

SERIAL ACQUISITION TECHNIQUES FOR DS-CDMA SIGNALS IN FREQUENCY-SELECTIVE MULTI-USER MOBILE CHANNELS

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ABSTRACT

This paper compares the mean acquisition time performance of two serial search acquisition schemes over frequency-selective multipath Rayleigh fading channels. Both the conventional cell-by-cell detection and the novel joint twin-cell detection are characterised. In contrast to the majority of published results considering only one correct timing state (H_1 cell) in the uncertainty region of the pseudo noise (PN) sequence, this paper aims to analyse the mean acquisition time performance of a serial search acquisition scheme considering multiple timing states in the uncertainty region. The mean acquisition time performance comparison between the conventional cell-by-cell detection and the joint twin-cell detection shows that the latter can achieve significantly improved acquisition time performance at almost the same complexity.

1. INTRODUCTION

In a practical pseudo-noise (PN) sequence acquisition system usually there exist multiple in-phase states (H_1 cells) in the uncertainty region [1][2], where the received PN sequence and its locally generated replica may reside within the desired small timing offset. The number of H_1 cells is determined by the pull-in range of the code tracking loop, by the search step size and the channel characteristics. For example, for a baseband early-late tracking loop or for a non-coherent early-late tracking loop [3] having a total normalized time difference of Δ between the early and late discriminator channels, the acquisition timing offset should be less than $T_c \Delta$ in order that there is at least one H_1 hit during the search process, which leads to an offset between the received and the locally generated PN sequence that is within the pull-in region, where T_c represents the chip duration. However, there are always at least two adjacent H_1 cells in the uncertainty region and their related offsets are within the pull-in region of the tracking loop, provided that the search step size does not exceed $T_c \Delta/2$ and when non-fading channels are concerned [1][2]. If, however frequency-selective fading channels are considered [4], then more than two H_1 cells are possible in the uncertainty region of the search process due to multipath effects.

Despite the existence of multiple H_1 cells in almost any practical PN code acquisition system, the majority of published results concerning the mean acquisition time (MAT)

performance have been based on the assumption that there is one and only one H_1 cell in the uncertainty region. The performance of the acquisition system considering multiple H_1 cells has received comparatively little attention in the literature with the exception of [4]. The goal of this paper, therefore, is to quantify the performance of the proposed serial search acquisition system under the hypothesis that there are multiple H_1 cells in the uncertainty region of the PN sequence. Specifically, in this paper we assume that the pull-in region of the code tracking loop is $(-T_c/2, T_c/2)$, i.e. $\Delta = 1$ and the search step size is $T_c/2$.

2. SEARCH AND DETECTION MODES

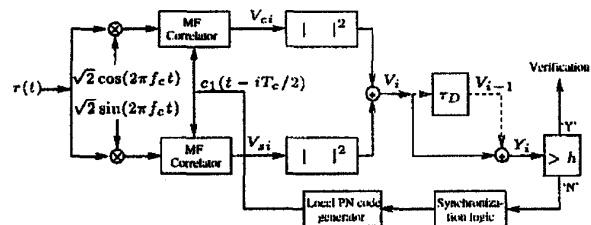


Figure 1: Acquisition block diagram.

The block diagram of the serial search mode and the detection mode is shown in Fig.1. The received signal is first down-converted to in-phase (I) and quadrature (Q) components. Two I-Q passive matched filters (or active correlators) perform correlation between the locally generated PN code and the in-phase and the quadrature-phase baseband signals. The I-Q matched-filter correlator performs the multiplication of the I or Q component of the received signal with its locally stored code replica $c(t - iT_c/2)$ in Fig.1 and integrates this product over the interval of $\tau_D = MT_c$ seconds, where τ_D represents the integral dwell time and M is an integer. The outputs of the I-Q matched filters are then squared and summed to give an output variable, which is expressed as V_i in Fig.1.

In this contribution two detection modes having a similar implementation complexity will be characterised, when signals transmitted over multipath fading channels are considered and multiple H_1 cells are assumed in the uncertainty region. The first is the conventional cell-by-cell detection scheme [1], in which the cells in the uncertainty region are searched and tested cell-by-cell independently. The gener-

ation of the decision variable Y_i is indicated by the continuous line in Fig.1, which is expressed as $Y_i = V_i$. Let h in Fig.1 be a threshold set for making a decision, whether the phase of the received PN signature sequence and the locally generated PN sequence is within the required small timing offset, so as to terminate the search mode and to proceed to the so-called verification mode, which is not analysed in this paper. Whenever the decision variable Y_i of Fig.1 exceeds the threshold h , the system assumes that the corresponding delay of the locally generated PN sequence is the correct delay and proceeds to the verification mode. Otherwise, if Y_i does not exceed h , the relative phase of the locally generated PN sequence is readjusted, in order to update the decision variable Y_i , and the above process is repeated.

The second detection mode is the so-called joint twin-cell detection scheme [5], in which the search and detection block diagram includes both the continuous and dashed lines in Fig.1. The statistics of the final decision variable are given now by those of the sum of two adjacent output variables, which is now expressed as $Y_i = V_{i-1} + V_i$. However, if the search mode detected a so-called false-alarm during the detection of Y_{i-1} , the term V_{i-1} in the decision variable Y_i would be set to zero. The search mode of joint twin-cell detection is similar to that of the conventional cell-by-cell detection, except that $Y_i = V_{i-1} + V_i$ or $Y_i = V_i$, which is decided by whether a false-alarm happened during the $(i-1)$ th detection.

Since each cell is classified as one of the two states, namely, H_1 and H_0 , hence, the first search mode with conventional cell-by-cell detection can be described as a two-state random Markov process [6], since each decision variable is decided by one cell, while the second search mode with joint twin-cell detection can be described as a four-state random Markov process [5], since the final decision variable is now decided by two cells. The acquisition performance of the serial search using the above two detection modes will be estimated over frequency-selective multipath fading channels associated with the multiple H_1 cells hypothesis in the following Sections.

3. MEAN ACQUISITION TIME

Due to the finite search step size and due to receiving multiple replicas of the transmitted PN sequence in multipath fading environments, usually there exist more than two states, in which the locally generated and the received sequence may become synchronous, hence satisfying the multiple H_1 cell hypothesis, as mentioned in Section 1.

Let P_{D_i} and β_i represent the detection and miss probabilities associated with the i -th detection attempt, leading to $\beta_i = 1 - P_{D_i}$. Then from Viterbi's Eq.(3.23) in [2] we obtain that if the number of cells in the uncertainty region is high, ie $q \gg 1$, then the MAT can be expressed as:

$$\bar{T}_{acq} \approx \frac{[1 + P_M(\lambda)](1 + K\alpha)}{2[1 - P_M(\lambda)]} \cdot (q\tau_D) \quad (1)$$

for a search mode with λ number of H_1 cells in the uncertainty region, where $P_M(\lambda) = \prod_{i=1}^{\lambda} \beta_i$ represents the total miss probability of a search over the full uncertainty region. Furthermore, α represents the false alarm probability associated with a H_0 cell, ie the probability of reaching a state as a consequence of accepting an incorrect hypothesis due to registering a high correlation peak, while $K\tau_D$ represents

the 'penalty time' associated with determining that there is a false alarm and with re-entering the search mode.

4. THE TRANSMITTED SIGNALS

The communication model under consideration consists of U simultaneous transmitters, which includes $U - 1$ data transmission users (who have completed acquisition) and one initial synchronization user (whose PN sequence has to be acquired by the base station). We assume that the first user is the initial synchronization user, whose performance has to be evaluated. Each user is assigned a unique CDMA sequence, which spreads the data. In this paper random signature sequences having a common chip rate of $1/T_c$ are considered. The processing gain is $G = T/T_c$, and $1/T$ is the information bit rate. Let $\{c_j^{(k)}\}$ denote a binary $\{+1, -1\}$ sequence with $c_j^{(k)}$ taking values of ± 1 with equal probability, and let

$$c_k(t) = \sum_{j=-\infty}^{\infty} c_j^{(k)} P_{T_c}(t - jT_c), \quad (2)$$

denote the signature sequence of the k th user, where $P_{T_c}(t) = 1$ for $0 \leq t \leq T_c$ and equals zero otherwise. The data waveform

$$b_k(t) = \sum_{i=-\infty}^{\infty} b_i^{(k)} P_T(t - iT), \quad (3)$$

consists of a sequence of mutually independent rectangular pulses of duration T and their amplitude takes values of ± 1 with equal probability. Hence the transmitted signal for the k th user is expressed as:

$$s_k(t) = \sqrt{2P_k} b_k(t) c_k(t) \cos(2\pi f_c t + \varphi_k), \quad (4)$$

where P_k represents the transmitted power of the k th user, f_c is the common carrier frequency and φ_k is the phase introduced by the k th modulator, which is modelled as a random variable uniformly distributed over $[0, 2\pi]$.

However, the presence of data modulation in the initial synchronization signal complicates the code synchronization process at the receiver in various ways [7]. Therefore, in many DS-SS systems the transmitter aids the initial synchronization by transmitting the phase-coded carrier signal without data modulation at the beginning of each transmission. Hence, in our analysis we shall assume for simplicity that there is no data modulation imposed on the signals transmitted for initial synchronization.

5. THE CHANNEL MODEL

A widely accepted model for a frequency-selective multipath fading channel is a finite-length tapped delay line with a tap spacing of one chip [8], where the L tap weights $\{\alpha_{ki}\}$ are assumed to be independent identically distributed (iid) Rayleigh random variables with probability density function (pdf) given by [8]:

$$f_{\alpha_{ki}}(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right), \quad x \geq 0, \quad (5)$$

where $E[\alpha_{ki}^2] = 2\sigma^2$, and the phases $\{\psi_{ki}\}$ are assumed to be uniformly distributed random variables in $[0, 2\pi]$, which

are independent of $\{\alpha_{ki}\}$. Furthermore, we assume that the fading is sufficiently slow in order to guarantee that the amplitude of the chips over the integral dwell time fades identically.

Then, the received signal at the base station can be viewed as the sum of the initial synchronization phase-coded carrier signal (the signal-of-interest), the $U - 1$ data signals (multi-user interference signals) and the additive white Gaussian noise (AWGN), yielding:

$$r(t) = \sum_{l=0}^{L-1} \sqrt{2P_R} \alpha_{1l} c_1(t - \tau_1 - lT_c) \cos(2\pi f_c t + \theta_{1l}) \\ + \sum_{k=2}^U \sum_{l=0}^{L-1} \sqrt{2P_I} \alpha_{kl} b_k(t - \tau_k - lT_c) c_k(t - \tau_k - lT_c) \\ \cdot \cos(2\pi f_c t + \theta_{kl}) + n(t), \quad (6)$$

where τ_k is the relative time delay associated with an asynchronous transmission scheme, $\theta_{kl} = \varphi_k - \psi_{kl} - 2\pi f_c(\tau_k + lT_c)$, which are modelled as iid random variables uniformly distributed in $[0, 2\pi]$ and $n(t)$ represents the AWGN with a double-sided power spectral density of $N_0/2$. Note that, since the $U - 1$ interfering users are in the data transmission process, we assume that their signals are ideally power-controlled and the average received power from each interfering signal is expressed as P_I . However, for the initial synchronization user it is impossible to realize ideal power-control before successful synchronization. This user can only invoke open-loop power control according to the estimation of the channel state, and hence the average received power at the base station from the initial synchronization user is usually different from that of the data transmission users, which is denoted in Eq.(6) as P_R . Moreover, we let $\rho = P_I/P_R$.

6. MEAN ACQUISITION TIME PERFORMANCE

In this Section, both the serial search scheme using conventional cell-by-cell detection and the joint twin-cell detection were characterised and compared based on their mean acquisition time (MAT) performance. As an application for the serial search with the above two detection schemes, we considered a periodic PN sequence of length 1024. Consequently, the number of search intervals in the uncertainty region of the serial search mode, was $q = 2048$, since the search step size was set to $T_c/2$. For convenience, we considered the normalized MAT, which was derived from the mean acquisition time given by Eq.(1) divided by the bit duration of $T = GT_c$, when different total miss probability and different false alarm probability were considered. The total miss probability and the false alarm probability were calculated for a given correlation threshold h , SNR/chip and for other relevant parameters values. The parameters used in our experiments are shown in the Figures. Note that three different energy-to-noise ratios were used in our analysis, namely SNR/chip, SNR per M chips, i.e the energy over the integral dwell time ($\tau_D = MT_c$ seconds) to noise ratio, and the SNR/bit, i.e the energy over the bit duration ($T = GT_c$ seconds) to noise ratio.

Fig.2 and Fig.3 show the normalized mean acquisition time performance both versus the normalized threshold h'

and the SNR/chip for the serial search modes using conventional cell-by-cell detection (Fig.2) and joint twin-cell detection (Fig.3), respectively. It is clear from Fig.2 and Fig.3 that an inappropriate choice of the detection threshold h' can lead to severe increase of the mean acquisition time, but the sensitivity of the MAT to the threshold decreases, as the SNR/chip increases. For any given SNR/chip value there exists an optimal choice of the threshold h' , which minimizes the value of the MAT. In addition, for any given normalized threshold h' , the MAT decreases, as the SNR/chip increases, and finally reaches a residual value, which is essentially due to the finite false alarm probability, and its associated 'penalty-time' required to revert to search.

In Fig.4 we evaluated and compared the mean acquisition time performance of the serial search schemes using both conventional cell-by-cell detection and joint twin-cell detection, with respect to the number of resolvable paths at the base station versus the signal-to-noise ratio per chip or SNR/chip. Observe that, for low SNR/chip values an increased number of resolvable paths can decrease the MAT, but for high SNR/chip values a high number of resolvable paths increases the MAT above the cross-over zone near -17dB. If we assume that a practical acquisition system operates at an average SNR/bit in the range of 5dB ... 20dB, which implies that the average SNR/chip is in the range of -16dB ... -1dB, then it is concluded that for this type of acquisition system a high number of resolvable paths associated with severe dispersion will degrade the MAT performance. From the results we find that the MAT performance of the joint twin-cell detection is about an order of magnitude better, than that of the conventional cell-by-cell detection. Moreover, the MAT performance of the joint twin-cell detection is more robust to the variation in the number of resolvable paths for a given threshold and a given SNR/chip, than that of the conventional cell-by-cell detection.

Fig.5 presents the MAT performance of the above two detection methods against the normalized threshold h' . For any given number of resolvable paths at the base station, and for a given SNR/chip, there is an optimal choice of the threshold h' , which leads to the minimum MAT. At the optimal value of h' we observe that for the conventional cell-by-cell detection or joint twin-cell detection the MAT performance is improved, although not dramatically, when the number of resolvable paths increases. However, if the value of the threshold is set inappropriately, especially when it is set above its optimum value, the MAT will significantly increase, as the number of resolvable paths increases. However, as we noted for Fig.4, the MAT performance of the joint twin-cell detection improved more significantly and became also more robust to the number of resolvable paths in a wide range of the normalized threshold h' from about 7 to 25, than that of the conventional cell-by-cell detection, assuming a given number of resolvable paths at the base station. Note furthermore that in a practical acquisition system, the threshold must not be set to a low value, because too low a threshold usually leads to too high a number of false alarms, and hence, due to the associated time delay, to an increased MAT.

The effect of the number of active users on the MAT performance is shown in Fig.6. The curves were plotted versus the number of simultaneously transmitting users, U , with SNR/chip values of -15dB, -10dB, -8dB. Hence, the

corresponding SNR/bit values are 6dB, 11dB and 13dB. As expected, the MAT of the serial search systems using both detection schemes increases, when the number of active users increases.

Finally, in Fig.7 and Fig.8 we evaluated the effect of varying the received power of the user-of-interest on the MAT performance for both detections. The curves of Fig.7 were plotted against the SNR/chip value, while the curves of Fig.8 were shown against the number of active users, U . The ratio of the interfering users' power to that of the user-of-interest, ρ , was taking values of $\rho = 10, 1, 0.1$, respectively. From the results we observe that in the range of SNR/bit values of 5dB ... 20dB or SNR/chip values of -16dB ... -1dB the MAT performance of both detection schemes was explicitly improved, when we increased the power of the user-of-interest. Moreover, it can be seen that the MAT performance of the joint twin-cell detection is more robust to the change of the power of the user-of-interest, than that of the conventional cell-by-cell detection. However, from a system capacity point of view, increasing the power of the initial synchronization users implies increasing the interference inflicted to the data transmission users, which consequently decreases the capacity of the system. Hence, in mobile DS-CDMA systems using the approach of increasing the initial synchronization user's transmitting power to aid acquisition should consider the trade-off between the mean acquisition time and the system capacity.

7. CONCLUDING REMARKS

The mean acquisition time performance of the conventional cell-by-cell detection and joint twin-cell detection has been compared over frequency-selective multipath fading channels. The results are applicable to the reverse link of a mobile DS-CDMA communication system using binary phase-shift keying (BPSK). The effects of multiple access interference, that of the number of resolvable paths at the base station and that of the received power of the initial synchronization user were investigated. From the results we conclude that the mean acquisition time performance of the serial search acquisition system using joint twin-cell detection is more robust to multiple access interference, to the detection threshold, to the number of the frequency-selective multipath components, and to the received power of the user-of-interest, than that of the conventional cell-by-cell detection. Moreover, the mean acquisition time performance of the joint twin-cell detection is significantly better than that of the conventional cell-by-cell detection.

8. ACKNOWLEDGEMENT

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9. REFERENCES

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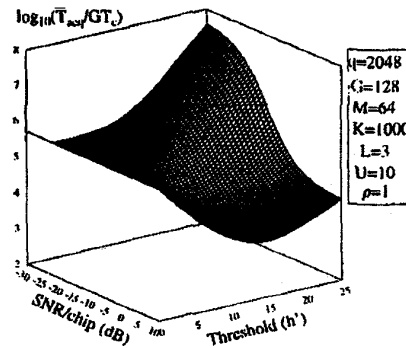


Figure 2: Mean acquisition time (MAT) versus SNR/chip and normalized threshold h' performance for the serial search scheme using conventional cell-by-cell detection with $q = 2048$ cells in the uncertainty region, processing gain of $G = 128$, integral dwell time of $\tau_D = 64T_c$, ie $M = 64$, 'penalty time' of $1000\tau_D$, ie $K = 1000$, $L = 3$ resolvable paths, $U = 10$ active users and an interfering user power to user-of-interest power ratio of $\rho = 1$.

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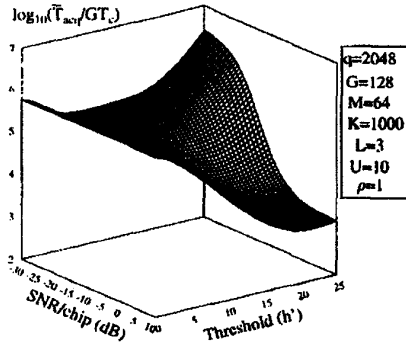


Figure 3: MAT versus SNR/chip and normalized threshold h' performance for the serial search scheme using joint twin-cell detection.

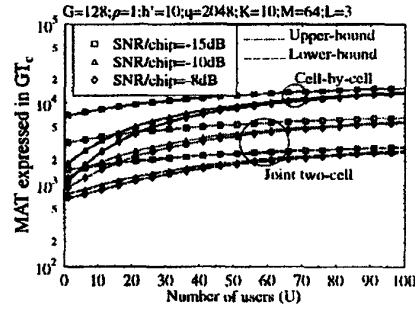


Figure 6: MAT expressed in bit durations, i.e. $T = GT_c$ versus the number of users, U , for the serial search scheme using conventional cell-by-cell detection and joint twin-cell detection.

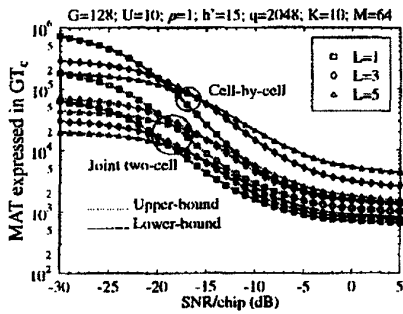


Figure 4: MAT expressed in bit durations, i.e. $T = GT_c$ versus SNR/chip performance for the serial search scheme using conventional cell-by-cell detection and joint twin-cell detection for $L = 1, 3, 5$.

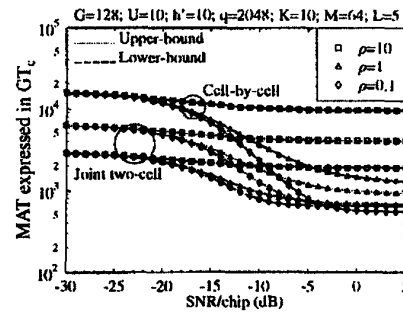


Figure 7: MAT expressed in bit durations, i.e. $T = GT_c$ versus SNR/chip performance for the serial search scheme using conventional cell-by-cell detection and joint twin-cell detection.

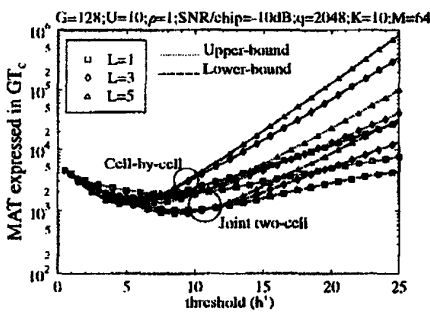


Figure 5: MAT expressed in bit durations, i.e. $T = GT_c$ versus the normalized threshold h' performance for the serial search scheme using conventional cell-by-cell detection and joint twin-cell detection for $L = 1, 3, 5$.

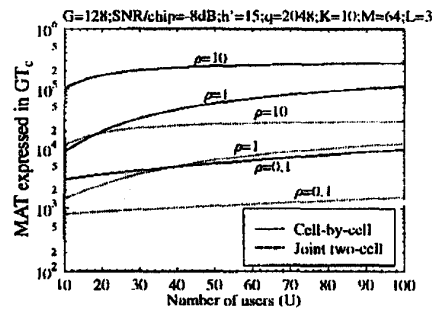


Figure 8: MAT expressed in bit durations, i.e. $T = GT_c$ versus the number of users, U , performance for the serial search scheme using conventional cell-by-cell detection and joint twin-cell detection parameterised by ρ , the ratio of the interfering user's power to that of the user-of-interest.