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# An introduction to cellular IoT: Signal processing aspects of NB-IoT

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# Outline…

**NB-IoT layers**

NB-IoT layer functions: PDCP, RLC, MAC
Congestion control : ACB and EAB
Power efficiency: PSM, I-DRX, C-DX

**NB-IoT Idle and Connected Mode Procedures**

Idle Mode
Connected Mode

**NB-IoT DL synchronization methods**

System model
Cell search
Timing and frequency acquisition

**NB-IoT UL synchronization**

NPRACH preamble design
NPRACH estimation methods 1 and 2

**NB-IoT in ISM bands**

Characteristics - Alternatives for NB-IoT

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# NB-IoT DL Synchronization: Cell search and initial sync

**Objective:** an algorithm to provide an initial timing and frequency acquisition and efficiently search for the serving cell ID.

After the RF processing and blocking filtering, a coarse subframe timing is jointly obtained with CFO by employing NPSS time domain (TD) correlations.

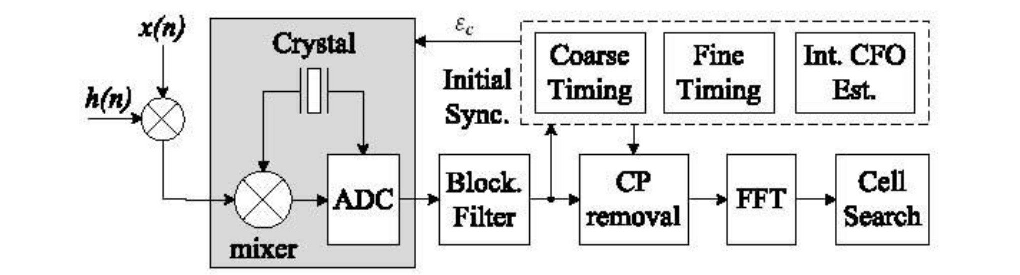


Fig. 1. Block diagram for the NB-IoT receiver to show the processing chain for cell search and initial synchronization procedure.

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.

# NB-IoT DL Synchronization:
## Patterns

Figure shows a 3MHz LTE carrier in which an anchor PRB is assigned to NB-IoT for an in-band operation.

Since LTE employs OFDM, the NB-IoT band is defined as a contiguous set of 12 sub-carriers forming one PRB.

A single radio frame (10 ms) consists of 10 sub-frames. Each sub-frame is divided into 2 slots with equal periods, where a slot is composed of 7 OFDM symbols.

Since the signal is sampled at 1920 ksamples/s, the CP length, *L*, of the first symbol in each slot is 10 samples and those of the other symbols are 9 samples long. The TD OFDM symbol spans *N* = 128 samples.

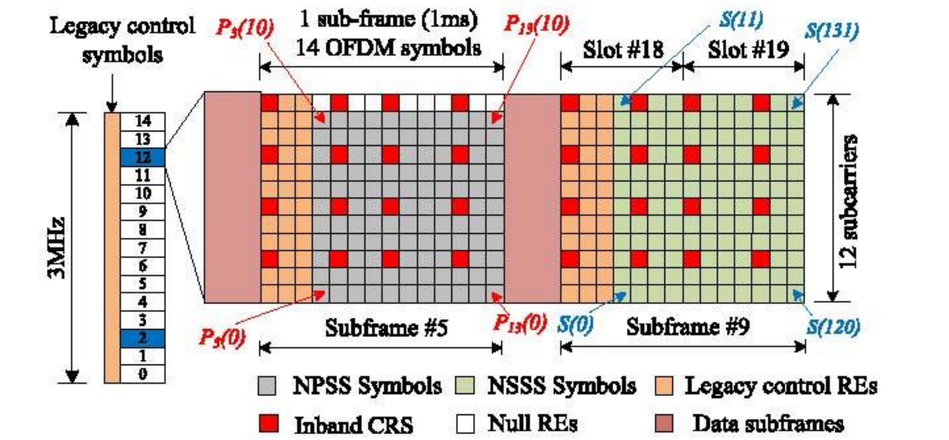


Fig. 2. Radio frame structure for in-band NB-IoT systems with two Tx antennas. The allocated RB is expanded in time to show the NPSS/NSSS symbols mapping. Two anchor PRBs are highlighted for 3MHz LTE-A cell. $P_l(k)$ and $S(k)$ illustrate the mapping for NPSS and NSSS, respectively.

CRS: cell specific reference signal

# NB-IoT DL Synchronization: NPSS and NSSS signal patterns

NPSS (TDO and CFO estimation)

- Subframe Number : 5
- Subframe periodicity: 10 ms
- Sequence pattern periodicity: 10 ms

NSSS (CPID and frame timing estimation)

- Subframe Number: 9
- Subframe periodicity: 20 ms
- Sequence pattern periodicity: 80 ms

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# NB-IoT DL Synchronization:
## NPSS and NSSS signals …

NPSS and NSSS are constructed from a frequency domain Zadoff-Chu (ZC) sequence where NPSS length is 11 samples while the NSSS consists of 132 samples.

ZC sequences satisfy the Constant Amplitude Zero Autocorrelation (CAZAC) property which limits the Peak to Average Power Ratio (PAPR) and provides ideal cyclic autocorrelation.

NPSS, $P_l(k)$, is generated such that

$$P_l(k) = Q(l)e^{-j\pi uk(k+1)/11}, \quad 0 \leq k \leq 11, \quad 3 \leq l \leq 14$$

The sequence root *u* = 5, and $Q(l)$ is a modulation sequence given by

$$\{1, 1, 1, 1, -1, -1, 1, 1, 1, -1, 1\}$$

NPSS is mapped to subframe 5 of every radio frame.

# NB-IoT DL Synchronization:
## NPSS and NSSS signals …

In NB-IoT system, there are 504 unique physical cell IDs. However, all of them are only indicated by the NSSS. The NSSS, *S(k)*, is generated according to

$$S(k) = \overline{C}_q(k')e^{-j2\pi\theta_f k}e^{-j\pi uk''(k''+1)/131}, \qquad 0 \leq k \leq 132,$$
$$k'' = k\ mod\ 131, \qquad k' = k\ mod\ 128$$

where the root sequence, *u*, is related to the cell ID, $u = (N_{ID}^{Ncell}\ mod\ 126 + 3)$

the cyclic shift is related to the radio frame index, $\theta_f = \frac{31}{132}(n_f/2)\ mod\ 4$

$$\overline{C}_q(k') = 2C_q(k') - 1 \qquad q = \lfloor N_{ID}^{Ncell}/126 \rfloor$$

$C_q(k)$ forms 4 complementary 128-bits binary sequences.

NSSS is mapped to the last 11 OFDM symbols of subframe 9 in frames even

$$n_f\ mod\ 2 = 0$$

# NB-IoT DL Synchronization:
## Signal model

Let *x(n)* be a transmitted baseband OFDM signal. The received signal is

$$r(n) = [x(n) \star h(n)]\, e^{-j2\pi\epsilon_c n/N} + w(n)$$

where *h(n)* is the impulse response of the multipath channel, *w(n)* represents AWGN, and $\star$ denotes convolution.

CFO is typically normalized to the sub-carrier spacing, where the total normalized CFO is represented by two terms: the fractional CFO and the integer CFO, $\epsilon_c = \epsilon_I + \epsilon_F$

A FFT is used to synthesize the received symbols to the FD

$$R_l(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r_l(n) e^{-j2\pi kn/N} + w(n), \quad 0 \le k \le N-1$$

where $r_l(n)$ represents the *l*-th OFDM symbol after CP removal.

# NB-IoT DL Synchronization:
## Timing and frequency acquisition

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.

# NB-IoT DL Synchronization:
## Timing and frequency acquisition

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.

For that purpose, a fast two-stage procedure can be applied while the sampling rate is kept at 1.92 MHz.

# NB-IoT DL Synchronization: Timing and frequency acquisition…

First step is to employ an averaged TD autocorrelation to explore the repetitive nature of NPSS across OFDM symbols.

Fractional CFO estimation comes with a coarse timing in this stage. Since NPSS repeats every 10 ms, the autocorrelation window would be over $N_w$ = 19200 samples.

Autocorrelation from different windows are coherently averaged over *M* consecutive windows

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

where $N_s'$ = 137 is the OFDM symbol period such that a single sample is dropped every 959 samples to maintain timing continuity.

NPSS modulation sequence *Q(.)* is used to filter the auto-correlation such that NPSS de-spreading maximizes the averaged auto-correlation at the proper timing.

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# NB-IoT DL Synchronization: Timing and frequency acquisition…

Coarse timing and fractional frequency offset can jointly be acquired such that

$$\hat{\tau} = \arg\max_{\forall k} |\mathcal{R}(k)|, \quad 0 \leq k \leq N_P$$

$$\hat{\epsilon}_F = \frac{N}{2\pi N_s'} \angle \mathcal{R}(\hat{\tau})$$

Due to a possible sampling frequency error, it is expected that the maximum autocorrelation 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 $\delta$ is a design parameter.

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# NB-IoT DL Synchronization:
## Timing and frequency acquisition…

After fractional CFO compensation, the 2nd step for initial acquisition employs NPSS matched filter (MF) to jointly acquire the fine symbol timing and integer frequency offset.

Define the cross-correlation $\Lambda_n(\tilde{\tau}, \epsilon_I)$ within a correlation window *n* as

$$\Lambda_n(\tilde{\tau}, \epsilon_I) = \sum_{n=\tilde{\tau}-\delta}^{\tilde{\tau}+\delta-N_P-1} r(n)p^*(n-\tilde{\tau}+\delta)e^{\frac{j2\epsilon_I(n-\tilde{\tau}+\delta)}{N}}$$

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 $\tilde{\tau} \in [\hat{\tau}-\delta, \hat{\tau}+\delta]$

MF: matched filter

# NB-IoT DL Synchronization: Timing and frequency acquisition…

The idea is to introduce progressive phase shifts for the reference TD NPSS before applying the crosscorrelation.

Hypotheses are defined to generate the pre-correction phase shifts as a function of the claimed integer frequency offset. It is generally assumed that the oscillator mismatch produces

$$\epsilon_I \in [-2, +2]$$

The decision statistics is averaged over *P* consecutive NPSS windows to further reject noise. Maximizing the average cost function allows to obtain

$$(\hat{t}, \hat{\epsilon}_I) = \arg \max_{\forall \tilde{\tau}, \epsilon_I \in [-2,+2]} \left| \frac{1}{P} \sum_{n=0}^{P-1} \Lambda_n(\tilde{\tau}, \epsilon_I) \right|$$

Complexity: the 2nd step requires 5(2δ + 1)$N_p$ multiplication per window which is low compared to a flat NPSS MF that requires 5$N_p N_w$ multiplications to exhaustively search for the timing and integer frequency offset.

$N_p = 1508, N_w = 19200$

# NB-IoT DL Synchronization:
## Cell search

Since NSSS sequence spreads across multiple OFDM symbols, fractional CFO would introduce high distortion to the received sequence, unless compensated.

For example, a small fractional CFO of 1.275 KHz would introduce a phase difference of

$$2\pi \times 1.275 \times [(128+9)*10+(128+10)]/1920 \approx 2\pi ,$$

across the whole NSSS sequence, where 1508 are the 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 subject to the accuracy of the initial NPSS synchronization mechanism.

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# NB-IoT DL Synchronization:
## Cell search…

An optimal matched filter (MF) detection aims at maximizing the SNR for AWGN channels but the main challenge comes from its complexity. We consider 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

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

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*.

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# NB-IoT DL Synchronization:
## Cell search…

To improve performance at very low SNR and low mobility channels, the final decision statistic is obtained by averaging the MF outputs over *M* consecutive windows

$$\overline{\Lambda}(i, n_f) = \frac{1}{M} \sum_{m=0}^{M-1} \Lambda_m(i, n_f)$$

The estimated cell ID and frame timing is then evaluated as,

$$\{\hat{N}_{ID}^{Ncell}, \hat{n}_f\} = \arg\max_{\forall i, n_f} \left|\overline{\Lambda}(i, n_f)\right|$$

ZC properties can be used to reduce the complexity of the evaluations.

# NB-IoT DL Synchronization:
## Some results

To illustrate the performance of the presented procedure, the baseband downlink NB-IoT system has been simulated assuming:

- sampling rate of 1.92 MHz,
- 128-point FFT,
- 15 kHz sub-carrier spacing,
- two TX antennas and one RX antenna
- AWGN and Typical urban (TU) channels

- Simulations were performed over 104 sub-frames over independent channel realizations.
- Frequency offset is assumed to be 25.5 KHz.

# NB-IoT DL Synchronization:
## Some results:
## coarse timing acquisition & fractional CFO estimation

Only one coverage scenario is considered SNR = −13 dB.  A NMSE is used as a metric to the fractional frequency offset performance.

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*.

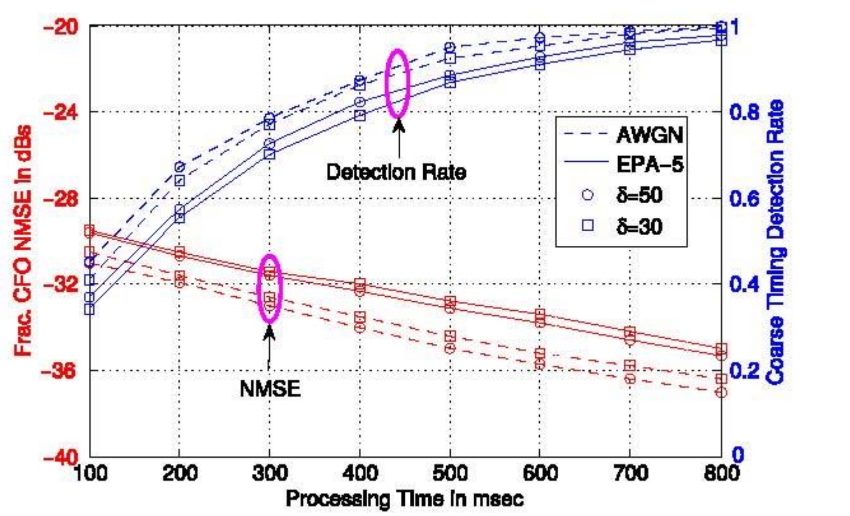


Fig. 4.  Coarse symbol timing and fractional frequency offset estimation performance for different channel conditions, where $\delta = 30$ or 50 samples.

EPA-5: Extended pedestrian A model (5Hz)

# NB-IoT DL Synchronization:

## Some results: cell ID and frame number detection

Imperfect conditions are considered, where symbol timing error is assumed to be within cyclic prefix while residual CFO may vary.

Since fading performance, residual CFO sweeping is applied to define the maximum tolerance at which cell search can almost achieve the ideal performance (no CFO and no symbol timing error).

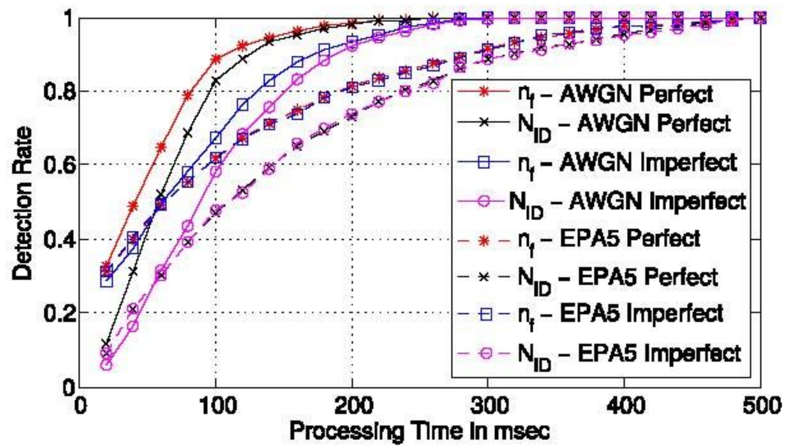


Fig. 3. Cell ID and frame numbering detection rates for perfect and imperfect conditions for AWGN and EPA-5 channels. Imperfect conditions refer to a residual CFO of 375Hz and $\pm 4$ samples as timing error, while SNR $= -13$dBs

# NB-IoT DL Synchronization:
## Some results: fine timing estimation

When autocorrelation is complete, the fractional CFO is corrected 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 CFO so that cell search has the sufficient synchronization conditions to succeed.

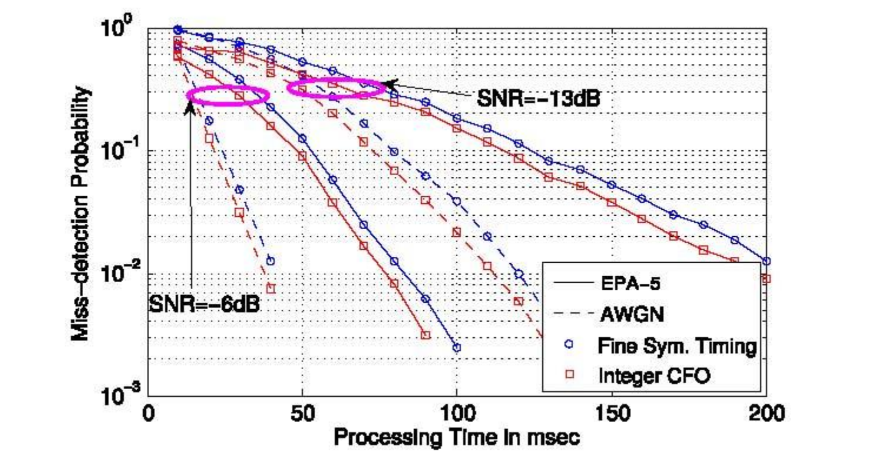


Fig. 5. Miss-detection rate for the fine symbol timing and integer CFO estimation versus processing time under different channel conditions. SNR of $-6$ and $-13$ dBs are considered and $\delta = \pm 30$.

It is illustrated the performance for refining the timing based on NPSS approach versus the processing time for different channel conditions and SNR values.

# NB-IoT DL Synchronization:
## Simulation results

Based on the previous results, the 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 plus 100 ms for symbol refining in addition to 350 ms for cell search).

The minimum required time for only synchronization (without cell search) is reported to be 1254 ms.

# Conclusions

- An algorithm for initial timing and frequency acquisition and search cell ID was discussed.
- After describing the basic characteristics of the NPSS and NSSS signals, their models are considered.
- Using an autocorrelation of NPSS, the fractional CFO and coarse timing is obtained.
- A 2nd stage is based on a matched filter (cross-correlation between the received signal and NPSS) to obtained a refined subframe timing and the integer frequency offset.
- Finally, cell ID is obtained based on a decision statistics using NSSS.