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Research

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RESEARCH

Methods for improving the accuracy of frequency shift estimation in 5G NR

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Abstract

Frequency synchronization is a necessary operation for all wireless communication systems. Due to the wide frequency range defined for 5G NR systems, this procedure becomes critical. To ensure high transmission rates and the use of high-order modulation, up to 256 QAM for 5G communication systems, it is necessary to ensure high frequency synchronization accuracy. In this article, we have reviewed various approaches to implementing frequency synchronization and proposed, in our opinion, the most effective method for correcting the frequency shift of the signal.

Keywords: 5G NR; frequency synchronization; synchronization signals; cyclic prefix

1 Introduction

FIFTH GENERATION (5G) is a continuation of the LTE-A mobile communication system standard. In 5G NR, the focus is on significantly increasing data transfer rate and new types of traffic, such as: "enhanced Mobile Broadband" (eMBB), "Ultra-Reliable Low-Latency Communication" (URLLC) and "Massive Machine-Type Communications" (mMTC).

The 5G standard supports types of modulation not previously supported by LTE such as 256 QAM. 4G operates at frequencies below 6 GHz while 5G uses extremely high frequencies up to 52 GHz [1]. The high-frequency band is less loaded than the low-frequency band, which means that 5G has new frequency ranges for data transmission. In addition, the 5G standard can support user mobility up to 500 km/h [2].

To achieve these goals, a new physical layer design has been developed that supports high carrier frequencies, wide frequency bands, as well as the use of spatial multiplexing (MIMO) technologies and beamforming. All this imposes additional synchronization requirements. High accuracy of the frequency shift estimation is also an urgent task for measuring equipment since it is necessary to ensure maximum accuracy of the signal parameters estimation. The key contributions of this paper are summarized as follows:

- In this paper, we considered the basic methods of frequency synchronization and presented their algorithm based on the synchronization block in 5G NR.
- We propose methods for estimating the frequency shift, which makes it possible to increase the accuracy by using both reference and information symbols, in contrast to basic methods.

- We conducted a simulation experiment and compared the existing synchronization methods with our proposed methods. The results of the experiment are presented in the corresponding section of the paper.

The article is organized as follows: Section 2 provides an overview of the physical layer of 5G NR; Section 3 describes frequency synchronization methods; Section 4 contains simulation results.

2 Overview of the 5G NR physical layer

This section provides an overview of the physical layer of the 5G NR standard based on the 3GPP specification (38.211)[3]. It presents the structure of the radio frame and describes the main signals that are used for synchronization.

2.1 5G NR Frame Structure

Compared to LTE, the most significant difference is that in the 5G NR standard, it is now possible to change the slot duration by changing the interval between subcarriers. In LTE, the slot duration is fixed and is 0.5 ms, and the frequency interval between subcarriers is $\Delta f = 15$ kHz.

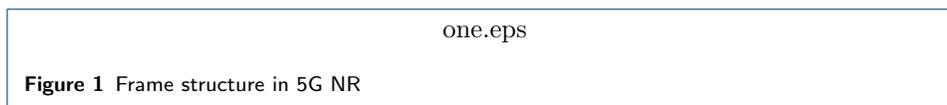
Numerology defining of the supported subcarrier spacing in NR, is described in the specification 38.211[3]. Not every numerology can be used for all physical channels or signals. For each specific physical channel, there is a list of supported numerology. Table 1 shows which numerologies can be used for physical channels.

Table 1 Supported numerologies

Numerology	Subcarrier spacing, kHz	Type of cyclic prefix	Supported for Data (PDSCH, PUSCH)	Supported for Sync (PSS, SSS, PBCH)
1	15	Normal	Yes	Yes
0	30	Normal	Yes	Yes
2	60	Extended	Yes	No
3	120	Normal	Yes	Yes
4	240	Normal	No	Yes

For frequency synchronization in communication systems, the frequency interval between subcarriers plays an important role. The smaller is the interval between subcarriers, the greater is the impact of frequency desynchronization on the operation of the communication system.

The structure of the radio frame varies depending on the type of numerology. However, regardless of the numerology, the lengths of a single radio frame and a subframe are the same. The length of the radio frame is always 10 ms, and the length of the subframe is 1 ms. The structure of the radio frame is shown in Figure 1.



The resource grid for NR is identical to the grid for LTE. But the distance between subcarriers (hereinafter referred to as SCS) and the number of OFDM symbols within the radio frame varies depending on the numerology. Synchronization signals (primary and secondary), as well as the PBCH signal of the SS/PBCH block, are

used for synchronization in NR. There is also another name – Synchronization Signal Block (SSB). Consider the time-frequency structure of the NR synchronization block (SSB). It can be represented as a resource grid as shown in Figure 2. The following is a brief description of the SSB block:

- The SSB block consists of 240 subcarriers (20 resource blocks).
- Subcarriers are numbered in ascending order from 0 to 239 within the SSB block.
- SS (PSS and SSS) and PBCH in NR are transmitted in the same block of four OFDM symbols.

two.eps

Figure 2 Time-frequency structure of a SS/PBCH block

The transmission scheme of the SSB block in the time domain in NR is more complex than in LTE. LTE has only one SSB transmission pattern in the time domain while NR has multiple SSB transmission patterns in the time domain. These patterns have a different number of SSB blocks. There are difference in the location of these blocks and frame depending on the distance between the subcarriers.

2.2 5G NR Synchronization Signals

The primary and secondary synchronization signals are used to determine the radio frame boundary and the physical cell identifier. The synchronization signals are individual for each cell and depend on the unique value of the physical cell identifier that takes values from 0 to 1008. The ID is divided into 336 groups ($N_{ID}^{(1)}$) and it consists of three different sectors ($N_{ID}^{(2)}$). The user equipment (UE) determines the value of ($N_{ID}^{(2)}$) from the primary synchronization signal and ($N_{ID}^{(1)}$) from the secondary synchronization signal. Based on the obtained values, the value of the cell ID is calculated using the formula:

$$N_{ID}^{(ceil)} = 3 \cdot N_{ID}^{(1)} + N_{ID}^{(2)}. \quad (1)$$

2.2.1 Primary signal synchronization

PSS is a special physical layer signal that is used to synchronize radio frames. The following is a brief description of the primary sync signal:

- mapped to 127 subcarriers;
- consists of 127 m-sequence values;
- used for downlink frame synchronization;
- one of the critical factors determining the physical Cell ID.

The primary synchronization signal (PSS) is a binary pseudo-random m-sequence with a duration of 127 samples, which is formed depending on the number $N_{ID}^{(2)}N_{ID}^{(2)}$ in the range from 0 to 2. The PSS is always located in the first symbol of the OFDM synchronization block and occupies subcarriers with indexes from 57 to 183. From the valid values of $N_{ID}^{(2)}N_{ID}^{(2)}$ we can conclude that PSS has three possible values of the m-sequence.

The formation of the PSS is shown below:

$$d_{PSS}(n) = 1 - 2 \cdot x(m), \quad (2)$$

where,

$$m = (n + 43 \cdot N_{ID}^{(2)}) \bmod 127 \quad 0 \leq n < 127, \quad (3)$$

$$x(i+7) = [x(i+4) + x(i)] \bmod 2, \quad (4)$$

and,

$$x = [1110110]. \quad (5)$$

2.2.2 Secondary signal synchronization

A secondary synchronization signal (SSS) of 127 samples is generated from a combination of two m-sequences that are generated depending on the group $N_{ID}^{(1)}N_{ID}^{(1)}$ in the range from 0 to 335. The SSS is always in the third symbol of the OFDM SSB block. SSS is used to detect a group of cell IDs. The formation of the SSS is shown below:

$$\begin{aligned} d_{SSS}(n) &= [1 - 2 \cdot x_0((n + m_0) \bmod 127)] \cdot [1 - 2 \cdot x_1((n + m_1) \bmod 127)], \\ m_0 &= 15 \cdot \frac{N_{ID}^{(1)}}{112} + 5 \cdot N_{ID}^{(2)}, \\ m_1 &= 15 \cdot N_{ID}^{(1)} \bmod 112, \\ 0 &\leq n < 127, \end{aligned} \quad (6)$$

where,

$$\begin{aligned} x_0(i+7) &= (x_0(i+4) + x_0(i)) \bmod 2, \\ x_1(i+7) &= (x_1(i+4) + x_1(i)) \bmod 2, \end{aligned} \quad (7)$$

and,

$$\begin{aligned} x_0 &= [0000001], \\ x_1 &= [0000001]. \end{aligned} \quad (8)$$

3 Synchronization procedure

This section describes the basic steps of establishing a 5G connection.

For the case of initial access (idle mode), the user terminal must start the cell search procedure. Using PSS, SSS, and special synchronization algorithms, the UE evaluates and corrects frequency shift. In the next section, we presented some frequency synchronization algorithms

After the PSS is decoded, the user terminal can detect the cell ID sector. Then, the user terminal can decode the SSS and detect the cell ID group.

After determining the cell ID, the base station should identify a suitable SSB in the SS burst. As discussed in Sec. II, each subcarrier interval has a different sync block layout with different first symbol indices. Each SSB corresponds to a specific beam of the radiating pattern formed at the base station. Each SSB has a unique number called the SSB index, and the identification of which SSB is found depends on where the UE is. The UE measures the demodulation reference signal power (DMRS PBCH), and from the measurement result, the UE can identify the SSB index with the greatest signal power. This SSB is the best beam for the UE.

The UE selects the best beam and decodes the master information block (MIB). MIB contains PBCH information, such as system frame number (SFN), numerology, subcarrier spacing, and so on. Successful PBCH decoding ensures receiving of physical downlink control channels (PDCCH) and physical downlink channels (PDSCH), which contain the remaining minimum system information (RMSI) and other system information (OSI).

Based on the necessary parameters, which are included in the MIB, the UE can decode the system information block (SIB) that is transmitted by the next generation node base station (gNB) over the PDSCH and includes random access channel (RACH) resources.

The procedure for establishing a connection over a RACH consists of five steps [4]. Once the connection is established, the base station begins transmitting data to the UE and receiving data from the user terminal (Figure 3).

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Figure 3 Initial access procedure

The frequency synchronization procedure is part of the connection procedure. It is performed at the first stage after finding the PSS and SSS sequences in the signal.

To access the UE network, you need to get the correct time and frequency synchronization to restore the gNB service cell ID. This first operation is known as the initial cell search, and various algorithms for estimating and correcting frequency and time offsets can be used to perform it correctly.

Next, we looked at various frequency synchronization algorithms and propose the most effective approach in our opinion.

4 Methods of frequency synchronization

In this section, various methods for estimating the frequency shift in 5G were considered. The algorithms are described in detail.

4.1 Frequency Synchronization Method Using PSS

In a frequency synchronization method using PSS, a cross-correlation function is calculated between a received PSS sequence with a known PSS sequence at the receiver.

To estimate the frequency shift from the PSS sequence, it is necessary to find the shift by which the frequency has changed over the duration of the PSS symbol. For this, the samples of the received and known PSS sequences are divided into two equal parts. Then, two cross-correlation functions (CCF) corresponding to the parts of the received and known signals are calculated. The phase shift for the symbol is calculated as the difference of the phase shift for half of the symbol [6]. Figure 4 shows the PSS synchronization procedure.

four.eps

Figure 4 PSS frequency synchronization procedure

Denote the first part of the pilot symbol as $\dot{p}_1(k) = \dot{s}_p(k)$, where $k = [1...N/2]$, and the other part as $\dot{p}_2(k) = \dot{s}_p(k + N/2)$. The first part of the received OFDM symbol is $\dot{s}_1(k) = \dot{s}_r(k)$ and the second part is $\dot{s}_2(k) = \dot{s}_{rx}(k + N/2)$, $k = [1...N/2]$. The correlation coefficients are calculated as follows:

$$\begin{aligned}\dot{R}_1 &= \sum_{k=1}^{N_1/2} \dot{s}_1(k) \cdot \dot{p}_1(k), \\ \dot{R}_2 &= \sum_{k=N_1/2+1}^{N_1} \dot{s}_1(k) \cdot \dot{p}_1(k).\end{aligned}\tag{9}$$

The correlation coefficients (4) is used to estimate the frequency shift:

$$\Delta \hat{f} = \frac{\arg(\dot{R}_1^* \cdot \dot{R}_2)}{2 \cdot \pi \cdot T}.\tag{10}$$

where $T = N/f_s$ is the duration of the pilot sequence, \dot{R}_1^* is a conjugate value of \dot{R}_1 .

4.2 Frequency Synchronization method using a Cyclic Prefix

This method involves the use of a cross-correlation function to find the correlation between the cyclic prefix and the last counts of the OFDM symbol on the basis of which this cyclic prefix was formed [5]. Since the phase shift is present throughout the symbol, the correlation between these two parts allows finding the frequency shift in each symbol.

This method can also be used to more accurate estimate multiple symbols. At the first stage, a rough estimate of the frequency shift is made based on the first OFDM symbol that comes in. Then, the frequency shift obtained by the rough estimate is corrected in a certain number of accepted symbols and the shift frequency in each

of them is recalculated. The rough and accurate estimates are made using the cyclic prefix.

The first step is to find the correlation coefficient:

$$\dot{R} = \sum_{k=1}^{N_1} \dot{s}(k) \cdot \dot{s}_{ref}(N - N_1 + k). \quad (11)$$

where \dot{s} is the estimated OFDM symbol, N is the total OFDM symbol length, and N_1 is the length of the cyclic prefix.

Next, the frequency shift is estimated:

$$\Delta \hat{f} = \frac{\arg(\dot{R})}{2 \cdot \pi \cdot T}. \quad (12)$$

A more accurate estimate is obtained by averaging the estimates obtained after compensating for the rough estimate. Figure 5 shows a schematic diagram of the frequency estimation algorithm for the cyclic prefix.

five.eps

Figure 5 CP frequency synchronization procedure

4.3 Proposed Frequency Synchronization Method using PSS and SSS

In this method, the frequency is estimated from the PSS and SSS sequences. The correlation coefficient between the reference and the received PSS can be obtained after synchronization and finding $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$ for SSS and PSS. The correlation coefficient is found as follows:

$$\dot{R}_1 = \sum_{k=1}^N \dot{s}_{rPSS}(k) \cdot \dot{s}_{refPSS}(k). \quad (13)$$

Since the symbol with the SSS sequence, contains the PBCH channel data to find the correlation coefficient it is necessary to transform the symbol. For this, a direct Fourier transform is performed and subcarriers of the PBCH channel are removed from the symbol. An inverse Fourier transform is then performed to return the signal to the time domain. It is also necessary to convert the reference SSS found after synchronization to an OFDM symbol without a PBCH. Next, the correlation coefficient between the reference received and transformed SSS is calculated:

$$\dot{R}_2 = \sum_{k=1}^{N_1} \dot{s}_{rSSS}(k) \cdot \dot{s}_{refSSS}(k). \quad (14)$$

The frequency shift is estimated using the correlation coefficients:

$$\begin{aligned}\Delta\hat{f}_1 &= \frac{\arg(\dot{R}_1)}{\pi \cdot T}, \\ \Delta\hat{f}_2 &= \frac{\arg(\dot{R}_2)}{\pi \cdot T}.\end{aligned}\tag{15}$$

The final value of the frequency shift is calculated as the average between $\Delta\hat{f}_1$ and $\Delta\hat{f}_2$:

$$\Delta\hat{f} = \text{avr}(\Delta\hat{f}_1, \Delta\hat{f}_2).\tag{16}$$

4.4 Proposed Frequency Synchronization Method using Information OFDM Symbols

In this method, the frequency is estimated in two stages. At the first stage, a rough estimate of the frequency shift is made, which can be implemented using one of the previously considered methods. At the second stage, an additional estimation of the frequency shift is made using not only synchronization signals, but also OFDM information symbols, which allows you to significantly increase the resulting estimated value.

The first step is to get a rough estimate of the frequency shift $\Delta\hat{f}_{rough}$ (calculated as in (16)) and the phase shift $\Delta\phi_{rough}$. Figure 6 shows the proposed frequency estimation algorithm.

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Figure 6 Functional diagram of the proposed method

Next, we perform the operation of correcting the frequency shift, according to the obtained rough estimate, for the received sequence of OFDM symbols as follows:

$$\dot{s}_r^*(k) = \dot{s}_r(k) \cdot \exp(j \cdot k \cdot (-1) \cdot \Delta\phi_{rough}).\tag{17}$$

where $k = [1 \dots N_1]$, N_1 is the number of samples in the sequence used in the second step of estimating the frequency shift, $\Delta\phi_{rough} = 2 \cdot \pi \cdot \Delta\hat{f}_{rough} / f_s$ is the phase shift caused by the frequency shift over the sampling interval $1/f_s$.

The second stage of the proposed method consists in reconstructing the service and information OFDM symbols in PBCH, PDSCH and PDCCH channels. For an accurate frequency estimate, the received OFDM symbols are demodulated. Then, based on the demodulated data, the OFDM symbols are regenerated. The resulting symbols provide an accurate estimation of the frequency shift.

To perform the second stage of frequency shift estimation, it is necessary to know the location of the PDCCH and PDSCH channels in the frequency-time grid. To transmit PDCCH and DCI (downlink control information), use CORESET (control resource set), a set of physical resources in the downlink resource grid. The CORESET represents the position on the time-frequency stack where a particular

device can receive a PDCCH. After decoding the MIB, the receiver determines the frequency resources of the CORESET in common numerology by shifting from the location of the detected SSB and the band specified in TS 38.213, section 13, Tables from 13-1 to 13-10 [4]. After successful decoding of the PDCCH, the UE can read the DCI information, which ensures that the UE resources are distributed across the PDSCH and PUSCH. If the UE cannot decode the PDCCH, then the UE will not know the location of the PDSCH resources and will continue trying to decode the PDCCH using a different set of PDCCH candidates (PDCCH CCE Aggregation level). Using DCI, MIB, and Cell ID, the PDSCH configuration is determined.

Frequency estimates $\Delta\hat{f}_3$, $\Delta\hat{f}_4$, $\Delta\hat{f}_5$ are calculated according to the algorithm described in subsection 4.1. The accurate estimation of the frequency shift is calculated as the average of the score across all symbols:

$$\Delta\hat{f} = \text{avr}(\Delta\hat{f}_3, \Delta\hat{f}_4, \Delta\hat{f}_5). \quad (18)$$

The obtained estimate $\Delta\hat{f}$ is correct if, after the correction of the frequency shift carried out at the first stage, the phase shift for half the duration of the sequence $\hat{s}_r^*(k)$ does not go beyond the interval $[-\pi, \pi]$.

The last stage is additional frequency correction according to the formula 17.

5 Experimental simulation

This section describes the simulation parameters and the results obtained during the simulation.

The parameters of the signal used in the simulation can be seen in Table 2.

Table 2 Signal parameters

Parameter	Value
Subcarrier frequency spacing	30 kHz
CP Duration	2.34 ms
OFDM Duration	33.3 ms
FFT Size	512
cellID	102
Number of SSB blocks	8
Number of RB	20
Bandwidth	5 MHz

Figure 7 shows a scheme of a simulation experiment. The simulation was performed in the Octave program.

seven.eps

Figure 7 Scheme of the simulation experiment

For simulation, a standard SSB block with a frequency interval between subcarriers of 30 kHz is formed. Next, a frequency shift of 300 Hz was introduced. Frequency estimation simulations are performed at various values of the signal-to-noise ratio (SNR). The first step was to choose the SNR value. Then the frequency shift was estimated at a given SNR value. At each step, the frequency was estimated 40 times, after which the average estimate was calculated over 40 iterations. After estimating

the mean square error (RMSE) from the introduced shift, a new SNR value was selected. The SNR value ranges from 0 to 50 in steps of 2.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^n (\Delta f_{ij} - \bar{f}_j)^2}{n}}. \quad (19)$$

where Δf_{ij} is the estimated frequency, \bar{f}_j is the introduced frequency shift, n is the number of iterations.

6 Experimental Results and analysis

This section describes the results obtained during the experimental simulation.

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Figure 8 Estimation of the frequency shift

Figure 8 shows the dependence of the frequency estimation error on the value of the signal-to-noise ratio in the channel. As can be seen from the graphs, at low SNR values in the channel, the PSS and cyclic prefix estimation methods have a fairly large error in estimating the frequency. The most effective method in the first case is the method of estimation by information symbols, which has a minimal error in estimating the frequency at low SNR values. In the second case, the method of estimation by PSS and SSS proved to be the best.

The frequency estimate for the cyclic prefix proved to be better than the PSS estimate since the correlation coefficient of the cyclic prefix is calculated more accurately because of the larger number of symbols.

The method that gives the lowest error in frequency estimation is the all-symbols estimation method. It has the longest correlated parts, but at the same time, it is the most complex of all the methods.

7 Conclusion

In this paper, various methods for estimating the frequency shift in 5G were considered. Their effectiveness was also compared depending on the SNR value. In the course of the simulation, results were obtained that show the effectiveness of the PSS and SSS estimation methods, as well as the estimation of information symbols with a low SNR in the transmission channel. These methods can be used not only in communication systems, but also in measuring equipment to improve the accuracy of measurements.

Appendix

Acknowledgements

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Abbreviations

5G NR	Fifth Generation New Radio
CCF	Cross-Correlation Functions
CORESET	Control Resource Set
CP	Cyclic Prefix
DMRS	Demodulation Reference Signal Strength
DCI	Downlink Control Information
eMBB	enhanced Mobile Broadband
gNB	next generation Node Base Station
LTE	Long Term Evolution
MTC	Massive Machine-Type Communications
MIMO	Multiple Input Multiple Output
MIB	Master Information Block
OFDM	Orthogonal frequency-division multiplexing
OSI	Other System Information
PBCH	Physical Broadcast Channel
PDCCCH	Physical Downlink Control Channels
PDSCH	Physical Downlink Shared Channel
PSS	Primary Synchronization Signal
QAM	Quadrature Amplitude Modulation
RACH	Random Access Channel
RMSI	Remaining Minimum System Information
SCS	SubCarrier Spacing
SFN	System Frame Number
SIB	System Information Block
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
URLLC	Ultra-Reliable Low-Latency Communication
UE	User Equipment

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

Competing interests

The authors declare that they have no competing interests

Authors' contributions

All authors read and approved the final manuscript.

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Figures

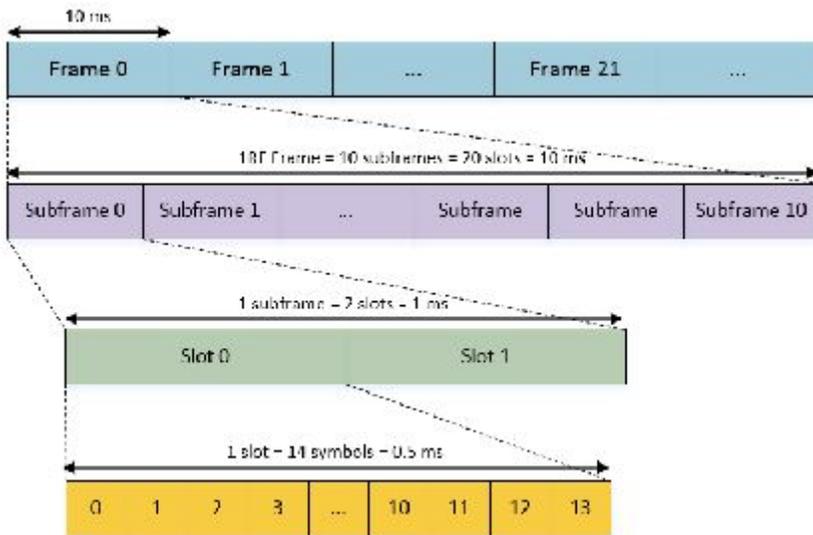


Figure 1

Frame structure in 5G NR

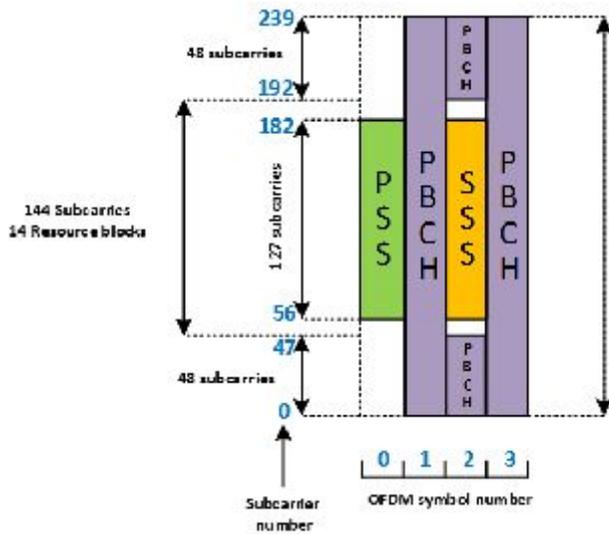


Figure 2

Time-frequency structure of a SS/PBCH block

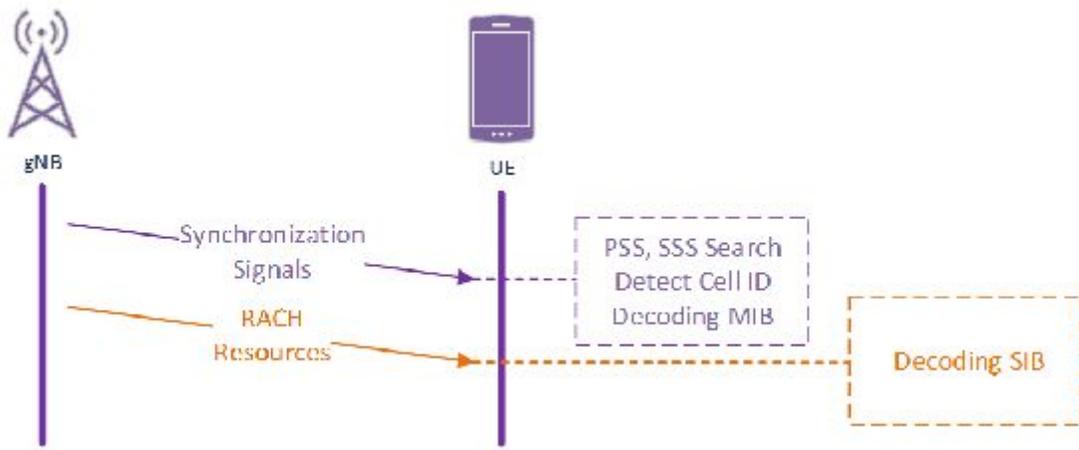


Figure 3

Initial access procedure

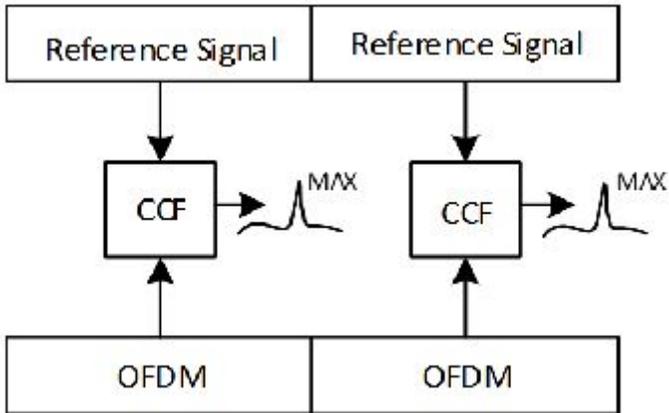


Figure 4

PSS frequency synchronization procedure

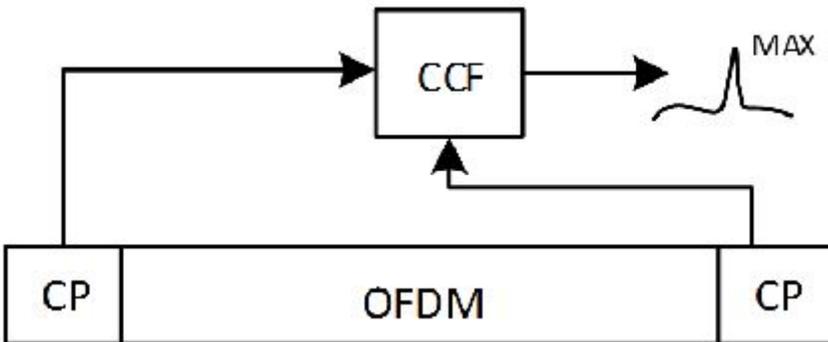


Figure 5

CP frequency synchronization procedure

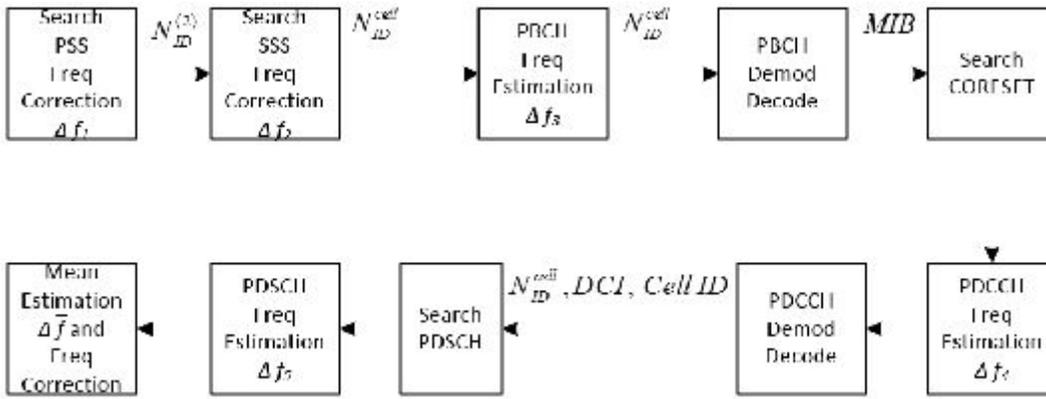


Figure 6

Functional diagram of the proposed method

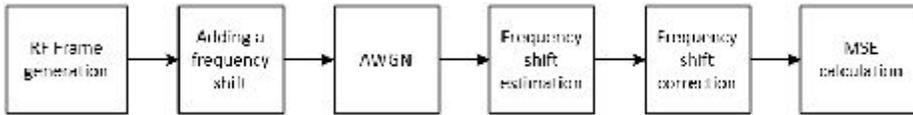


Figure 7

Scheme of the simulation experiment

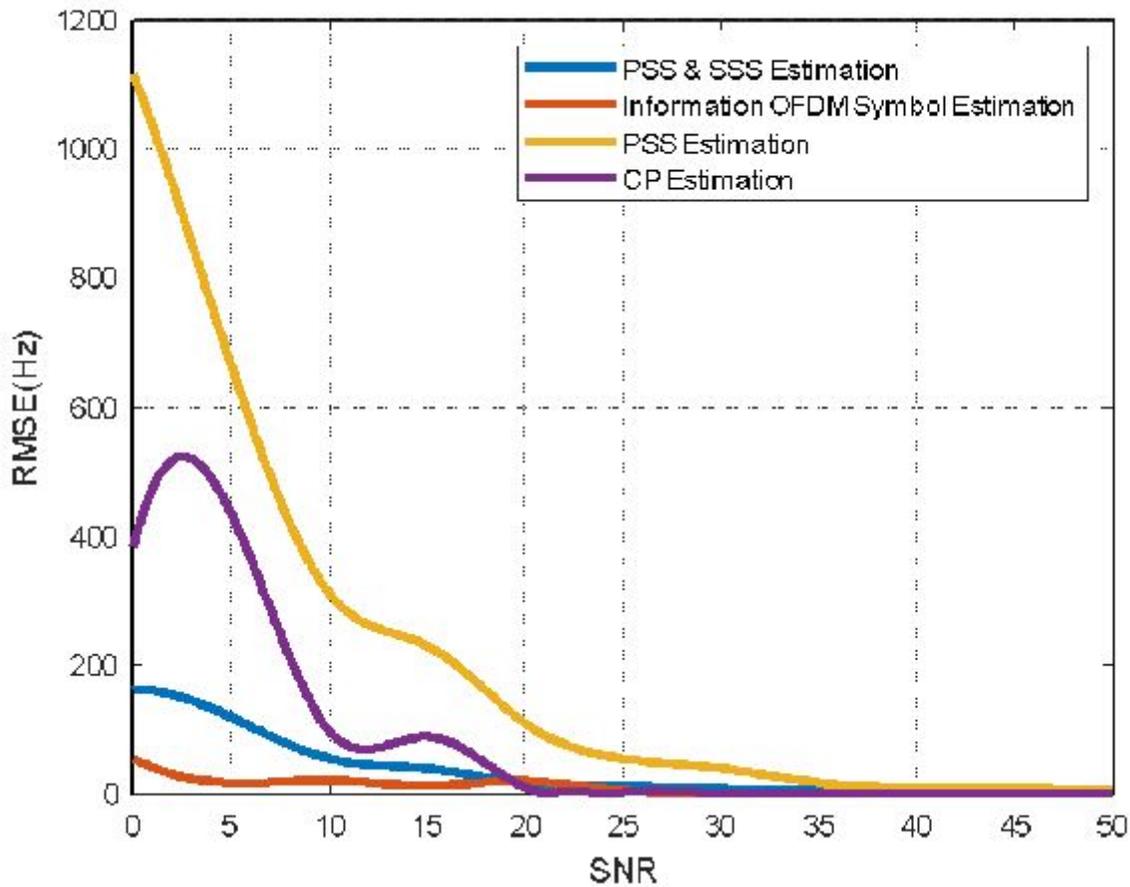


Figure 8

Estimation of the frequency shift