioning Radio Systems

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Abstract - Satellite-based localization using the global positioning systems (GPS) has attracted ever growing attention in the last few years. In this work, we present a signal processing technique for initial code acquisition and synchronization of a GPS signal, such as the one used by position location techniques in 3G wireless scenarios. Several computer simulations have been accomplished to validate the proposed PHD method for the acquisition and synchronization of a GPS signal, under a possible systematic frequency error or a nominal frequency offset. The numerical results obtained from our simulation trials confirm the validity of such approach which overcomes the conventional non-coherent techniques.

1 Introduction

Rapid pseudo-noise (PN) code acquisition methods have gained ever growing attention in the radio access of mobile communications of the last few years [1]-[4]. In order to exploit the advantages of a direct sequence-spread spectrum (DS/SS) signal in a code division multiple access (CDMA) system, receivers must first be able to synchronize the locally generated PN code with the incoming PN code. This contribution, considering some of these issues, addresses algorithms for the PN code synchronization in a Global Positioning System (GPS), proposing the application of a new method inspired by the Pisarenko Harmonic Decomposition (PHD) [6]. This method, recently introduced by Giunta et al. in [5], and originally proposed for the initial code synchronization of wideband-CDMA (W-CDMA) mobile systems is here extended and applied to the acquisition and synchronization of a GPS signal, under a possible systematic frequency error or a nominal frequency offset. As a consequence, the acquisition of a GPS signal poses a two dimensional search problem, where the carrier offset of the received signal caused by the Doppler effect and the phase of the (pseudo-noise) coarse acquisition code have to be determined simultaneously.

The integration of GPS signals, within the 3rd generation wireless networks, is depicted in the 3GPP (3rd Generation Partnership Project) specification and has set specific targets for the accuracy of position location (PL) services. These are: - network-based solutions: 100 meters for 67% of calls and 300 meters for 95% of calls - handset solutions: 50 meters for 67% of calls and 150 meters for 95% of calls [7]. There are also regulations referring to horizontal and vertical accuracy, response time (no delay, low delay and delay tolerant), coverage and estimates of the accuracy of the measurement, and so on. As a consequence, the ability to support position location within wireless networks provides network operators with additional value added services, as well as users with a host of new applications. This includes navigation, localization based services, network management and security applications. Obviously, in this working environment, information accuracy about users' position is a crucial to be satisfied in order to use in the optimal way both the cells and base stations resources. Therefore, several PN code acquisition techniques have been investigated in the literature [2], [8]-[11].

Conventional initial acquisition methods are based on serial multi-dwell hypothesis tests, based on non-coherent correlation from a number of synchronization data blocks. In particular, conventional testing methods for the presence of a synchronization code signal (with a given spreading code offset) rely on power detection [1]. Conversely, differentially coherent combining, widely used in many frequency-control schemes to exploit local phase coherence, was proposed in [12] to avoid the effect of systematic frequency and phase errors, modeled as constant over several slots. Such a method operates under the hypothesis of linear phase shift in all the slots of each frame, due to Doppler effect or frequency offsets. Nevertheless, such a general assumption on phase variation may result in a venturous hypothesis.

Testing for the presence of useful signal should discriminate over the two opposite cases of acquired or mismatched code offset that are often referred to as *in-sync* and *out-of-sync* conditions. These cases differ because the output of a matched filter is ideally constant in the former condition, while it randomly varies in the latter one. In fact, it is well known that the user codes employed are orthogonal only if the users are chip-synchronized with each other. In practice, any pair of codes may present a relevant cross-correlation for nonzero chip offset. Such a residual correlation acts as a random variable (the codes are usually modulated by independent data streams), characterized by a noise-plus-interference variance depending on the effective time synchronization. The system performance, based on constant false alarm (CFAR) criterion, depends on the achieved probability of detection. When the testing variables are (asymptotically) Gaussian, the threshold can be asymptotically tuned from the analytic evaluation of the first- and second-order moments of the testing variables. In particular, the CFAR test is accomplished in two successive parts: first, a threshold is determined to limit the false-alarm probability P_{FA} at a given reduced value (also named *size* of the test); second, the probability of detection P_D (also named *power* of the test) is evaluated for the threshold previously determined. The probability of false alarm must be tuned to guarantee a very low number of possible false alarms, which eventually imply a relevant penalty time to the acquisition device. Large probabilities of detection (up to 100%) are typical of well-performing testing variables [13].

This work, extending previous analysis [5], presents a method exploiting local phase coherence (inspired by the Pisarenko estimation) allowing global frequency estimation in the presence of random phase noise for GPS signal acquisition and synchronization. In fact, non-coherent techniques are suited in the presence of random (unpredictable) phase (and/or) frequency; conversely, differentially coherent methods effectively apply when the phase jitter is predictable, such as while a systematic frequency error occurs [12]. In this work, we present for the acquisition and synchronization stage of a GPS signal, comparing the numerical outcomes of the new PHD algorithm with the ones obtained using the conventional approach (i.e. power detector). Several computer simulations have been accomplished to validate the proposed PHD method, comparing its performance with the conventional power detector approach. The results are expressed in terms of probability of detection (P_D) versus typical signal-to-noise ratios (SNRs) of practical interest. The real cost of the proposed method is practically the same. In fact, the same structure of block correlators (implemented by matched filters) may be used. Moreover, the obtained results evidence the robustness of the presented method, which overcomes the conventional non-coherent techniques in some reference operating case of GPS systems for PN code synchronization and acquisition.

The remainder of this work is organized as follows. Section 2 shows the basic frameworks of non-coherent code-acquisition procedures. In Section 3, the proposed method, inspired by the Pisarenko Harmonic Decomposition, is presented. Numerical results obtained through wide simulation trials and characterized for a GPS signal such as the one used by position location techniques in the 3rd generation wireless networks, are showed in Section 4 before the conclusions of the work briefly depicted in Section 5.

2 Non-Coherent Acquisition Techniques

In this Section, the basic frameworks of non-coherent code acquisition techniques are described. Non-coherent techniques are suited in the presence of random (unpredictable) phase (and/or frequency); conversely, differentially coherent methods effectively apply when the phase jitter is predictable, such as while a systematic frequency error occurs [5]. Since the instantaneous phase in mobile communications may vary for any small movement of the mobile station, if the frequency may be assumed near constant along the whole estimation time, a twofold goal can be pursued in order to conjugate both these capabilities as showed in the following of this contribution. In this work, we present for the acquisition and synchronization stage of a GPS signal, comparing the numerical outcomes obtained with the new PHD algorithm with the ones obtained using the conventional approach (i.e. power detector).

Let $x(t)$ be the signal at the receiver input. It is filtered by the filter matched to the pulse waveform $w(t)$, obtaining a signal $r(t)$ that is the convolution of $x(t)$ and $w(t)$. Given D samples $\{r(iT_c), i=1,\ldots,D\}$ of its complex envelope, the conventional power detector first estimates the cross-correlation $\rho(k; n)$ (despreading the generic n-th data block, made of D chips) between $r(t)$ and the (known) code candidate $c(iT_c)$, shifted by kT_c (being T_c the chip period):

$$\rho(k;n) = \frac{1}{D}\sum_{k=1}^{D} r(iT_c + nD)\cdot c^*(iT_c + kT_c), \tag{1}$$

with $k = 0, 1, 2, \ldots$ and where $c^*(\bullet)$ denotes complex conjugate. Then, the power detector accumulates N samples of the square magnitude of the estimated cross-correlation $\rho(k; n)$, in order to avoid the effect of the frequency and phase uncertainty [14]:

$$z(k) = \frac{1}{N}\sum_{n=1}^{N} \left|\rho(k;n)\right|^2 = \frac{1}{N}\sum_{n=1}^{N} \rho^*(k;n)\cdot \rho(k;n). \tag{2}$$

The k-th currently examined decision variable $z(k)$ is then compared with proper pre-selected thresholds. A threshold value, η, is established for desired detection and false alarm probabilities. If $z(k)$ exceeds η in any given cell(s), a verification procedure is initiated; otherwise, noise only is assumed, and the procedure is repeated for the next cell. The two opposite cases of acquired or mismatched code offset are often referred to as in-sync and out-of-sync conditions. These cases differ because the output of a matched filter is ideally constant in the former condition, while it randomly varies in the latter one. In fact, it is well known that the user codes employed are orthogonal only if the users are chip-synchronized with each other. In practice, any pair of codes may present a relevant cross-correlation for nonzero chip offset. Such a residual correlation acts as a random variable (the codes are usually modulated by independent data streams), characterized by a noise-plus-interference variance depending on the effective time synchronization. Testing for the presence of useful signal should discriminate over the following two hypotheses: H_1 presence of signal, in-sync case; H_0: absence of signal, out-of-sync case. In other words, the in-sync condition corresponds to the case of presence of the tested code while the out-of-sync case states the absence of that code with the considered time offset.

The system performance, based on constant false alarm (CFAR) criterion, depends on the achieved probability of detection. When the testing variables are (asymptotically) Gaussian, the threshold can be asymptotically tuned from the analytic evaluation of the first- and second-order moments of the testing variables. In particular, the CFAR test is accomplished in two successive parts: first, a threshold is determined to limit the false-alarm probability P_{FA} at a given reduced value (also named size of the test); second, the probability of detection P_D (also named power of the test) is evaluated for the threshold previously determined [15]. The probability of false alarm must be tuned to guarantee a very low number of possible false alarms, which eventually imply a relevant penalty time to the acquisition device. Large probabilities of detection (up to 100%) are typical of well-performing testing variables [13]. In the next Section, we show the code-acquisition procedure exploiting the Pisarenko Harmonic Decomposition, for a GPS signal, such as the one used by position location techniques in the 3rd generation wireless networks

3 Proposed Algorithm

GPS signal acquisition is a two-dimensional search in time (code phase) and frequency defined from an uncertainty region. The C/A code dimension is associated with the replica code. The Doppler dimension is associated with the replica carrier. The uncertainty in both Doppler and C/A code phase suggests that a 2-dimensional uncertainty region must be searched in order to locate the received signal. When the GPS receiver has no almanac available, the code uncertainty region is 1023 chips, and the Doppler uncertainty region is about –11000 Hz ~ +11000 Hz typically [16]. Each Doppler search increment is called a Doppler bin, and each C/A code phase search increment is called a code bin. The combination of one code bin and one Doppler bin is a cell. In a serial search, the searching procedure is executed one cell at a time in sequence, while in a parallel search (multi-correlator), groups of cells are tested simultaneously. An alternative detector of the one represented by (2) can be expressed as follows [5]:

$$y(k) = \left| \frac{1}{N} \sum_{n=1}^{N} \rho^*(k; n-1) \cdot \rho(k; n) \right| . \tag{3}$$

As before, the k-th currently examined decision variable $y(k)$ is then compared with proper pre-selected thresholds: the in-sync condition (hypothesis H_1) corresponds to the case of presence of the tested code with the time offset kT_c, while the out-of-sync case (hypothesis H_0) states the absence of that code with the considered offset.

The testing variable $y(k)$, expressed by (3), is inspired by the Pisarenko Harmonic Decomposition method [12], [17] with one harmonic series. In our scheme, let us consider the random series of N cross-correlation estimates $[\rho(k;1) \ldots \rho(k;n-1) \ldots \rho(k;n) \ldots \rho(k;N)]$. If the series can be modelled as an unknown complex harmonic series (due to the frequency offset ω) corrupted by an additive white complex random noise $\varepsilon(k;n)$, we obtain:

$$\rho(k;n) = |A(k)| \cdot e^{j\omega \cdot n + j\phi} + \varepsilon(k;n), \tag{4}$$

and the autoregressive Yule-Walker relationships apply here as a limit case, as in the PHD algorithm [12]. In particular, the first time lag of the autocorrelation:

$$E\left[\rho^*(k;n-1) \cdot \rho(k;n)\right] = |A(k)|^2 \tag{5}$$

is implicitly estimated by (3), and determines both the magnitude envelope $|A(k)|$ and the frequency offset ω, while neglecting the effect of the phase ϕ, assumed constant over N data blocks. As we show in the following, the proposed technique is somewhat superior to the non-coherent one. The real cost of the proposed method is practically the same, because the same structure of block correlators (implemented by matched filters) needs to be used. The only difference consists of the different processing required by the two methods: block-by-block multiplications of the estimated correlation by its current complex conjugate or, alternatively, by the conjugate of the correlation estimated from the previous synchronization data block. Moreover, assuming that the phase jitters may randomly vary a little with time from one slot to another, the local phase coherence of two subsequent correlations may be exploited, as in our method, by accumulating a number of conjugate products between correlation pairs of subsequent synchronization data blocks.

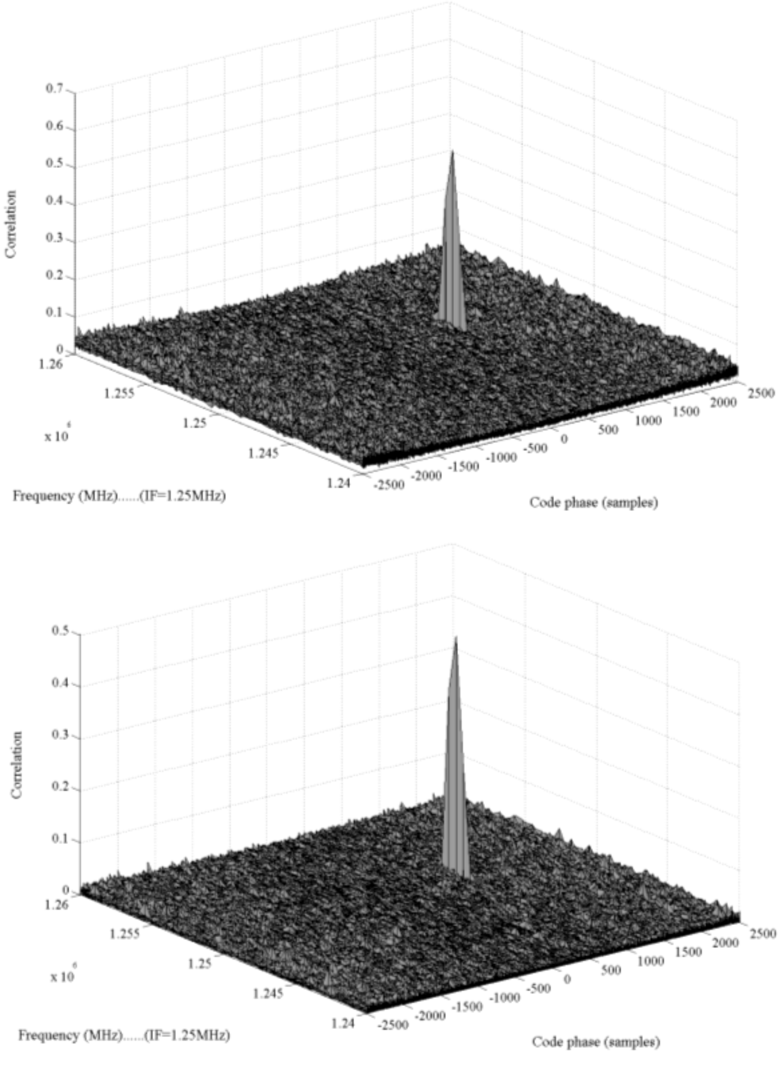

Fig. 1 Three-Dimensional (3-D) representation of the correlation peaks of the acquisition phase for: (a) the conventional power detector approach; (b) the PHD method, both with a SNR=-19dB.

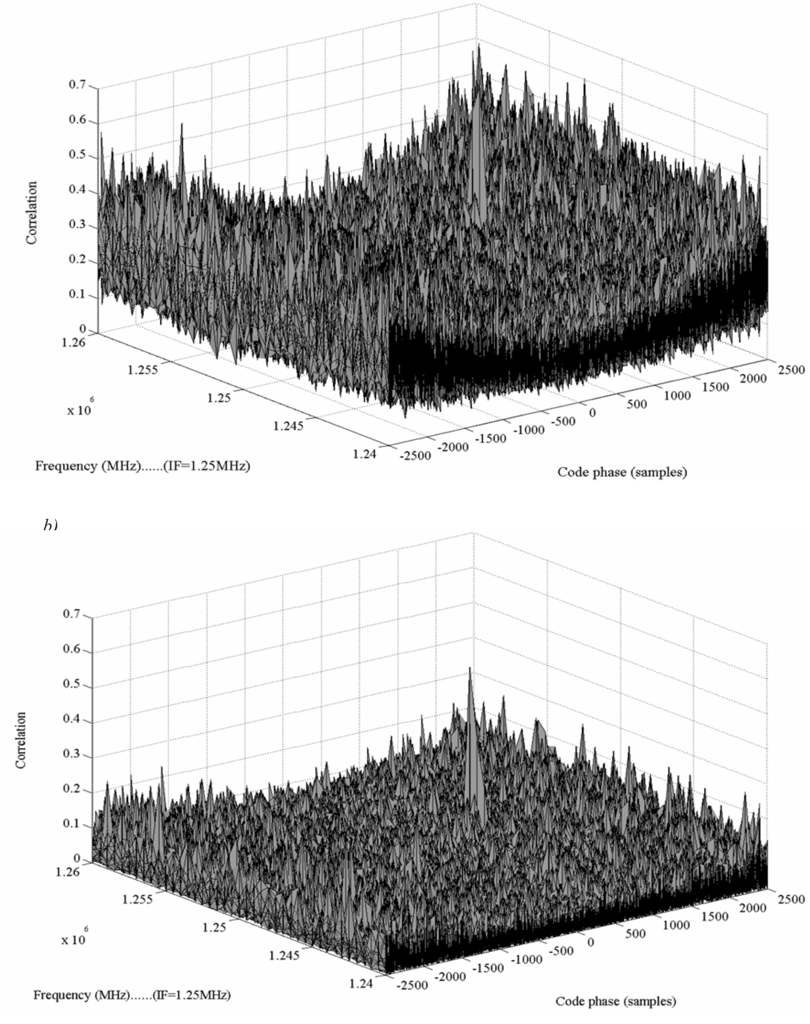

Fig. 2 Three-Dimensional (3-D) representation of the correlation peaks of the acquisition phase for: (a) the conventional power detector approach; (b) the PHD method, both with a SNR=-28dB.

4 Simulation Results

In order to validate the proposed PHD method, comparing its performance with the conventional power detector approach, several computer simulations have been accomplished.

In our simulations, referring to the classical model of a GPS receiver [16], 1 ms of C/A code modulated with navigation data and corrupted by white additive Gaussian noise has been considered. The signal has an Intermediate Frequency (IF) of 1.25 MHz, a sampling frequency of 5 MHz and, consequently, the chip period is given by T_c = 0.2 ms. Moreover, a Doppler bin of 500 Hz has been used. The obtained performance of the two methods has been compared for several signal-to-noise ratios (SNRs) of practical interest and for several frequency and code shifts. In particular, Figure 1 and Figure 2 show a 3-D representation of the correlation peaks of the acquisition phase for the conventional power detector approach and the PHD method, evaluated with a SNR = -19 dB and a SNR = -28 dB, respectively. It can be easily seen from the graphs that the correlation peak corresponding to the effective code (i.e. to an acquisition) is much more detectable with the proposed method than the conventional approach, using the same signal-to-noise ratio. This behaviour reflects in an enhancement of the performance of the new method versus the conventional one. In fact, the PHD technique can be performed using the same SNR and obviously using the same acquisition thresholds (i.e. with the same false alarm probabilities), reaching higher values in terms of detection as detailed in the following figures.

Figure 3 shows this performance enhancement of the PHD approach versus the conventional technique (i.e. the power detector). The results are expressed in terms of probability of detection (P_D) versus typical signal-to-noise ratios of practical interest. As it can be easily seen, the curve referring to the new method is always higher than the curve referring to the power detector (i.e. the PHD method overcomes the conventional approach in all the considered situations).

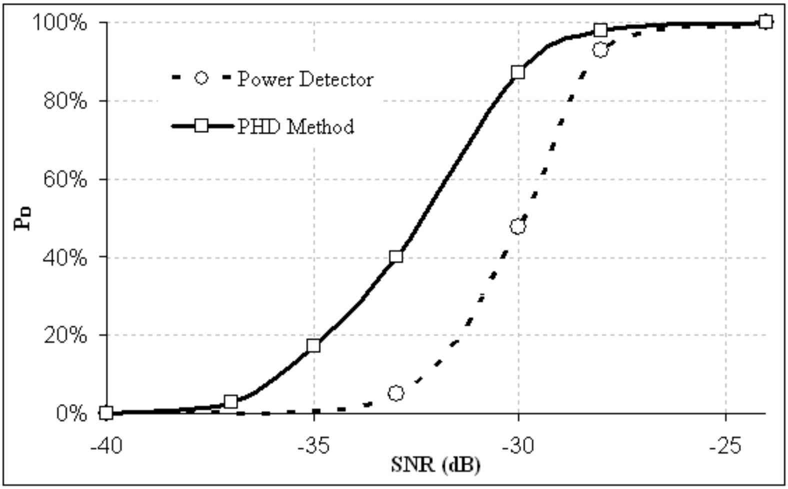

Fig. 3 Detection probability of the two methods, evaluated with a Probability of False Alarm $P_{FA} = 10^{-3}$, versus Signal-to-Noise Ratios of practical interest. Solid line represents the PHD algorithm while dotted line stands for the conventional power detector.

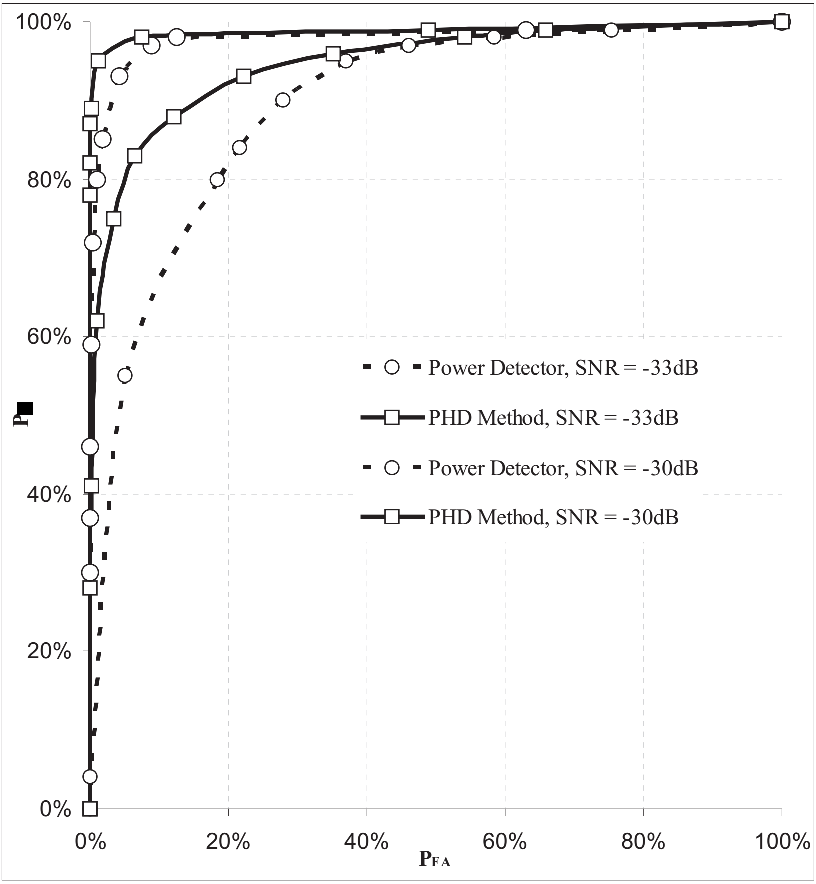

Fig. 4 Performance of the two approaches through the receiver's operating characteristic (ROC) evaluated at different signal-to-noise ratios. Solid lines represent the PHD algorithm while dotted lines stand for the conventional power detector.

Moreover as depicted in Figure 4, we evaluate the performance of the two approaches through the receiver's operating characteristic (ROC) [15]. The ROC is graphically represented in diagrams, where P_{FA} is on the horizontal axis and P_D on the vertical one. The *best* performing detector is the one which presents the minimum distance from the *ideal* point ($P_D = 1$ and $P_{FA} = 0$) in its ROC curve. An effective operating point is just the point of the curve near such an optimum case. As shown in Figure 4, the PHD method outperforms the conventional approach (i.e. power detector technique): in fact, with the same value for the false alarm probability (i.e. with the same acquisition threshold) the new method allows reaching higher values in terms of detection probability.

Therefore, the numerical results we obtained from our simulation trials show that the proposed technique is somewhat superior to the non-coherent one. This behaviour reflects in a performance enhancement providing the users to greatly improve positioning accuracy, continuity of service, availability and integrity.

In conclusion, the real cost of the proposed method is practically the same, because the same structure of block correlators (implemented by matched filters) needs to be used. Moreover, the obtained results evidence the robustness of the presented method, which overcomes the conventional non-coherent techniques in some reference operating case of GPS systems for PN code synchronization and acquisition

5 Conclusions

The 3rd Generation Partnership Project (3GPP) specification has set specific targets for the accuracy of position location (PL) services, integrating GPS signals, within the 3rd generation wireless networks. In this work, we have addressed algorithms for the pseudo-noise (PN) code acquisition and synchronization for a Global Positioning System (GPS) signal, such as the one used by position location techniques in the 3rd generation wireless networks (UMTS). We presented a method exploiting local phase coherence (inspired by the Pisarenko harmonic decomposition, PHD) allowing global frequency estimation in the presence of random phase noise.

In our wide simulation trials, we matched the conventional power detector testing method for the presence of a synchronization code signal and the obtained numerical results showed that the proposed technique is somewhat superior to the non-coherent one. The performance enhancement is obtained without increasing the computational complexity of the system. In fact, it has to be underlined that the real cost of the proposed method is practically the same, because the same structure of block correlators (implemented by matched filters) needs to be used. The simulation results obtained from our simulations evidence the sensitivity and robustness of the presented method, which overcomes the conventional non-coherent techniques in some reference operating case of GPS systems for PN code synchronization and acquisition.

6 References

[1] W.R. Braun, "PN acquisition and tracking performance in DS/CDMA systems with symbol-length spreading sequences", *IEEE Trans. on Commun*., vol. 45, pp. 1595-1601, Dec. 1997.

[2] Y. H. Lee, S. Tantaratana, "Sequential acquisition of PN sequences for DS/SS communications: design and performance," *IEEE J. Select. Areas Commun*., vol. 10, pp. 750–759, May 1992.

[3] G. Giunta, A. Neri, "Two-Dwell Code Acquisition Techniques by Advanced Spatio-Temporal Antennas for the Radio Access of 3G Mobile Communications", *IEE Conf. on 3G Mobile Commun Techn*., London, UK, June 25-27, 3G 2003, pp. 48-52, 2003.

[4] G. Giunta, F. Benedetto, "Improving the code acquisition performance in the radio access of spread spectrum communications by exploiting cell correlation", *IEE Conf. on 3G Mobile Commun. Techn.*, London, UK, Oct. 18-20, 3G 2004, pp. 262-266, 2004.

[5] G. Giunta, A. Neri, L. Vandendorpe, "Initial Code Synchronization of W-CDMA Mobile Systems Exploiting Local Phase Coherence and Pisarenko Estimation", *IEEE Trans. on Comm*., vol. 53, no. 1, pp.48-52, Jan. 2005.

[6] S.M. Kay and S.L. Marple, Jr., "Spectrum analysis: A modern perspective" *Proc. IEEE*, vol. 69, pp. 1380-1418, Nov. 1981.

[7] D. Kothris, M. Beach, B. Allen, P. Karlsson, "Performance assessment of terrestrial and satellite based position location systems", *IEE Conf. on 3G Mobile Commun. Techn.*, March 26-28, 3G 2001. pp. 211 – 215, 2001.

[8] S. Ahonen, P. Eskelinen, "Performance estimations of mobile terminal location with database correlation in UMTS networks", *4th Int. Conf. on 3G Mobile Commun. Techn., 3G 2003*, pp. 400 – 403, June 2003.

[9] H. Elders-Boll, U. Dettmar, "Efficient differentially coherent code/Doppler acquisition of weak GPS signals", *IEEE 8th Int. Symp. on Spread Spectrum Techn. and Appl.*, pp.731-735, Sept. 2004.

[10]F.D. Nunes, J.M.N. Leitao, "A new fast code/frequency acquisition algorithm for GPS C/A signals", *IEEE 58th Vehicular Techn. Conf. VTC 2003-Fall*, vol. 2, pp. 766-770, Oct. 2003.

[11]K.R. Shankar Kumar, A. Chockalingam, "Multicarrier DS-SS for GPS pseudolites: code-acquisition performance in the presence of data modulation", *IEEE 56th Vehicular Techn. Conf. VTC 2002-Fall*, vol. 1, pp. 146-150, Sept. 2002.

[12]Y.K. Jeong, O.S. Shin and K.B. Lee, "Slot synchronization for inter-cell asynchronous DS/SS receivers", *IEEE Trans. Wireless Comm.*, vol. 1, pp. 353-360, Apr. 2002.

[13]H.L. Van Trees, *Detection, Estimation, and Modulation Theory*, New York: Wiley, 1971.

[14]Y.-P.E. Wang and T. Ottosson, "Cell search in W-CDMA", *IEEE J. Sel. Areas Commun.*, vol. 18, pp. 1470-1482, Aug. 2000.

[15]H.S. Seo, C. Park and S.J. Lee, "A New Fast Acquisition Algorithm for GPS Receivers", *Proc. of the 2000 Int. Symp. on GPS/GNSS*, Dec. 2000.

[16]V. F. Pisarenko, "The retrieval of harmonics from a covariance function", *Geophys. J. Roy. Astron. Soc.*, pp. 347-366, 1973.

[17]J.-C. Lin, "Noncoherent sequential PN code acquisition using sliding correlation for chip-asynchronous direct-sequence spread-spectrum communications", *IEEE Trans. Commun.*, vol. 50, pp. 664-676, Apr. 2002.