On the Cell Search and Initial Synchronization for NB-IoT LTE Systems

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***Abstract*— In the Narrowband Internet-of-Things (NB-IoT) LTE systems, the device shall be able to blindly lock to a cell within 200-KHz bandwidth and with only one receive antenna. In addition, the device is required to setup a call at a signal-to-noise ratio (SNR) of −12.6 dB in the extended coverage mode. A new set of synchronization signals have been introduced to provide data-aided synchronization and cell search. In this letter, we present a procedure for NB-IoT cell search and initial synchronization subject to the new challenges given the new specifications. Simulation results show that this method not only provides the required performance at very low SNRs, but also can be quickly camped on a cell, if any.**

***Index Terms*—LTE, MTC, NPSS, NSSS.**

I. INTRODUCTION

WITH the large coverage and flexible data rates offered by cellular systems, scenarios defined by recent Long-Term-Evolution (LTE) releases emerge as the most promising solutions to enable wireless infrastructure of Machine Type Communication (MTC) technology and NB-IoT. Since the core IoT devices or massive MTC devices typically send small amounts of data and require extended coverage, a special category, namely NB-IoT, has been incorporated to LTE specifications to support IoT features [1]. The design targets for this special category require reduced complexity, promote battery longevity, and Enhanced Coverage (EC). The link budget of NB-IoT has a 20 dB improvement over conventional LTE-A [2]. NB-IoT intends to occupy a narrow bandwidth of only 200 KHz, which is not backward compatible to the supported bandwidths by the legacy LTE. Therefore, NB-IoT redefines the cell attach procedure including cell search and initial synchronization. During initial synchronization, carrier frequency offset (CFO) is estimated and compensated to enable proper signal detection. The User Equipment (UE) acquires the physical cell identification (ID) by employing the cell search procedure. To cope with these changes, NB-IoT employs new set of synchronization signals, namely Narrowband Primary Synchronization Signal (NPSS) and Narrowband Secondary Synchronization Signal (NSSS) [3], [4]. The new sequences have different bandwidth, mapping, periodicity, and generation when compared to the legacy LTE synchronization signals.

In this paper, we propose an algorithm to provide an initial timing and frequency acquisition and efficiently search for the serving cell ID. Further, current literature lacks the optimizations required for these algorithms. Thus, we rely on scenarios/results from the industry [3]–[5] not only to validate our realistic environment but also to validate our results. As shown in Fig. 1, after the RF processing and blocking filtering, a coarse subframe timing is jointly obtained with CFO by employing NPSS time domain (TD) correlations. Then, the received signal can be converted to the Frequency Domain (FD) after Cyclic Prefix (CP) removal. Cell ID and frame timing are acquired by utilizing matched filters to NSSS sequences. In fact, a new challenge is to keep the cell search and initial synchronization with high accuracy and reasonable processing time at very low SNRs. Therefore, an averaging mechanism tackles the trade-off between performance and processing time. The rest of the paper is organized as follows. The system and signal models are introduced in section II. In section III, the proposed cell search and initial synchronization procedure is presented. Finally, the performance is evaluated with computer simulations in section IV.

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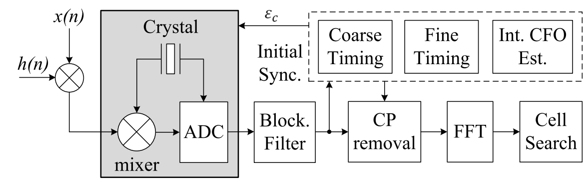

Fig. 1. Block diagram for the NB-IoT receiver to show the processing chain for cell search and initial synchronization procedure.

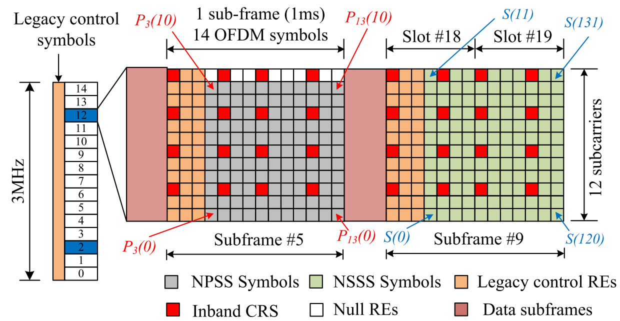

Fig. 2. Radio frame structure for in-band NB-IoT systems with two Tx antennas. The allocated RB is expanded in time to show the NPSS/NSSS symbols mapping. Two anchor PRBs are highlighted for 3MHz LTE-A cell. $P_l(k)$ and $S(k)$ illustrate the mapping for NPSS and NSSS, respectively.

II. SYSTEM AND SIGNAL MODELS

Fig. 2 shows a 3MHz LTE carrier in which an anchor Physical Resource Block (PRB) is assigned to NB-IoT for an in-band operation. Since LTE employs Orthogonal Frequency Division Multiplexing (OFDM) as a multi-carrier modulation technique, the NB-IoT band is defined as a contiguous set of 12 sub-carriers forming one PRB. A single radio frame is 10 ms which consists of 10 sub-frames. Each sub-frame is divided into two slots with equal periods. Unlike conventional LTE which defines two CP types with different patterns [6], NB-IoT in Release-13 supports only the normal CP type, where a slot is composed of 7 OFDM symbols. According to the standard [2], if the signal is sampled at 1920 KSamples/sec, the CP length, say L, of the first symbol in each slot is 10 samples and those of the other symbols are 9 samples long. Also, the TD OFDM symbol spans $N = 128$ samples.

Unlike legacy LTE-A, NPSS and NSSS sequences are constructed from a frequency domain Zadoff-Chu (ZC) sequence where NPSS length is 11 samples while the NSSS consists of 132 samples. Indeed, ZC sequences satisfy the Constant Amplitude Zero Autocorrelation (CAZAC) property which limits the Peak to Average Power Ratio (PAPR) and provides ideal cyclic autocorrelation. The NPSS, $P_l(k)$, is generated such that $P_l(k) = Q(l)e^{-j\pi uk(k+1)/11}$, where $0 \leq k < 11$, $3 \leq l < 14$ is the OFDM symbol index, the sequence root $u = 5$, and $Q(l)$ is a modulation sequence given by $\{1, 1, 1, 1, -1, -1, 1, 1, 1, -1, 1\}$, respectively. In NB-IoT system, there are still 504 unique physical cell IDs. However, all of them are only indicated by the NSSS. The NSSS, $S(k)$, is generated according to,

$$S(k) = \bar{C}_q(k')\, e^{-j2\pi\theta_f k}\, e^{-j\frac{\pi uk''(k''+1)}{131}}, \quad 0 \leq k < 132 \tag{1}$$

where $k'' = k \bmod 131$, $k' = k \bmod 128$, the root sequence, u, is related to the cell ID, N_{ID}^{Ncell}, by $u = (N_{ID}^{Ncell} \bmod 126)+3$, and the cyclic shift, θ_f, is related to the radio frame index, n_f, such that $\theta_f = \frac{31}{132}(n_f/2) \bmod 4$. The modulated sequence, $\bar{C}_q(k')$, is given by $\bar{C}_q(k') = 2C_q(k') - 1$, where q is a cell specific parameter that is given by $q = \lfloor N_{ID}^{Ncell}/126 \rfloor$ and C_q forms four complementary 128-bits binary sequences. NPSS is mapped to subframe 5 of every radio frame. NSSS is mapped to the last 11 OFDM symbols of subframe 9 in radio frames having $n_f \bmod 2 = 0$. Sequences are mapped to frequency sub-carriers in an increasing order, then applied across time as shown in Fig. 2.

Let $x(n)$ be a transmitted baseband OFDM signal. The received signal is given by,

$$r(n) = \Big[x(n) \star h(n)\Big]e^{j2\pi\varepsilon_c n/N} + w(n) = y(n) + w(n) \tag{2}$$

where $h(n)$ is the impulse response of the multipath channel, $w(n)$ represents the additive white Gaussian noise (AWGN), and $\star$ denotes convolution. In OFDM systems, CFO is typically normalized to the sub-carrier spacing where the total normalized CFO, ε_c, is represented by two terms: the fractional CFO, ε_F, and the integer CFO, ε_I, such that $\varepsilon_c = \varepsilon_I + \varepsilon_F$. A Fast Fourier Transform (FFT) engine is utilized to synthesize the received symbols to the FD which is given by (3), where $r_l(n)$ represents the l^{th} OFDM symbol after CP removal.

$$R_l(k) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} r_l(n)e^{-j2\pi kn/N}, \quad 0 \leq k < N \tag{3}$$

III. Proposed Initial Synchronization and Cell Search for NB-IoT Systems

In this section, we present the initial synchronization and cell search procedure for NB-IoT. The procedure has two parts: timing and frequency acquisition, followed by cell search.

A. Cell Search

In legacy LTE, where semi-synchronous network architecture is assumed, the Secondary Synchronization Sequence (SSS) can be coherently identified [7]. Unfortunately, according to the specifications [3], NPSS and NSSS may not be transmitted from the same antenna port. Hence channel estimates cannot be easily obtained. Also, NSSS samples are cyclic shifted according to the radio frame number and this quadruples the number of hypotheses to detect the cell ID. Indeed, in NB-IoT, cell search aims to acquire the cell ID and frame timing within an ambiguity of 80 ms. Frame timing is essential for UE to align the start of a possible broadcast channel detection whose repetition pattern rolls over every 80 ms. For NB-IoT systems, complexity and imperfect conditions are the main challenges for cell search.

Since NSSS sequence spreads across multiple OFDM symbols, fractional CFO would introduce high distortion to the received sequence. For example, a small fractional CFO of 1.275 KHz would introduce a phase difference of $2\pi \times 1.275 \times 1508/1920 \simeq 2\pi$ across the whole NSSS sequence, where 1508 represents the number of TD samples for NSSS sequence. This means that half of the sequence suffers from sign negation which is sufficient to mix between sequences. A possible consequence is to incorrectly detect the desired sequence especially that the sign may be the only differentiation between two NSSS sequences. A similar impact can be noticed from large timing drifts. For these reasons, cell search performance is subjected to the accuracy of the initial synchronization mechanism. To achieve certain performance, cell search can define targets for timing and frequency tolerances resulted from the initial synchronization stage. Fortunately, NB-IoT is designed such that initial synchronization can completely rely on only NPSS to achieve these targets.

An optimal matched filter (MF) detection aims at maximizing the SNR for AWGN channels but the main challenge comes from its complexity. We present a reduced complexity high performance MF approach for NB-IoT cell search. For a given NSSS window, m, the decision statistic for a bank of matched filters representing all possible NSSS combinations is defined by (4), where k_0 is the first sub-carrier to which NSSS is mapped, $R_l^m(k)$ is the received NSSS within window m, at sub-carrier k and OFDM symbol l, and $S_l^{\{i,n_f\}}(k)$ is one reference NSSS for cell ID i, frame number n_f, at sub-carrier k and OFDM symbol index l.

$$\Lambda_m(i, n_f) = \sum_{l=3}^{13}\sum_{k=k_0}^{k_0+11} R_l^{*m}(k)S_l^{\{i,n_f\}}(k) \tag{4}$$

To encourage noise rejection and to improve performance at very low SNR values and low mobility channels, the final decision statistic, $\bar{\Lambda}(i, n_f)$, is obtained by averaging the MF outputs over M consecutive windows such that $\bar{\Lambda}(i, n_f) = \frac{1}{M}\sum_{m=0}^{M-1}\Lambda_m(i, n_f)$. The estimated cell ID and frame timing is then evaluated as, $\{\widehat{N}_{ID}^{Ncell}, \widehat{n}_f\} = \arg\max_{\forall i, n_f}\left|\bar{\Lambda}(i, n_f)\right|$. To obtain the best gain, averaging has to be careful about which windows to average so that they follow the correct pattern of the possible frame timing, n_f. Fortunately, divide and conquer can be applied to reduce the number of multiplications to its one-fourth and hence reduce the complexity. The idea is that for every 4 cell IDs, there is a single root ZC sequence while the cells are differentiated according to the complementary sequences. Thus, computing the correlation can be divided into two sequential processes. During multiplication process, only ZC sequence is utilized to represent the reference NSSS. Next, accumulation is evaluated four times for each ZC sequence, where each complementary sequence is employed as weighting factors before applying the accumulation. Further optimization is possible by identifying the portions of the complementary sequences that are shared among multiple complementary sequences. This could save repeating the same accumulation for this portion again. At least, this process would save 199.5 K multiplications out of $504 \times 4 \times 132 \simeq 266$ K operations when compared to [8].

B. Timing and Frequency Acquisition

Similar to NSSS, fractional CFO can degrade the performance of NPSS detection. For this reason, it is essential to estimate and mitigate the fractional CFO before further NPSS processing for a possible integer CFO in addition to the fine symbol timing. In [3], a three step procedure is presented where the signal is processed at a lower sampling rate of 240 KHz to acquire coarse timing. Then, a refinement process is applied to introduce a sample accurate timing in addition to a relatively small frequency tolerance (i.e., ± 50 Hz) for decoding purposes. Instead of addressing a fractional timing issue in a separate timing refinement step [3], a fast two-stage procedure can be applied while the sampling rate is kept at 1.92 MHz. Indeed, initial synchronization is rarely repeated as long as UE is in a connected mode and hence power consumption might not be an issue for higher rates.

The first step is to employ an averaged TD auto-correlation function to explore the repetitive nature of the NPSS sequence across OFDM symbols [9]. Fractional CFO estimation comes with a coarse timing in this stage. Since NPSS repeats every 10 ms, the auto-correlation window would be over $N_w = 19200$ samples. Again, an averaging process is applied to reduce the noise effect. Before any further processing and assuming slow fading channels, the auto-correlation from different windows are coherently averaged over M consecutive windows, as given by (5), where $N_s' = 137$ is the OFDM symbol period such that a single sample is dropped every 959 samples to maintain timing continuity. In this expression, the NPSS modulation sequence is used to filter the autocorrelation such that NPSS de-spreading maximizes the averaged auto-correlation at the proper timing. Coarse timing and fractional frequency offset can jointly be acquired such that $\hat{\tau} = \arg\max_{\forall k} |\mathcal{R}(k)|$, $0 \le k < N_P$, and $\hat{\varepsilon}_F = \frac{N}{2\pi N_s'} \angle \mathcal{R}(\hat{\tau})$.

$$\mathcal{R}(k) = \sum_{m=0}^{M-1} \sum_{n=mN_w+k}^{(m+1)N_w+k-1} \Big[Q(\mathrm{mod}(\lfloor n/N_s' \rfloor, 11)) r(n) \Big] \times \Big[Q(\mathrm{mod}(\lfloor n/N_s' + 1 \rfloor, 11)) r(n + N_s') \Big]^* \tag{5}$$

Due to a possible sampling frequency error, it is expected that the maximum auto-correlation peak vary around the accurate symbol timing. Thus, a range of samples defined by $\hat{\tau} \pm \delta$ is utilized around $\hat{\tau}$ to refine the timing, where δ is a design parameter. After fractional CFO compensation, the second step for initial acquisition employs NPSS MF to jointly acquire the fine symbol timing and the integer frequency offset. Let us define the cross-correlation function, $\Lambda_m(\bar{\tau}, \varepsilon_I)$, within a correlation window m, as given by (6), where $p(n)$ is an N_P-samples sequence representing the concatenated TD OFDM symbols carrying the NPSS (i.e., $N_P = 1508$ samples) and $\bar{\tau} \in [\hat{\tau} - \delta, \hat{\tau} + \delta]$.

$$\Lambda_m(\bar{\tau}, \varepsilon_I) = \sum_{n=\hat{\tau}-\delta}^{\hat{\tau}+\delta+N_P-1} r(n) p^*(n - \hat{\tau} + \delta) e^{\frac{j2\pi\varepsilon_I (n-\hat{\tau}+\delta)}{N}} \tag{6}$$

The idea is to introduce progressive phase shifts for the reference TD NPSS sequence before applying the cross correlation. Hypotheses are defined to generate the pre-correction phase shifts as a function of the claimed integer frequency offset. It is generally assumed [10] that the oscillator mismatch produces an integer frequency offset in the range $\varepsilon_I \in [-2, +2]$. In order to preserve a good performance, the decision statistic is averaged over P consecutive NPSS windows to further reject the noise. Maximizing the average cost function over all possible integer frequency offsets and various timing offsets will provide a joint estimate for the refined subframe timing and the integer frequency offset as given by (7). In terms of complexity, the second step requires $5(2\delta + 1)N_P$ multiplications per window which is indeed a reduced complexity compared to a flat NPSS MF, that would consume $5N_w N_P$ multiplications, to exhaustively search for the timing and integer frequency offset.

$$(\hat{t}, \hat{\varepsilon}_I) = \arg \max_{\forall \bar{\tau},\, \varepsilon_I \in [-2, +2]} \left| \frac{1}{P} \sum_{m=0}^{P-1} \Lambda_m(\bar{\tau}, \varepsilon_I) \right| \tag{7}$$

IV. Simulation Results

To evaluate the performance of the presented procedure, the baseband downlink NB-IoT system has been simulated assuming a sampling rate of 1.92 MHz, 128-point FFT, 15 kHz sub-carrier spacing, two antennas at transmitter and one antenna at receiver. AWGN and EPA-5 standard channels were simulated [7]. EPA-5 has a large coherence time (maximum Doppler spread is 5 Hz). Simulations were performed over 10^4 sub-frames over independent channel realizations. The frequency offset is assumed to be 25.5 KHz.

Fig. 3 shows the performance of the cell ID and frame number detection rates for different channel conditions. Imperfect conditions are considered, where symbol timing error is assumed to be within cyclic prefix while residual CFO may vary. Since fading channels typically limit the performance, residual CFO sweeping is applied to define the maximum tolerance at which cell search can almost achieve the ideal performance obtained with no CFO and no symbol timing error. Although AWGN is affected due to Inter-Carrier Interference (ICI) effects, these simulations provide the acceptable range of imperfections that can be absorbed by the averaged matched filter outputs, where the maximum residual CFO is found to be 375 Hz unlike the restricted 50 Hz defined in [3].

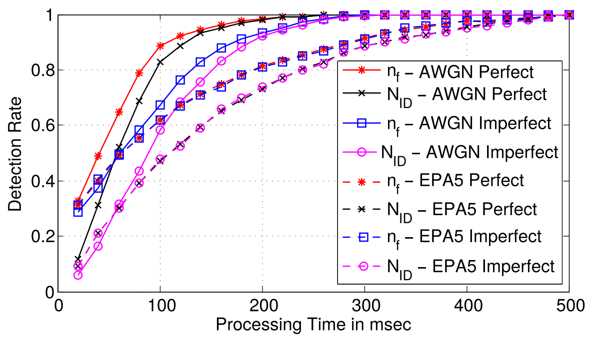

Fig. 3. Cell ID and frame numbering detection rates for perfect and imperfect conditions for AWGN and EPA-5 channels. Imperfect conditions refer to a residual CFO of 375Hz and ±4 samples as timing error, while SNR = −13dBs

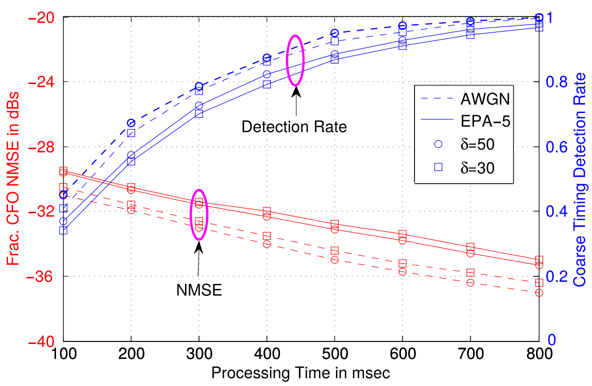

Fig. 4. Coarse symbol timing and fractional frequency offset estimation performance for different channel conditions, where $\delta = 30$ or 50 samples.

The performance of coarse timing acquisition and fractional CFO estimation is shown in Fig. 4 for different channel conditions. Only EC scenario is considered where SNR = −13 dBs. A normalized Mean Square Error (NMSE) is used as a metric to the fractional frequency offset performance. It is clear that both coarse timing and fractional CFO performances improve by increasing the tolerance amount δ. However, the complexity of the fine symbol timing increases for larger δ values. Therefore, a careful compromise has to be applied to select the proper value of δ. When autocorrelation is complete, the fractional CFO is corrected up front at the mixer. Then, NPSS cross-correlation is introduced to refine the symbol timing and to estimate the integer frequency offset. A well defined target for NPSS fine timing is to correct the symbol timing within CP (rather than the coarse timing defined within $\pm\delta$ samples) and to correctly estimate the integer frequency offset so that cell search has the sufficient synchronization conditions to succeed. Fig. 5 shows the performance for refining the timing based on NPSS approach versus the processing time for different channel conditions and SNR values. Indeed, for a fixed target performance, the NPSS algorithm converges quickly to the proper timing and frequency offset.

Based on the previous results, our initial synchronization and cell search can consume a total of 1050 ms to camp on a cell with 90% accuracy (i.e., 600 ms for coarse timing

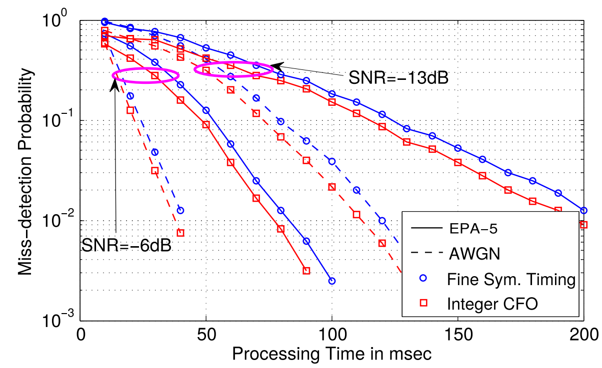

Fig. 5. Miss-detection rate for the fine symbol timing and integer CFO estimation versus processing time under different channel conditions. SNR of −6 and −13 dBs are considered and $\delta = \pm 30$.

plus 100 ms for symbol refining in addition to 350 ms for cell search). However, the minimum required time for only synchronization (without cell search) is reported to be 1254 ms based on the performance summary found in [5]. Thus, a significant time reduction can be achieved if a bit of power consumption is temporally paid by running the algorithms at higher sampling rate (i.e., 1.92 MHz) rather than 240 KHz presented in [3].

V. Conclusion

We presented a cell search and initial synchronization algorithm for NB-IoT systems that uses the new set of synchronization signals. Timing acquisition and initial CFO estimation are jointly acquired through two-stage time domain NPSS correlation. The cell ID and frame timing are captured by applying matched filters to NSSS sequences. The proposed algorithm can quickly lock the UE to the network under very low SNRs and in different fading conditions.

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