Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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Contents

1 | Coarse Downlink Time Synchronization in 5G-Wireless Networks

Time synchronization is the first and one of the most critical process in establishing the connection between the transmitter and receiver. The process of transmitting the data from the base-station to a user equipment is called **downlink communication**. Hence the process of finding the starting point or boundary of the frame transmitted by the base-station to UEs is called **downlink time synchronization**. In this experiment, we will introduce the audience to downlink time/frame synchronization in 5G networks.

1.1 | Why Time Synchronization?

The objective of communication, in general, is to reliably transmit data over the medium. This data, before transmission, is organized into frames, and each of these frames is communicated sequentially from the transmitter to the receiver. The sizes of these frames may vary depending on latency, data rate, and reliability requirements. At the physical layer, these frames are referred to as Orthogonal Time Frequency Division Multiplexing (OFDM) frames. The receiver accumulates frame samples zone by one, and once a frame's worth of samples is buffered, the complete frame or a group of frames is decoded together. Initially, when there is no secure link between the transmitter and receiver, the User Equipment (UE) doesn't know which sample marks the beginning of the frame or where the frame actually starts. Furthermore, attempting to decode the data blindly through brute force can overwhelm the system, resulting in high computational complexity. Hence, a robust, low-complexity method is required for frame synchronization in time.

1.2 | How Time Synchronization is Performed?

The time/frame synchronization is performed in 2 steps as stated below:

- Coarse Time Synchronization
- Fine Time Synchronization.

The coarse time synchronization estimates the integer sample offset (n_0) and the fine time synchronization estimates the fractional part of the sample offset (Δn_0) as shown in figure 1.1. The total time offset $n = n_0 + \Delta n_0$ gives the exact estimate of where the OFDM frame starts.

Figure 1.1: The sample offset estimation for time synchronization.

The fine synchronization is beyond the scope of this chapter and will be covered in the upcoming chapter. The coarse time sample offset is estimated is time domain based on running correlation. is typically performed in time domain based on time correlation method.

1.2.1 | Time Correlation based Coarse Time Synchronization

The received samples, denoted $y(n)$, are stored by the receiver in the buffer of size ($\geq N_{\mathrm{FFT}} + L_{\mathrm{CP}}$). The receiver is expected to know a $s(n)$ sequence of pilots which are broadcasted by the transmitter to facilitate the time synchronization. These pilots can be generated either in time domain or frequency domain. The time domain pilots are transmitted directly by RF chipset. On the other hand, frequency domain pilots loaded in OFDM resource grid are transformed in time domain and prefixed with a cyclic prefix before transmission as shown in fig. 1.2.
The receiver performs the running correlations with the possible pilot sequences,

$$r_i(n) = \sum_{l=0}^{N_{\mathrm{FFT}}-1} y(l+n) * s_i^*(l) \tag{1.1}$$

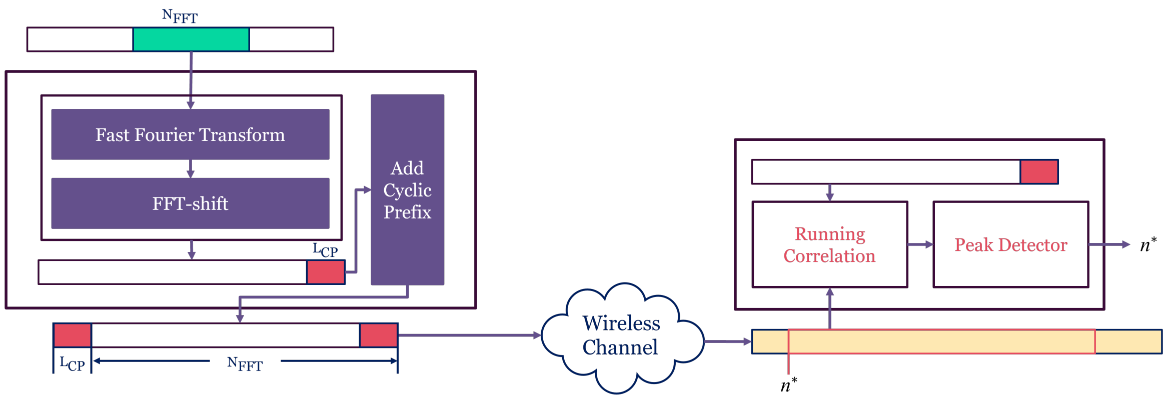

Figure 1.2: Frequency domain pilot generation and correlation based coarse time synchronization.

The output of running correlator is passed to peak detector which finds the sequence with a clear dominant spike and the index of the peak,

$$n^*, i^* = \underset{n,i}{\text{argmax}} \ r_i(n) \tag{1.2}$$

1.3 | Coarse Downlink Synchronization in 5G

The 5G networks used synchronization signal block (SSB) for downlink (DL) synchronization. SSB plays a crucial role in initial access when there is no common understanding of time and frequency between the base station (BS) and user equipment (UE). The SSB is used to time synchronization, frequency synchronization, carrier frequency offset (CFO) estimation, and acquiring master information block (MIB). The details of SSB is provided in provided in section.

1.3.1 | Structure of SSB

The SSB is 4 OFDM symbols duration and 20 resource blocks (240 sub-carrier) wide as shown in figure 1.3. It uses these time frequency resource to consists of 4 components crucial to meet the objective of downlink synchronization,

- Primary Synchronization Signal (PSS),
- Secondary Synchronization Signal (SSS),
- Physical Broadcast Channel (PBCH) symbols,
- Demodulation Reference Signal for PBCH (DMRS-PBCH)

SSB is transmitted in a burst called as SSB burst which carry 4, 8 or 64 synchronization signal blocks depending on the frequency band of operation. A burst spans a half frame transmitted by BS either in first half of the frame or second half of the frame. The SSB burst is transmitted periodically every 5ms/10ms/20ms/40ms/80ms/160ms based on network requirements. The shorter SSB burst period enables quick cell acquisition for UEs but higher network overhead. In this chapter, we will limit the scope of our discussion to PSS and its utility for downlink **time synchronization** and **cell camping**.

1.3.2 | Physical Cell Identities (PCID)

Physical Cell ID (PCID) in 5G refers to an identifier used to distinguish and identify different cells within a wireless network. It is specifically associated with the physical layer of the network and plays a crucial role in cell identification for both the user equipment (UE) and the network infrastructure. In 5G networks, PCID is a part of the cell identity information that helps UEs to differentiate between neighboring cells. The PCID is a numerical value assigned to each cell within a specific frequency band and represents a unique identifier for that cell. It is used by UEs to identify and communicate with the serving cell, especially in scenarios where multiple cells are operating on the same frequency. The PCID,

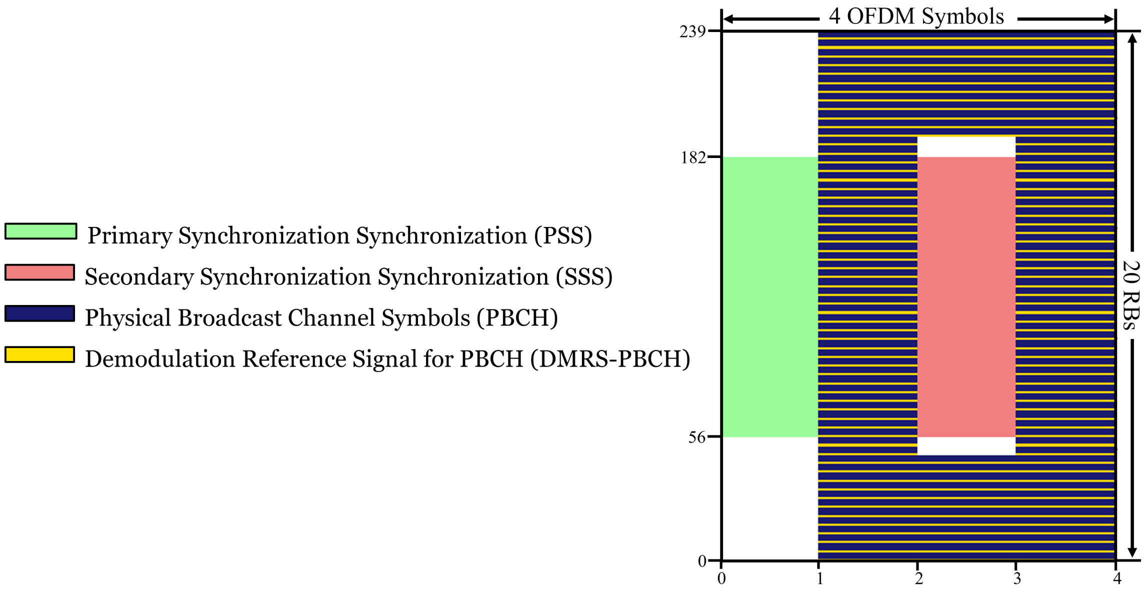

Figure 1.3: 5G Synchronization Signal Block (SSB).

along with other cell-specific parameters, aids in cell selection and reselection processes performed by UEs to maintain a stable and efficient connection as they move within the network coverage area.
The physical cell ID ($N_{\text{ID}}^{\text{cell}}$) is segregated into two parts cell ID-1 ($N_{\text{ID}}^{(1)}$) and cell ID-2 ($N_{\text{ID}}^{(2)}$) related via expression,

$$N_{\text{ID}}^{\text{cell}} = 3 * N_{\text{ID}}^{(1)} + N_{\text{ID}}^{(2)} \tag{1.3}$$

where $N_{\text{ID}}^{(2)}$ can take 3 values from the set $N_{\text{ID}}^{(2)} \in \{0, 1, 2\}$ and $N_{\text{ID}}^{(1)}$ can take 336 values from the set $N_{\text{ID}}^{(1)} \in \{0, 1, 2, \ldots, 335\}$ resulting in a total of 1008 PCIDs from the set $N_{\text{ID}}^{\text{cell}} \in \{0, 1, 2, \ldots, 1007\}$.

1.3.3 | PSS Generation

The generation of PSS is specified in section 7.4.2.2 of [1]. The generation uses $N_{\text{ID}}^{(2)}$ for seed computation. Its is m-sequence generated as follows,

$$d_{\text{PSS}}(n) = 1 - 2x(m) \tag{1.4}$$

where $m = (n + 43 * N_{\text{ID}}^{(2)})$ for $n = 0, 1, 2, \ldots, 127$ provides the 3 possible cyclic shifts of $0, 43, 86$ for $N_{\text{ID}}^{(2)} \in 0, 1, 2$ respectively to the base sequence $x(m)$. The base sequence is generated as follows,

$$x(i + 7) = (x(i + 4) + x(i)) \mod 2 \tag{1.5}$$

where boundary/initial conditions defines first 7 samples of x(n) as [x(6) x(5) x(4) x(3) x(2) x(1) x(0)] = [1 1 1 0 1 1 0].

Important: 5G PSS is choosen from a set of 3 possible sequence which are cyclic shifted version of a reference m-sequence. The UE when seeking to synchronize in time actually correlate the received sequence with 3 possible PSS sequence with an aim to estimate/detect following 3 parameters:

- cell ID-2 ($N_{\text{ID}}^{(2)}$),
- time sample offset (n_0),
- frequency offset (k_0).

1.4 | Results

In this section, we will demonstrate some important observations about the design of PSS which plays important role in the performance achievable in 5G networks.

Observation-1: The primary synchronization signals has excellent auto-correlation and cross-correlation properties for different cell ID-2.

This property results in accurate cell-ID 2 estimation in downlink. The figure 1.4 demonstrate the cross correlation property of time domain PSS corresponding to cell-ID (N_{ID}^{2}) 0, 1, and 2.

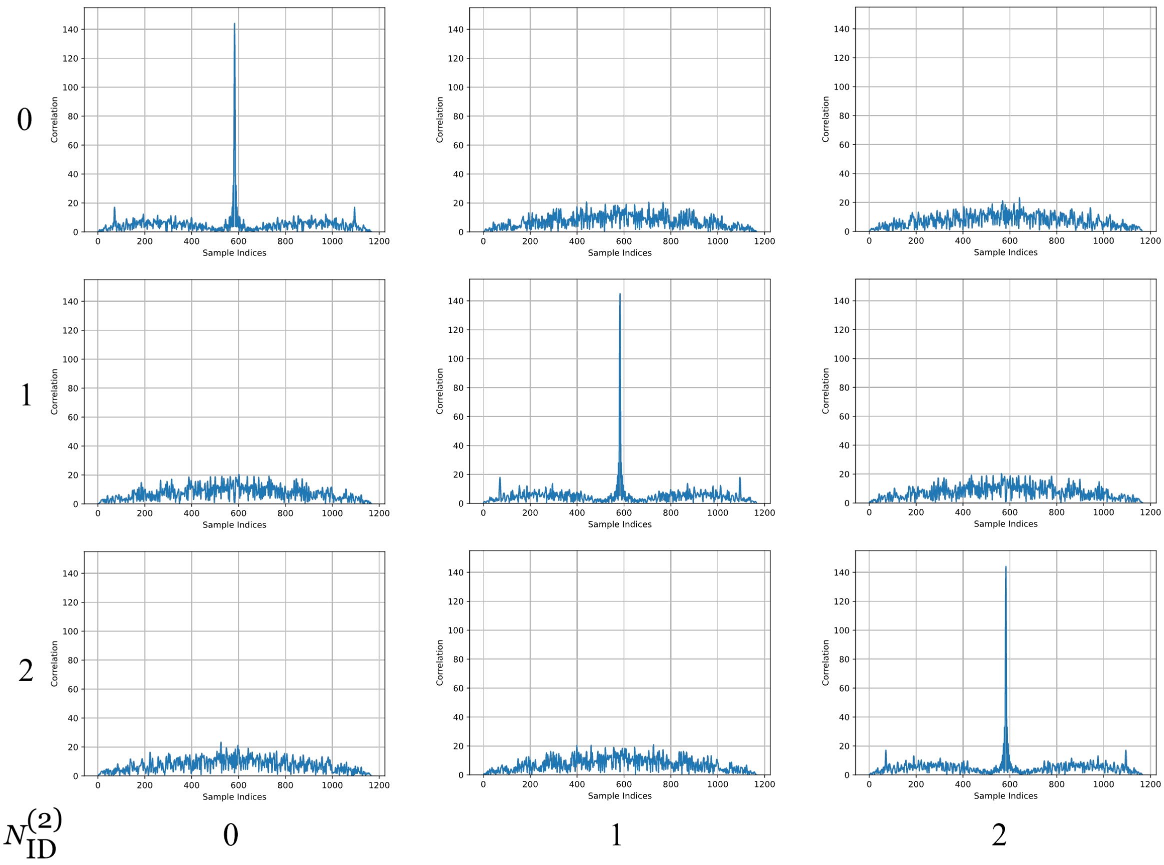

Figure 1.4: Correlation of PSS sequences for $N_{\mathrm{ID}}^{(2)} = 0, 1, 2$.

Observation-2: The primary synchronization signals is designed to have good time-frequency correlation properties.

The PSS can be loaded anywhere on the frequency sync raster which eventually is utilized in time domain to estimate the sample index indicate the first index of the OFDM frame. The final correlation plot 1.5 demonstrates the magnitude of the correlation between the selected PSS and received signal.

Observation-3: The PSS is designed to be robust against noise and interference. The UE can decode cell ID-2 $\left(N_{\mathrm{ID}}^{(2)}\right)$ even low transmit power and receiver gains.

The $N_{\mathrm{ID}}^{(2)}$ detection performance was analyzed for a a transmitter and receiver pair separated by a distance of 1 meter facing each other for transmitter and receiver gains stated in table 1.1.

The table 1.1 shows the detection of PSS at the UE SDR. The distance between the transmitter SDR and receiver SDR is kept at 1m. The results may vary when experiment is performed by students depending upon multi-path fading. It may be noted that for transmitter gain of -80 dB to -40 dB, PSS is not detected at receiver SDR. From -30 dB transmitter gain onwards, PSS is detectable for each receiver gain. These results may vary depending upon distances between two SDRs and objects therein creating multi-path.

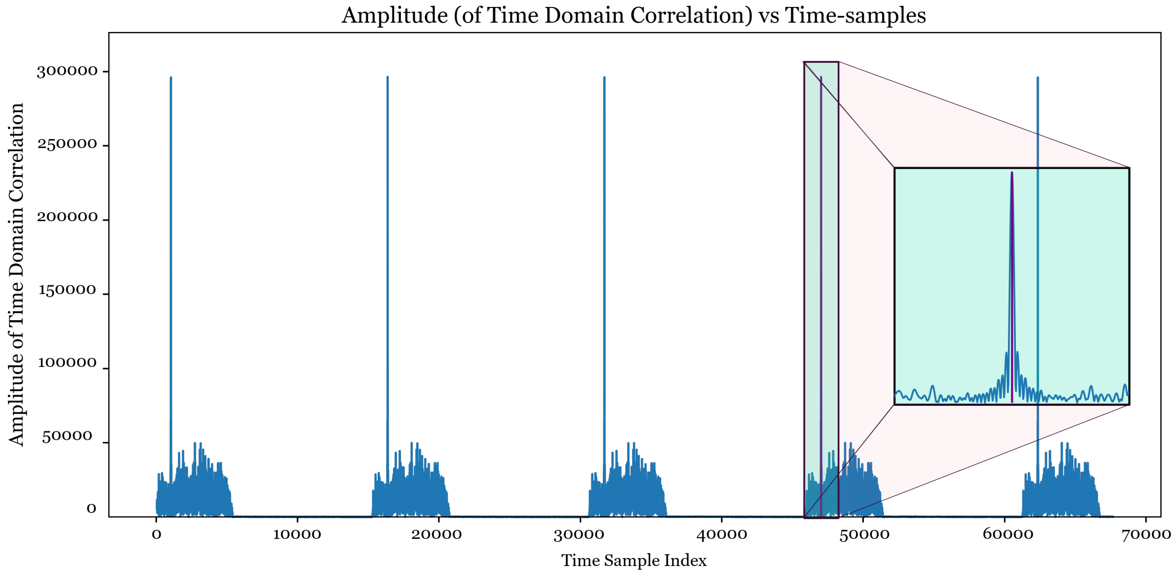

Figure 1.5: Coarse time synchronization using PSS in 5G networks.

Table 1.1: Detection of PSS (Not Detection: **ND** | Not Detection: **D**)

Rx Gain / Tx Gain	0	10	20	30	40	50	60	70
-80	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
-70	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
-60	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
-50	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
-40	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
-30	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**
-20	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**
-10	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**
0	**D**	**D**	**D**	**D**	**D**	**D**	**D**	**D**

1.5 | Useful Resources

The following are some good articles and papers that we believe are really good read to develop a deeper understanding from here onwards

- Time Synchronization code.
- P1 Procedure: Wide Beam management code [?? update the link].
- Arvind Chakrapani's paper on SSB/PBCH and PRACH design in 5G-NR.

2 | References

[1] TS 38.211 3rd Generation Partnership Project. Physical channels and modulation (Release 17). *Technical Specification Group Radio Access Network*, Version(v17.5.0):35–52, 2023-06.