LOS/NLOS DETECTION BY THE NORMALIZED RAYLEIGH-NESS TEST

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ABSTRACT

Deciding for the possible presence of a LOS component in a wireless radio link is preliminary to several operations that a communication receiver has to accomplish. In fact, NLOS radio models require more complex signal processing algorithms for data detection. We propose to adopt the normalized version of the Rayleigh-ness test (recently introduced for code acquisition purposes, as a measure of the Ricianity of the series under investigation) to obtain here a self-tunable test, independent of the actual power of the received signal. The achieved results evidence the robustness of the test.

1. INTRODUCTION

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 [1]-[9]. Thus, quickly achieving and then maintaining PN code synchronization is a critical issue to be satisfied because even a small misalignment can cause dramatic signal-to-noise ratio (SNR) degradation. The most widely used and studied methods for acquiring PN codes are: (maximum likelihood) full parallel search, serial search, and hybrid search. In each of these methods, correlations between the incoming and the locally generated PN sequence are realized. In the first case (full parallel search), correlations are formed for all possible PN code offsets. In simple serial search, only one of the correlations used in the full parallel search is formed, while hybrid search tests a small set of possible alignments in parallel and then repeats this test on another set of observations until the correct code offset is discovered. In all cases, a threshold test is performed to accept or reject the presence of useful signal characterized by a given code in the search region under investigation. The test sequentially searches for the most likely codes and their optimum timing shift as reliable candidates for code (and code offset) acquisition [2], [6].

Conventional testing methods for the presence of a pilot synchronization signal (with a given spreading code offset) rely on the power detector [7]. This test distinguishes between two different hypotheses: the *in-sync* condition (hypothesis H_1), which corresponds to the case of presence of the tested code with the offset detected by the receiver's systematic timing offset; and the *out-of-sync* case (hypothesis H_0) which conversely states the absence of that code with the considered offset [6]. The constant false alarm rate (CFAR) criterion, often employed to perform effective tests, is adopted to determine the threshold value. Power detector is chosen to limit the computational costs of the decision device, in order to allow faster sequential hypothesis rejection. That is because rejection is much more likely than acceptance in code serial search devices for spread spectrum communications [5]-[9].

In a recent development, the "Rayleigh-ness" test was introduced in [4] for code acquisition purposes, as a measure of the "Ricianity" of the series under investigation. In particular, the Rayleigh-ness test has been previously proposed regarding applications to non-coherent initial synchronization of the chip offset (code acquisition) in a symbol-length spreading sequence of DS-CDMA systems [4]. Addressing some of these issues, this work proposes a signal processing technique based on a normalized version of the Rayleigh-ness test for SS communication systems. Our goal is to obtain, via the proposed method, a self-tunable test that avoids the evaluation of the variance of the received symbols, i.e. the test is self-tunable in respect to the power of the received signal. The remainder of this work is organized as follows. The system model is described in the first half of Section II, while the basic frameworks of the Rayleigh-ness test are briefly summarized in the second half. In section III, the new normalized test is detailed, and in Section IV a number of numerical results are presented to assess the validity of the devised method. The paper's conclusions are finally drawn in Section V.

2. BASIC FRAMEWORKS

2.1 System Model

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 non-zero 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. In addition, let us consider an additive independent and identically distributed (i.i.d.) zero-mean complex Gaussian random series, say $\boldsymbol{H}=[\eta_1, \ldots, \eta_k]^T$, with variance $2\sigma^2$, that affects the estimated cross-correlation sample. It accounts for both the background noise and the random interference effects of the same code with erroneous shift (self-interference) or other co-users in the same cell (multi-user interference) [6]. Because we aim to perform a testing procedure suited in the presence of a large number of interferers, the Gaussianity of the series can be asymptotically assumed as a direct consequence of the central limit theorem. We are then assuming that the series at the output of a non-coherent correlator, matching the correct code shift, referred as $\mathbf{\Gamma'}=[\,|\mu+\varepsilon'_1|, \ldots, |\mu+\varepsilon'_k|\,]^T$ with mean $\mu\neq 0$, is corrupted by the zero-mean complex i.i.d. Gaussian random noise $\mathbf{E'}=[\,|\varepsilon'_1|, \ldots, |\varepsilon'_k|\,]^T$ with variance $2\sigma'^2$.

Testing for the presence of useful signal should discriminate over the following two hypotheses operating on the observed series $\mathbf{\Gamma} = [\,|R_1|, \ldots, |R_k|\,]^T$ whose samples are detected at the output of the matched filter (see Fig. 1): H_1 stands for the in-sync case (i.e. presence of signal), while H_0 represents the out-of-sync case (i.e. absence of signal). The statistical distribution of the observed variable is the Rice probability density function (PDF) in the former hypothesis, while reduces to the Rayleigh PDF in the latter case. As a consequence, the hypothesis testing is equivalent to decide for the "best fitting" statistical model of the real and positive-valued observed series $\mathbf{\Gamma} = [\,|R_1|, \ldots, |R_k|\,]^T$ between the Rayleigh and the Rice cases. Due to the central limit theorem, several testing variables asymptotically tend to Gaussian, whether the correlation error $\{\varepsilon_k\}$ is Gaussian or not. Under such an assumption, only the mean $E[Z|H_0]$ and the variance $\mathrm{var}[Z|H_0]$ of the testing variable Z should be estimated under the null hypothesis to compute the threshold [4].

2.2 "Rayleigh-ness" Test

A complete and extensive discussion on the Rayleigh-ness test can be found in [4]. This technique aims to state whether a real positive series is a portion of one realization of a Rayleigh-distributed random process. Such a Rayleigh-ness test can be performed to decide on the possible presence of a (statistically relevant) mean of the complex Gaussian model (i.e. $R_k = \mu + \varepsilon_k$) generating both Rayleigh ($\mu = 0$) and Rice ($\mu\neq 0$) distributions by the magnitude of the complex Gaussian variable (i.e., $|R_k|$), where $\{\varepsilon_k\}$ is the correlation error. In particular, let us consider for sake of notational convenience and without loss of generality in the following, the marginal statistical moments (referring to the I/Q components) of the random variables $\mathrm{Re}\{R_k\}$ (or, equivalently, $\mathrm{Im}\{R_k\}$), instead of the equivalent definitions in the complex domain. In practice, the term σ^2 accounts for the marginal variance of R_k (i.e., the variance of the real or imaginary part only). Let us also define the marginal kurtosis α of R_k as the ratio between the marginal fourth-order moment (i.e., that of the real or imaginary part only) and the square σ^4 of the marginal variance (being $\alpha = 3$ in the Gaussian case). The testing variable is represented by the following:

$$X = 2\cdot\left[\frac{1}{N}\sum_{k=1}^{N}|R_k|^2\right]^2 - \frac{1}{N}\sum_{k=1}^{N}|R_k|^4 \qquad (1)$$

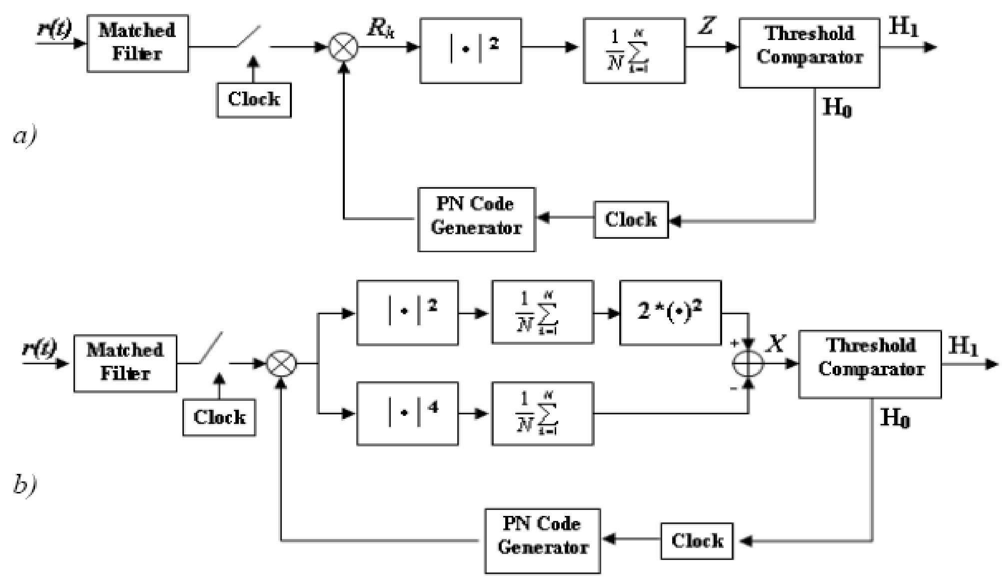

Fig. 1 Block schemes of the a) conventional power and b) Rayleigh-ness testing procedures

The Rayleigh-ness testing variable can be expanded as follows:

$$X = \frac{2}{N^2}\sum_{k=1}^{N}\left|\mu + \mathrm{Re}\left[\varepsilon_k\right] + j\,\mathrm{Im}\left[\varepsilon_k\right]\right|^2 + \\ -\frac{1}{N}\sum_{k=1}^{N}\left|\mu + \mathrm{Re}\left[\varepsilon_k\right] + j\,\mathrm{Im}\left[\varepsilon_k\right]\right|^4 \qquad (2)$$

Its mean value, after some algebra detailed in [4], can be expressed as:

$$E\left[X\right] = \mu^4 + 2\cdot\left(3-\alpha\right)\cdot\sigma^4 + \\ +\frac{2}{N}\left[4\mu^2\cdot\sigma^2 + 2\cdot\left(\alpha-1\right)\cdot\sigma^4\right] \qquad (3)$$

The testing variable X is asymptotically Gaussian ($N\rightarrow+\infty$) because of the central limit theorem, whether the correlation error $\{\varepsilon_k\}$ is Gaussian or not. In fact, the first term in (1) is the square of an asymptotically Gaussian variable with non-zero mean, whose variance goes to zero like 1/N. The second term, consisting of a sum of random variables, is asymptotically Gaussian from a direct application of the central limit theorem. The testing variable is then asymptotically Gaussian, since it is a linear combination of two asymptotically Gaussian random variables.

3. NORMALIZED "RAYLEIGH-NESS" TEST

One of the weakness points of the Rayleigh-ness test is represented by the fact that we have to estimate the variance of R_k in order to evaluate the testing variable X. In this Section, we present a normalized version of the Rayleigh-ness test that avoids the evaluation of the variance of the received symbols, i.e. the test is self-tunable in respect to the power of the received signal. We can divide each member of (1) by the variance of R_k and, after some algebra, we can obtain the following new testing variable:

$$\xi = \frac{\frac{1}{N}\sum_{k=1}^{N}\left|R_k\right|^4}{\left[\frac{1}{N}\sum_{k=1}^{N}\left|R_k\right|^2\right]^2} \qquad (4)$$

The normalized test now is as follows:

$$\xi \underset{H_0}{\overset{H_1}{\lessgtr}} \nu_\xi \qquad (5)$$

It means that if the testing variable is greater than the threshold value the algorithm decides for H_0, otherwise the choice is for H_1. Let us observe that equation (4) is equivalent to the ratio between the (estimated) variance of the same squared correlation samples $\{|R_k|^2\}$ and the (estimated) mean of the same samples. In fact, a conventional indicator only refers to one term, i.e. the mean output power. Conversely, a reduction of such variance in the in-sync condition will help the acquisition process (see also [6]) by means of the presence of the second term in the new testing variable (4). In our analysis, detailed in the results' Section, we have used the Constant False Alarm Rate (CFAR) procedure, often employed to perform effective tests [8]. 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 [4].

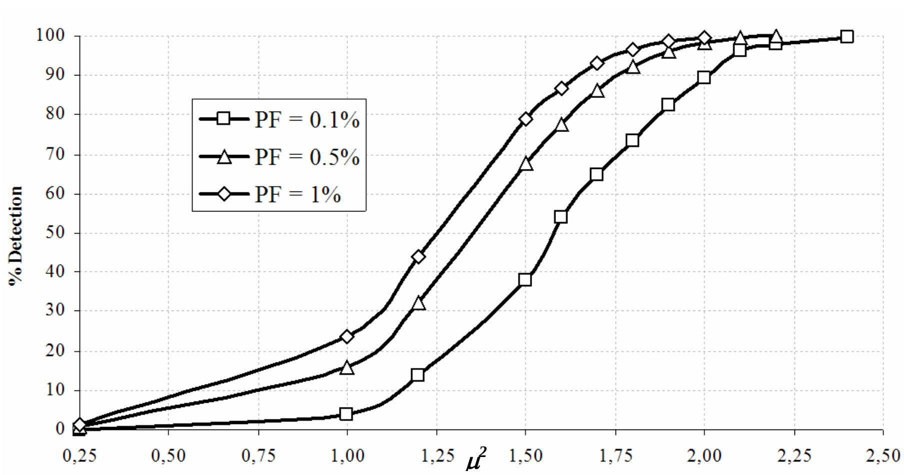

Fig. 2 Probability of false alarm versus the power of the LOS component

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 [3, 9]. The test threshold can be asymptotically tuned from a straightforward evaluation of the Gaussian integral for a fixed probability of false alarm, with μ=0, as follows:

$$\nu_\xi = E[\xi]\big|_{H_0} + \left(2\cdot \mathrm{var}[\xi]\big|_{H_0}\right)^{1/2}\cdot erf^{-1}\left(1-2\cdot P_{FA}\right) \qquad (6)$$

Furthermore, the asymptotic probability of detection (for the above threshold) can be similarly determined by means of the Gaussian error function in the case $\mu \neq 0$ by means of the expression:

$$P_D = \frac{1}{2}+\frac{1}{2}erf\left[\left(-\nu_\xi\big|_{H_1} + E[\xi]\big|_{H_1}\right)\cdot\left(2\cdot \mathrm{var}[\xi]\big|_{H_1}\right)^{-1/2}\right] \qquad (7)$$

In the next Section, wide simulation trials are conducted to prove the sensitivity of the theoretical approach and to verify the efficiency of the normalized test we propose here.

4. NUMERICAL RESULTS

In this Section, we show the performance of the system in terms of detection probability, P_D, for different values of practical interest of the parameter N (i.e. the number of samples) and of the parameter μ^2. It has to be underlined that this test can be used to decide for the presence of line-of-sight (LOS) or no-line-of-sight (NLOS) components. In fact, in a recent development, authors in [10] state that the Rician factor is defined as the ratio of power in the LOS path to power in the scattered paths and can be considered as a measure of the link quality. Since μ^2 is the power of the LOS component, its estimation (i.e. the estimation of the Rician factor) is also a measure of the quality of the link. This information is of high significance for location purposes in a wireless cellular network since time-of-arrival (TOA) and time-difference-of-arrival (TDOA) information based on LOS connections can be weighted stronger in a location computing algorithm and hence can lead to higher positioning accuracy. Otherwise, if the connection is identified as LOS it can be useful to adopt a 2-D signal processing (space-time processing) strategy with an antenna array, instead of using the high complexity of the TOA and TDOA methods.

In particular, Fig. 2 shows here the probability of detection evaluated versus the values of the parameter μ^2, for different false alarm probabilities (from 10^{-3} to 10^{-2}) and with N = 1000. As we can see, the behaviour of the curves for different P_F is very similar, hence, in all the following simulations we adopt the value of $P_F = 10^{-3}$, as done in the operating modes, to obtain detection probabilities of practical interest.

The resulting probability of detection with $P_F = 10^{-3}$ is depicted in Fig. 3 versus the value of the factor μ^2, i.e. the power of the LOS component. As we can easily see from the graph, the simulation results (dotted lines) well match the theoretical ones (solid lines) ensuring the correctness of the adopted mathematical model and assumptions of the previous Sections. The best working point on the graph is represented by the best trade-off between the computational complexity of the algorithm (i.e. the values of the requested number N of samples) and the values of the probability of detection in bad cases (i.e. with low values of the power of the LOS component, the parameter μ^2).

In order to verify these results, we have cross-matched the obtained data plotting in Fig. 4 the resulting probability of detection for different values of the power of the LOS component μ^2 versus the number N of samples. Once again, we are searching the best trade-off between the algorithm's efficiency (i.e. probability of detection of practical interest) and computational complexity (i.e. number of samples). We can see that for low values of μ^2 we always need a greater number of samples to obtain detection probability of practical interest. This is a consequence of the fact that, as stated in [10], for typical urban macro cellular environments with a root mean square delay spread on the order of 1 μs the Rician factor is equal to 1 (i.e. power on the main path equal to the power of the diffusive (multi-path) components. This means that the proposed test needs more samples before a correct acquisition shift is identified.

5. CONCLUSION

This work proposes a normalized version of the Rayleighness test, recently introduced in the literature, for code acquisition purposes, as a measure of the "Ricianity" of the series under investigation. Our goal is to obtain, via the proposed method, a self-tunable test that avoids the evaluation of the variance of the received symbols, i.e. the test is self-tunable in respect to the power of the received signal. We show the obtained outcomes versus different number of received samples and channel conditions (in terms of power of LOS component). Simulation results are used to show the robustness of this normalized test that can also be applied as a measure of the quality of the communication link to decide for the possible presence of LOS/NLOS components.

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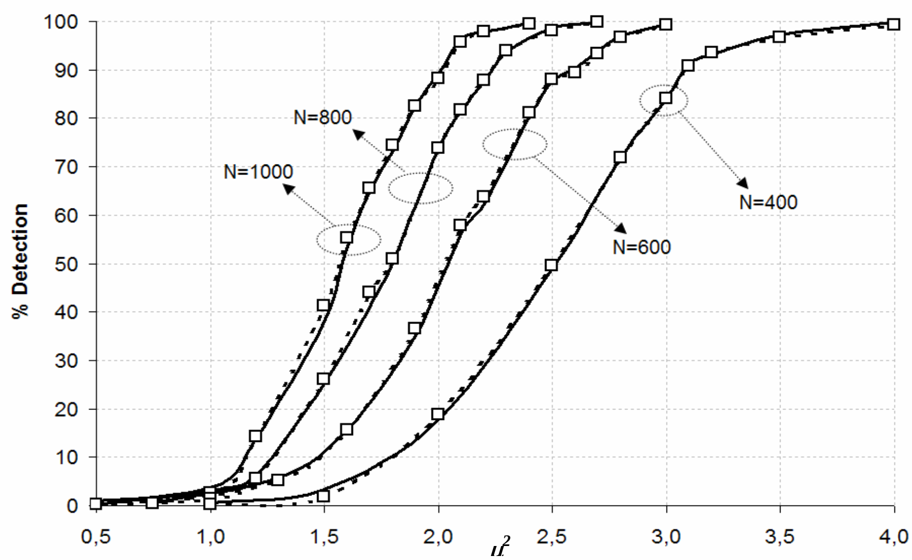

Fig. 3 Probability of detection (with $P_{FA} = 10^{-3}$) versus the power of the LOS component. (Simulation results: dotted lines; theoretical results: solid lines).

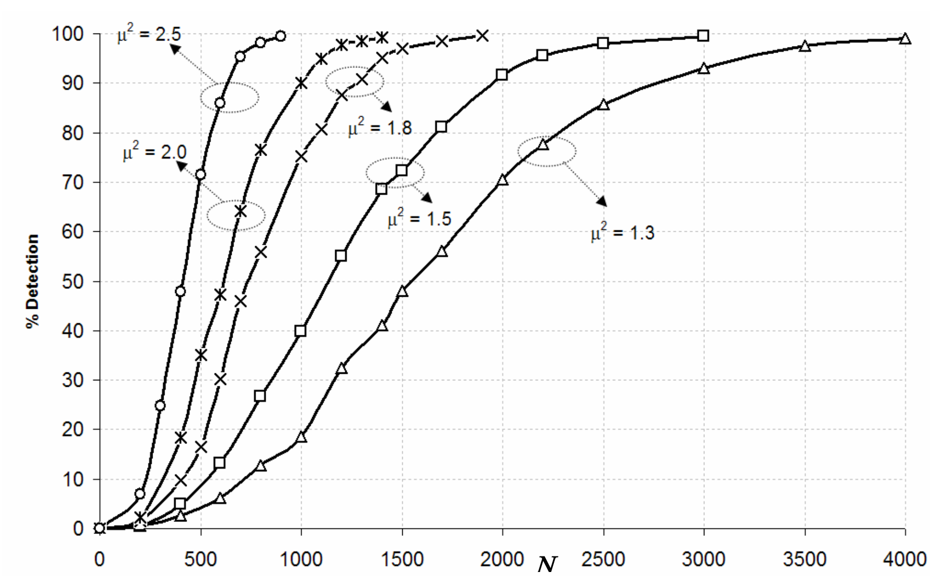

Fig. 4 Probability of detection (with $P_{FA} = 10^{-3}$) versus the number of estimated samples. (Simulation results: dotted lines; theoretical results: solid lines).