A SIMPLY-DIFFERENTIAL LOW-COMPLEXITY PRIMARY SYNCHRONIZATION SCHEME FOR 3GPP LTE SYSTEMS

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ABSTRACT

In this paper, downlink primary synchronization for LTE systems is investigated, including time synchronization and sector identification. The proposed scheme exploits the Primary Synchronization Signal which is generated from known Zadoff-Chu sequences. Unlike the conventional schemes, in which time synchronization is first processed then the demodulated OFDM symbols are cross-correlated with the known Zadoff-Chu sequences for sector identification, the proposed scheme simultaneously achieves both tasks. To this aim, the received signal is differentially auto-correlated and compensated with a frequency offset whose value depends on the used Zadoff-Chu sequence. The same metric allows detecting both the symbol timing and the sector identifier. Simulation results, carried in additive white Gaussian noise and Rayleigh multipath channels, show the efficiency and reliability of the proposed primary synchronization scheme. We note that, compared to former methods, the proposed one not only leads to performance enhancement but also realizes a considerable complexity reduction.

***Index Terms*—** 3GPP LTE, OFDM, time synchronization, sector search, Zadoff-Chu sequences

1. INTRODUCTION

The Long Term Evolution (LTE) is an upcoming mobile communication standard specified by the 3rd Generation Partnership Project (3GPP) with orthogonal frequency-division multiple access and single-carrier frequency-division multiple access being adopted respectively in Downlink (DL) and uplink access schemes [1]. The Orthogonal Frequency Division Multiplexing (OFDM) technique was chosen for its robustness to multipath fading channels, high spectral efficiency and simple receiver architecture [2]. However, it is well known that OFDM systems are very sensitive to synchronization errors which makes accurate synchronization a requisite processing at the User Equipment (UE) receiver.

In order to transfer data correctly, the UE must be synchronized with the serving cell. Each cell is identified by the cell identifier (cell-ID), composed of the Sector identifier (S-ID) and the Group identifier (G-ID). The S-ID is defined by the Primary Synchronization Signal (PSS) and the G-ID is defined by the Secondary Synchronization Signal (SSS) sent regularly for synchronization and cell search purposes. The overall DL synchronization performance depends heavily on a robust PSS detection as it is the first processed task. The PSS is generated from a 63-length Zadoff-Chu (ZC) sequence which is characterized by its near-perfect correlation properties.

In many of the existing primary synchronization approaches as in [3]-[5], time synchronization is first processed. Then, sector identification is performed through a cross-correlation between either the extracted frequency domain OFDM symbols and the three known ZC sequences or the received time domain signal with known PSS candidates. Even if robust PSS identification is obtained thanks to ZC sequences properties, the full-length correlation incurs a high computational load and the S-ID determination delay is unsuitable in high-mobility environment.

In this paper, a robust and low-complexity PSS detection algorithm is proposed. Its main contribution is the particularity of joint S-ID determination and time synchronization. Unlike the conventional algorithms, the proposed one introduces a simply-differential correlation based metric that carries PSS start detection and S-ID determination in a unique step. Hence, fast and reduced-complexity primary synchronization is offered.

The rest of the paper is organized as follows. Section 2 reviews the LTE specification and primary synchronization signal. The proposed time synchronization and S-ID detection algorithm is described in Section 3. Then, simulation results are displayed in Section 4. Finally, the conclusion is drawn in Section 5.

2. OVERVIEW OF LTE SYSTEM

LTE, as a transition from the 3rd generation to the 4th generation, has achieved greater capacity and higher speed of mobile telephone networks. It provides scalable carrier bandwidths from 1.4 MHz to 20 MHz and supports both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) modes. We here focus on the FDD mode.

2.1. LTE downlink frame structure

In LTE systems, the transmitted signal is organized into radio frames of $10ms$ duration, each consisting of 10 sub-frames of length $1ms$ which are further divided into two slots of $0.5ms$ each. Depending on whether normal or extended CP is used, a slot contains 7 or 6 OFDM symbols of duration equal to $66.7\mu s$ each. Among them, two OFDM symbols are reserved for synchronization and cell search purposes. These symbols, known as primary and secondary synchronization signals (PSS and SSS), are sent regularly (in each sub-frame) at the last two OFDM symbols of slot 0 and slot 10. Data are mapped on a time-frequency resource grid consisting of elementary units called resource elements defined as one 15 kHz sub-carrier by one symbol. Resource elements aggregate into resource blocks having dimensions of 12 consecutive sub-carriers in the frequency domain over 6 OFDM symbols for extended CP or 7 OFDM symbols for normal CP [6].

2.2. Primary Synchronization Signal

As its name specifies, the PSS is used for synchronization as well as cell search and more precisely sector identification. Three identities are defined, each specified by a ZC sequence that we here denote by d_u, of root u, generated in frequency-domain according to

$$d_u(n) = e^{-j\frac{\pi u n(n+1)}{N_{zc}}},\ 0 \leq n \leq N_{zc} - 1, \qquad (1)$$

where N_{zc} stands for the sequence length which is standardized to 63 samples. The PSS is designed to use one out of three possible ZC sequences of root $u \in \{25, 34, 29\}$ which defines the S-ID (ranging from 0 to 2). We note that the 32^{nd} sample is omitted and only 62 samples of the ZC sequence are mapped on the 62 centered sub-carriers in the transmission bandwidth. This means that the five resource elements at each side of the synchronization sequence are set to zero [6].

The corresponding time-domain signal is generated using an IFFT, whose size as well as the number of sub-carriers set to zero in both sides of the ZC sequence depend on the system bandwidth. Sub-carriers that are not used for transmission of synchronization signals can be used for data transmission.

2.3. OFDM signal

The OFDM signal is obtained from the summation of subcarriers modulated using QAM or PSK. The modulator/demodulator can be easily implemented by IFFT/FFT. The OFDM system employs an FFT of size $N_u = 2^n$ samples and a CP of N_g samples, forming an OFDM symbol of length $N = N_u + N_g$. We note that, in the LTE specifications, the first OFDM symbol of each slot has a CP longer than the other symbols, that we here denote by N_{g1}.

We consider a frequency selective multipath channel of P paths with memory length L and impulse response coefficients denoted by h_l, $l = 0, 1, ..., L-1$. A misalignment between the local oscillators of the transmitter and the receiver induces a frequency offset normalized with respect to subcarriers spacing and denoted by ν. In this case, the received samples are expressed as

$$r_k = e^{j2\pi\nu k/N_u} \sum_{l=0}^{L-1} h_l s_{k-l} + \omega_k, \qquad (2)$$

where s_k stands for the k^{th} transmitted sample, ω_k is the k^{th} sample of a zero-mean complex Additive White Gaussian Noise (AWGN) of variance σ_ω^2.

3. TIME SYNCHRONIZATION AND SECTOR SEARCH

3.1. Conventional approaches

Actually, the PSS detection in LTE systems has been considerably studied in many works. In [3], the CP based autocorrelation is first employed to grossly determine the symbol timing. Then, the S-ID is determined by cross-correlating the 62 centered sub-carriers of the extracted frequency-domain symbols with replicas of known ZC sequence candidates. In [4], lagged auto-correlation was developed to estimate a coarse symbol start. Then, the accurate symbol start and the S-ID are estimated by cross-correlating either the received signal (before FFT) with the PSS candidates or the extracted symbols (after IFFT) with the ZC sequence candidates. An adaptive algorithm was proposed in [5] for S-ID search once symbol detection is carried as in [3]. This algorithm correlates the extracted OFDM symbols with the three ZC sequence candidates using either non-differential correlation or differential correlation, depending on the channel delay spread. We note that the two-step processing adopted in most of the existing primary synchronization approaches delays the cell-search procedure.

3.2. Proposed approach

To make the detection faster, we here propose a robust PSS detection scheme whose aim is to reduce time synchronization and S-ID search complexity with a sufficiently high accuracy. To this purpose, we suggest a simply-differential correlation based metric that jointly detects the S-ID and the PSS start in a single reduced-complexity stage. The metric is hereafter detailed for two scenarios: first when ZC sequence is exploited directly in time domain, then when it is transmitted in frequency domain (after IFFT).

3.2.1. *Time-Domain based metric*

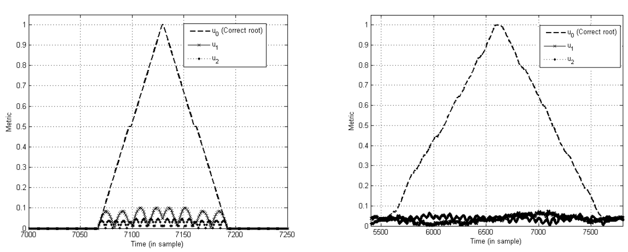
This metric makes use of the sequence λ, that we define as the differential correlation outcome of the l^{th} received sample with its q-shifted counterpart: $\lambda_l = r_l^* r_{l+q}$. When the received samples coincide with the PSS and under noiseless conditions, λ becomes

$$\begin{aligned}\lambda_l &= e^{j\pi ul(l+1)/N_{zc}} e^{-j\pi u(l+q)(l+q+1)/N_{zc}} \\ &= e^{-j\pi u(2ql+q^2+q)/N_{zc}}.\end{aligned} \tag{3}$$

When compensated with its complex conjugate, λ_l turns into a constant for samples taken in the ZC sequence. We exploit this aspect to define the metric M^u that sums the compensated elements over N_{zc} samples as

$$M^u(k) = \left| \sum_{l=k}^{k+N_{zc}-1} \lambda_l e^{\frac{j\pi u}{N_{zc}}(2ql+q^2+q)} \right|. \tag{4}$$

As shown in figure 1.a, the magnitude of the metric corresponding to the sector with the highest signal presents an important peak compared to the other correlation terms due to orthogonality between the chosen ZC sequences. Simultaneously, the peak provided by the correlation with the correct ZC sequence candidate indicates the ZC sequence position within the OFDM symbol, thus allowing time synchronization as the ZC sequence position within the radio frame is already known.



(a) Time domain (b) Frequency domain

Fig. 1. The proposed metric M^u under noiseless conditions.

It is worth to note that the metric M^u in (6) must be carried three times (once for each root u) to get the expected result, which leads to an exhaustive treatment similar to that of the conventional previously cited approaches. Yet, the present metric has the advantage of possible recursive implementation for complexity reduction as

$$M^u(k+1) = M^u(k) + m^u(k+N_{zc}) - m^u(k), \tag{5}$$

where

$$m^u(k) = \lambda_k e^{\frac{j\pi u}{N_{zc}}(2qk+q^2+q)}. \tag{6}$$

In the initial metric (6), the computation of each element $M^u(k)$ requires $2N_{zc}$ complex multiplications, which must be carried three times for the three possible ZC sequence roots. However, (7) reduces the number of complex multiplications to only 4 with additional 2 complex additions whose computational load is trifling compared to that of the complex multiplication. Thus, $2N_{zc} - 4$ complex multiplications (96%) are saved.

3.2.2. *Frequency-Domain based metric*

The previous equations (6) and (7) are provided for ZC sequences taken in time domain, which is not the case in LTE specifications. Due to duality between time domain and frequency domain ZC sequences, the IFFT of a ZC sequence preserves its properties and remains a ZC sequence, yet with different root [8]. Hence, the metric in (6) is applicable in the LTE system yet with the different root u' of the new ZC sequence resulting from the IFFT of the original ZC sequence. As u' is unknown, we propose to determine off-line the optimal compensation frequency $\delta = u'q/N_{zc}$, which offers near-best performance, for each of the three possible ZC sequences and for a given shift q. In the sequel, we search the best couple (u', q) (in the sense of frequency compensation) for each original ZC sequence. To this aim, we use the function below for each initial root u

$$F^u(\delta, q) = \left| \sum_{n=0}^{N_u-1} \alpha(n)\alpha^*(n+q) e^{\frac{-j2\pi n}{N_u}\delta} \right|, \tag{7}$$

where α stands for the N_u-point IFFT output of the initial ZC sequence of root u. The search of the best compensation frequency is carried in two phases. First a coarse frequency δ_c^u is determined using a slightly large step. Then, $F^u(\delta, q)$ is refined around δ_c^u with a very thin step to get a finer compensation frequency δ_f^u. Figure 2 shows the curves of δ_f^u search around δ_c^u for the optimal shift values q_{opt}^u (corresponding to each original ZC sequence). The three maximum arguments δ_f^u (for the three ZC original roots) will be used at the receiver in the compensation of λ_l terms phases (λ being the differentially correlated version, using the shift q_{opt}^u, continuously calculated on the received signal).

It is worth to note that, respecting the LTE specified signal, the sum in the metric (6) must now be carried from 0 to $N_u - 1$ (the length of the oversampled ZC sequence) and the compensation term for the k^{th} index becomes $e^{\frac{j2\pi k}{N_u}\delta}$.

As shown in figure 1.b, when carrying the metric with the new parameters (δ_f^u and an N_u sliding window) and for the correct root, it keeps the triangular shape with a gap wider than that of the initial metric in (6). Also, it exhibits a plateau of length equal to the CP length minus the channel memory. To overcome the plateau effect, we here find the points to the left and right, which are 90% of the timing metric maximum, average these two 90% times and add $N_g/2$ samples to find the PSS start estimate.

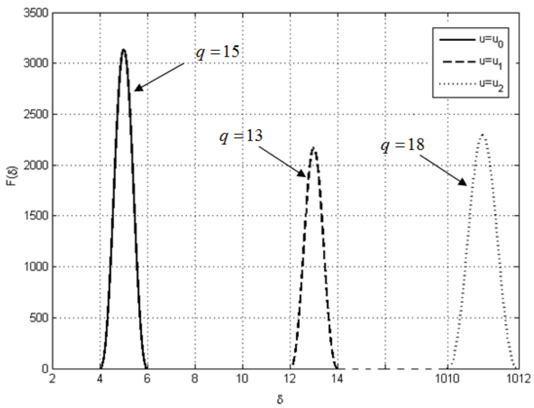


Fig. 2. The metric $F^u(\delta, q)$ for different roots u (fine search around δ_c^u for a shift q_{opt}^u).

4. SIMULATION AND NUMERICAL RESULTS

In this section, performance of the proposed time synchronization and sector identification approach are evaluated and compared to the considered benchmarks [3] (non-differential based approach) and [5] (differential based approach) denoted respectively by Approach 1 and Approach 2. Time synchronization is evaluated in terms of symbol start Correct Detection Rate (CDR) and estimation variance. The CDR is defined as the percentage of realizations where the estimated symbol start coincides with the true one. The sector search is evaluated in terms of Failure Detection Rate (FDR) of the S-ID. Monte Carlo simulation method is here adopted for 10^5 trials. The detailed simulation parameters are given in table I (specified in [7]).

Parameter	value
Channel bandwidth	10 MHz
Sampling frequency	15.36 MHz
Number of IFFT points, N_u	1024
Cyclic prefix duration, N_g	72
Sub-carrier spacing	15 KHz
Number of Tx/Rx antenna	1/1
Channel	AWGN/ 7-path Rayleigh
Modulation	4-QAM

Table 1. Simulation Parameters

Figure 3 presents the CDR of the considered approaches in the case of AWGN and Rayleigh multipath channels. In the latter channel, an error of 4 samples centered on the exact symbol start (±2 samples) is tolerated for the approaches 1 and 2. In both cases, the proposed approach provides satisfactory detection accuracy and outperforms the considered benchmarks. Indeed, from SNR value of 5 dB, the detection becomes perfect (CDR of 100%) in the AWGN channel and it stagnates at a rate of 98% in the Rayleigh multipath channel. We note that Approach 1 and 2 provide almost the same detection performance that stagnates at CDR of about 79% and 52% in the AWGN and Rayleigh multipath channels, respectively.

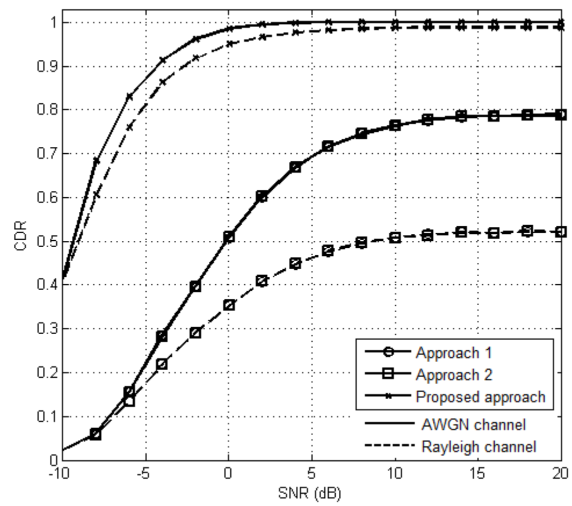


Fig. 3. Correct Detection Rate of the symbol start in the case of AWGN and Rayleigh multipath channels.

Consistently with the previous results, the low variance of the symbol start estimate presented in figure 4 ensures the efficiency of the proposed approach, compared to the considered benchmarks. To enhance the performance of the blind approaches 1 and 2, the detection is averaged over several OFDM symbols (a whole slot of 7 OFDM symbols) as explained in [3]. In the AWGN channel, the proposed approach provides the lowest variance that vanishes at SNR value equal to 10 dB, whereas the curves of the benchmarks stagnate at values of about 10 squared samples. However, in the Rayleigh channel, the proposed approach provides slightly higher variance for SNR values lower than 0 dB. For higher SNR values, the proposed estimator outperforms the considered benchmarks realizing a gain of about 3 dB.

Figure 5 shows the failure detection rate of the sector identifier search. Generally, all approaches provide satisfactory detection. In the case of AWGN channel, a perfect S-ID detection is achieved from SNR values of -7 dB, -2 dB and 2 dB respectively for the proposed approach, differential-based approach and non-differential based one. For very low SNR values (-9 in the AWGN channel and -7 in the Rayleigh multipath channel), Approach 2 outperforms the proposed approach and it always provides better detection than Approach 1. For a failure detection rate of 10^{-3}, gains of about 4 dB and 2 dB are realized by the proposed approach in the AWGN and Rayleigh multipath channels respectively.

We also assess the complexity of the considered ap-

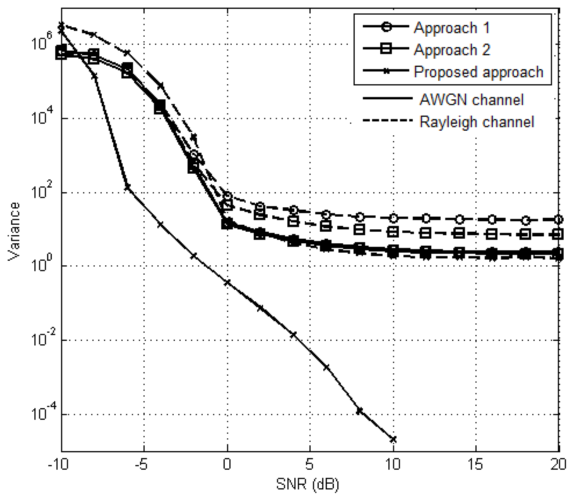


Fig. 4. Symbol start estimation variance in the case of AWGN and Rayleigh multipath channels.

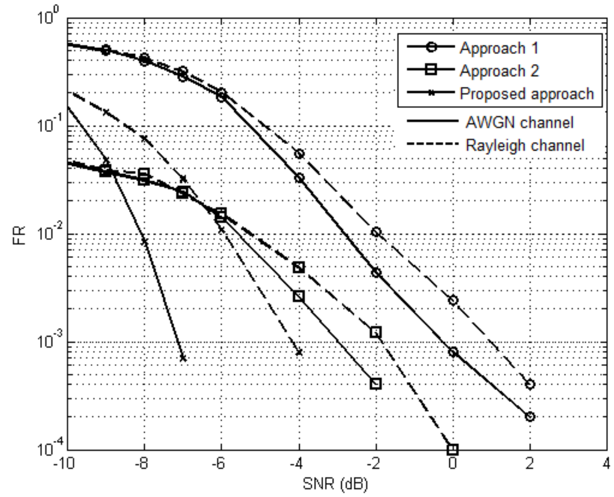


Fig. 5. FDR of the sector ID in the case of AWGN and Rayleigh multipath channels.

proaches needed to accomplish the primary synchronization during one slot, which is presented in table II. The complexity is evaluated in terms of Number of Complex Multiplications (NCM). We define the slot length as $N_s = 7N_u + 6N_g + N_{g1}$.

Approach	NCM	Num. Exp.
Approach 1	2x$N_s + (62^2)$x7x3	96.1 10^3
Approach 2	2x$N_s + (62^3)$x7x3	50.2 10^5
Proposed approach	3x4xN_s	92.2 10^3

Table 2. Computational complexity comparison among the three PSS detection approaches (numerical example)

It is observed, that the proposed approach has the lowest computational complexity compared to both of the considered benchmarks. Indeed, numbers of 4 10^3 and 49 10^5 complex multiplications are saved compared to the non-differential correlation based approach and the differential correlation based approach, respectively. Furthermore, as shown in the previous results, the proposed approach offers much better performance than the benchmarks.

5. CONCLUSION

In this paper, we proposed a robust and reduced-complexity time synchronization and sector search approach for LTE systems. Unlike the conventional approaches, the proposed one has the particularity of combining time synchronization and sector search in a single stage. Indeed, the same simply-differential metric was used to jointly estimate the PSS start and the sector ID. Simulation investigated in AWGN and multipath Rayleigh channels showed the robustness and the efficiency of the proposed approach. Furthermore, its reduced complexity, compared to the considered benchmarks, makes it suitable to working in a high-mobility environment with a frequent handover being performed.

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