Modern Wireless Networks

Initial Access

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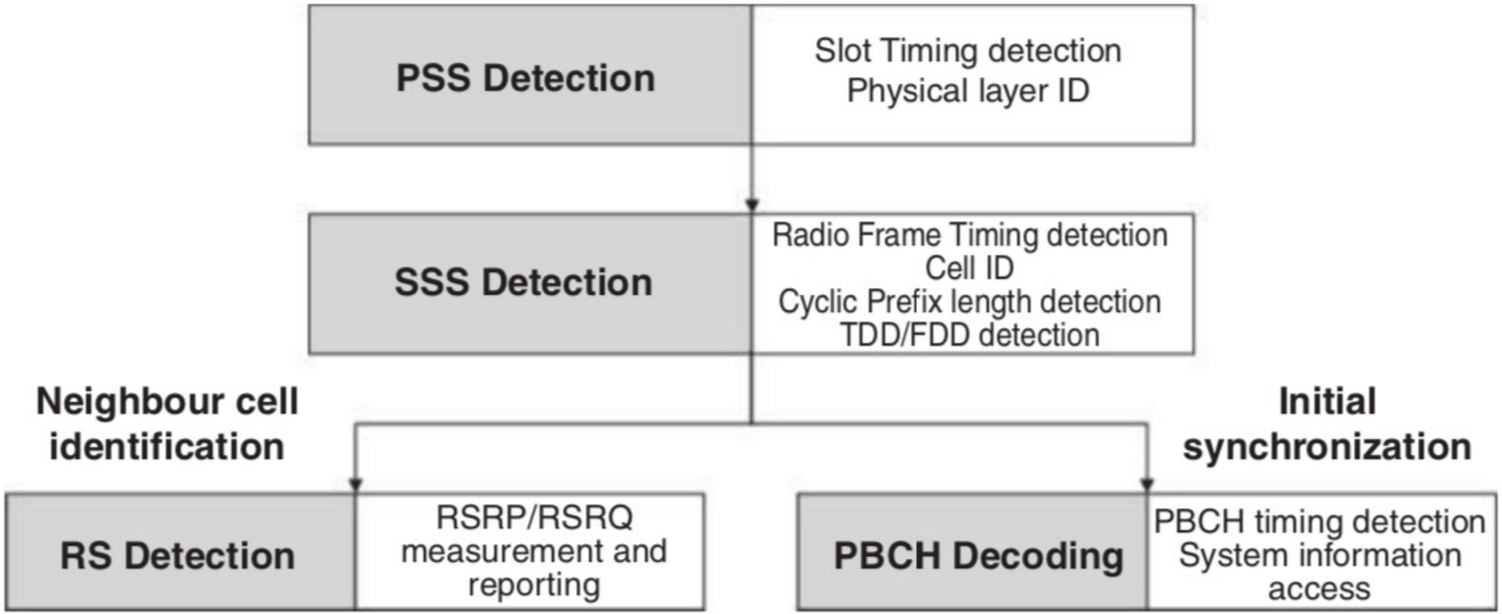
Cell Search

- Symbol and frame timing acquisition
  - the correct symbol start position is determined
- Carrier frequency synchronization
  - required to reduce or eliminate the effect of frequency errors arising from a mismatch of the local oscillators between the transmitter and the receiver
- Sampling clock synchronization
- Determination of the physical-layer cell identity of the cell

Information Acquired in Each Step

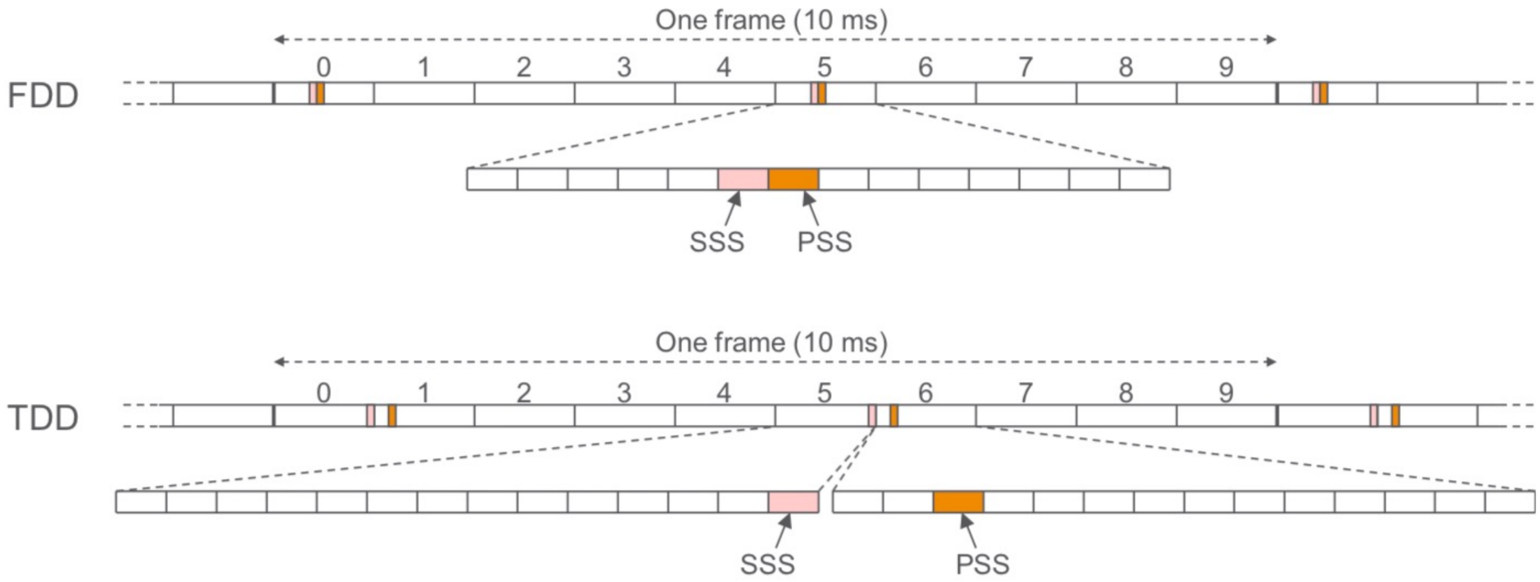


Synchronization Signals

- Primary & Secondary Synchronization Signal (PSS & SSS)
- FDD:
  - PSS is transmitted within the last symbol of the first slot of subframes 0 and 5
  - SSS is transmitted within the second last symbol of the same slot, that is, just prior to the PSS.
- TDD:
  - PSS is transmitted within the third symbol of subframes 1 and 6, that is, within the DwPTS
  - SSS is transmitted in the last symbol of subframes 0 and 5, that is, three symbols ahead of the PSS

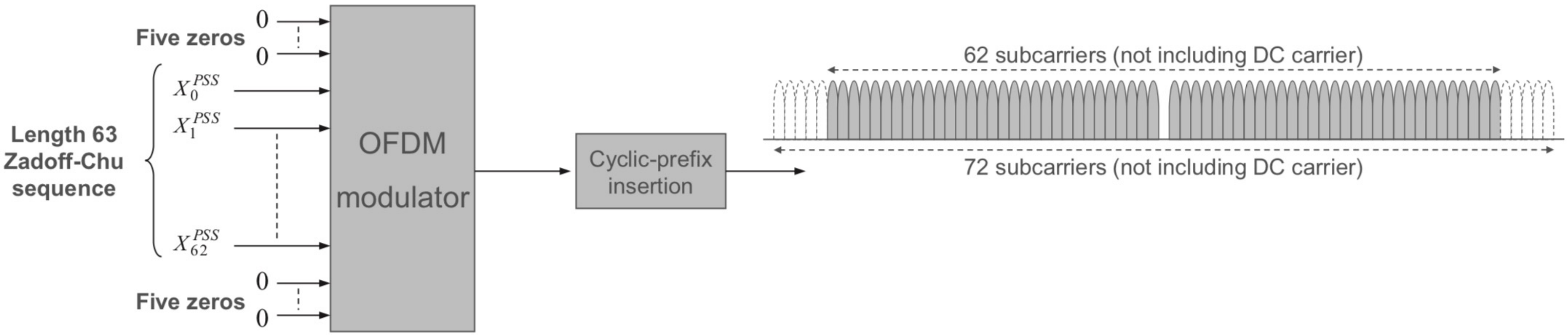
Synchronization Signal Structure

- Time-domain structure difference between FDD and TDD allows for the device to detect the duplex mode of the acquired carrier if this is not known in advance



PSS Structure

- Transmitted over central 6 Resource Blocks (12 SC)
- Does not depend on Bandwidth (varies from 6-110 RB)
- Allows UE to sync without prior knowledge of channel
- Only 62 SC used, UE can use 64-pt FFT to decode

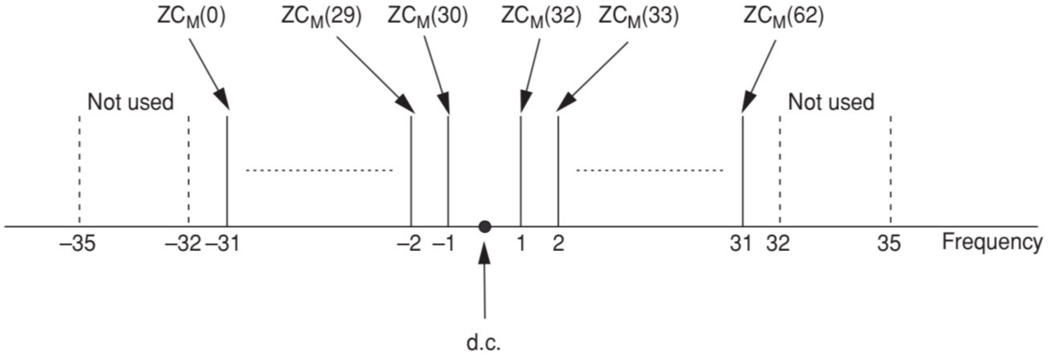


PSS Generation

- PSS is constructed from a frequency-domain Zadoff-Chu (ZC) sequence of length 63, with the middle element punctured to avoid transmitting on the d.c. subcarrier

$$ZC_M^{63}(n) = \exp\left[-j\frac{\pi M n(n+1)}{63}\right], \quad n = 0,\ 1, \ldots, 62$$

M=29, 34, 25 for LTE

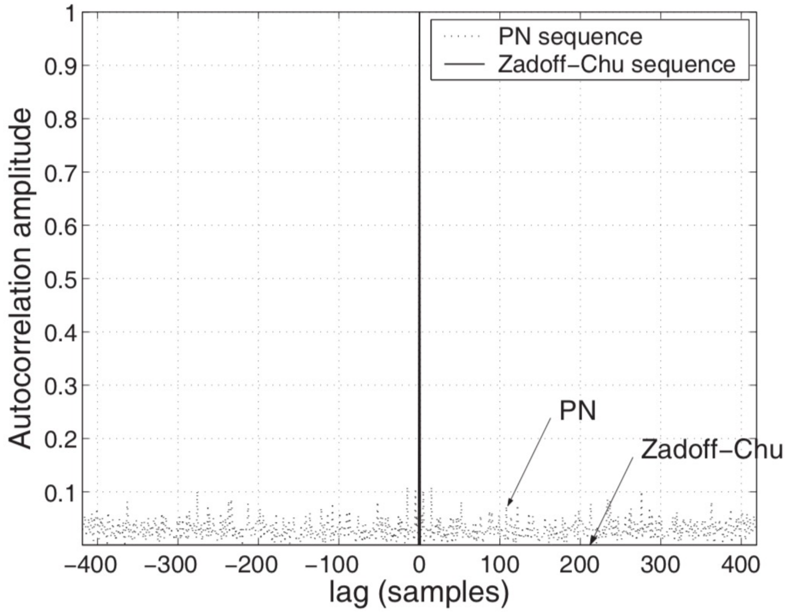


Properties of ZC Sequence

- Property 1:
  - A ZC sequence has constant amplitude
  - Limits the Peak-to-Average Power Ratio (PAPR)
  - Simplifies the implementation as only phases need to be computed and stored, not amplitudes

Properties of ZC Sequence

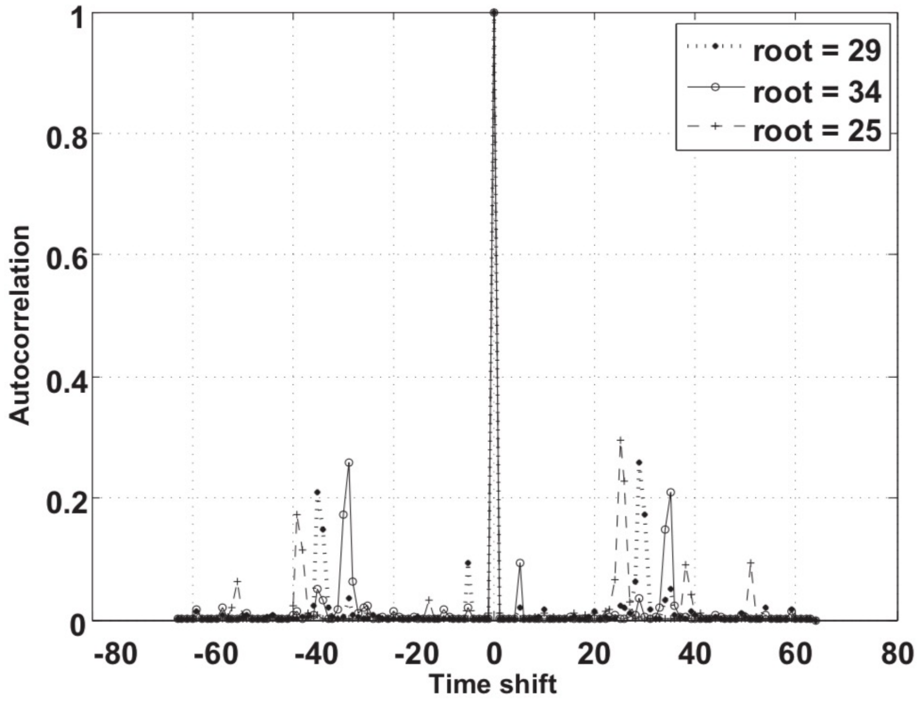
- Property 2:
  - ZC sequences of any length have 'ideal' cyclic autocorrelation (i.e. the correlation with its circularly shifted version is a delta function)
  - Constant Amplitude Zero Autocorrelation (CAZAC) property
  - Creates a Zero-Correlation Zone (ZCZ) between the two sequences
  - It allows multiple orthogonal sequences to be generated from the same ZC sequence



The ZC periodic autocorrelation is exactly zero for $\sigma \neq 0$ and it is non-zero for $\sigma = 0$

Properties of ZC Sequence

- Property 3:
  - The absolute value of the cyclic cross-correlation function between any two ZC sequences is constant if sequence indices ae relatively prime
  - Three PSS sequences are used in LTE (M=29, 34, 25)



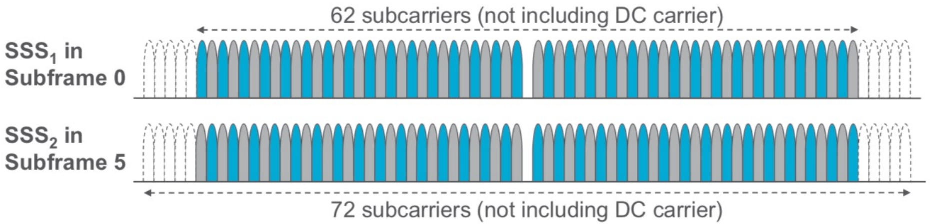
Cell Identity Arrangement

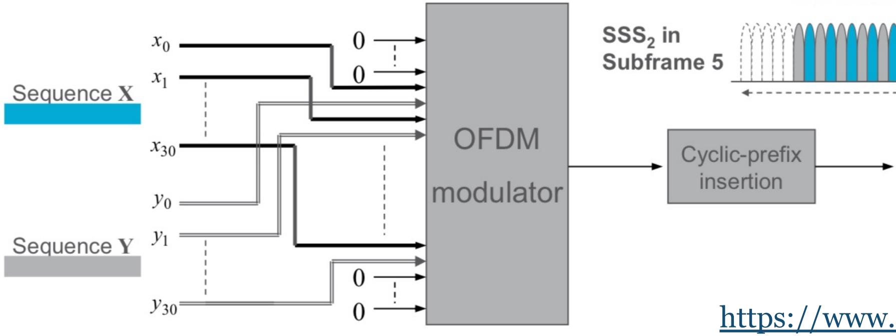
- Physical Cell Identity for a cell can be 0-503.
- $N_{ID}^{Cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$
- $N_{ID}^{(1)}$ = physical layer cell identity group (0 to 167)
- $N_{ID}^{(2)}$ = identity within the group (0 to 2)
- $N_{ID}^{(2)}$ is known after decoding PSS

$N_{ID}^{(2)}$	Root (M)
0	25
1	29
2	34

SSS Structure

- The SSS sequences are based on maximum length sequences, known as M-sequences
- An m-sequence is a pseudorandom binary sequence
- It can be created by cycling through every possible state of a shift register of length n
- This results in a sequence of length $2^n - 1$



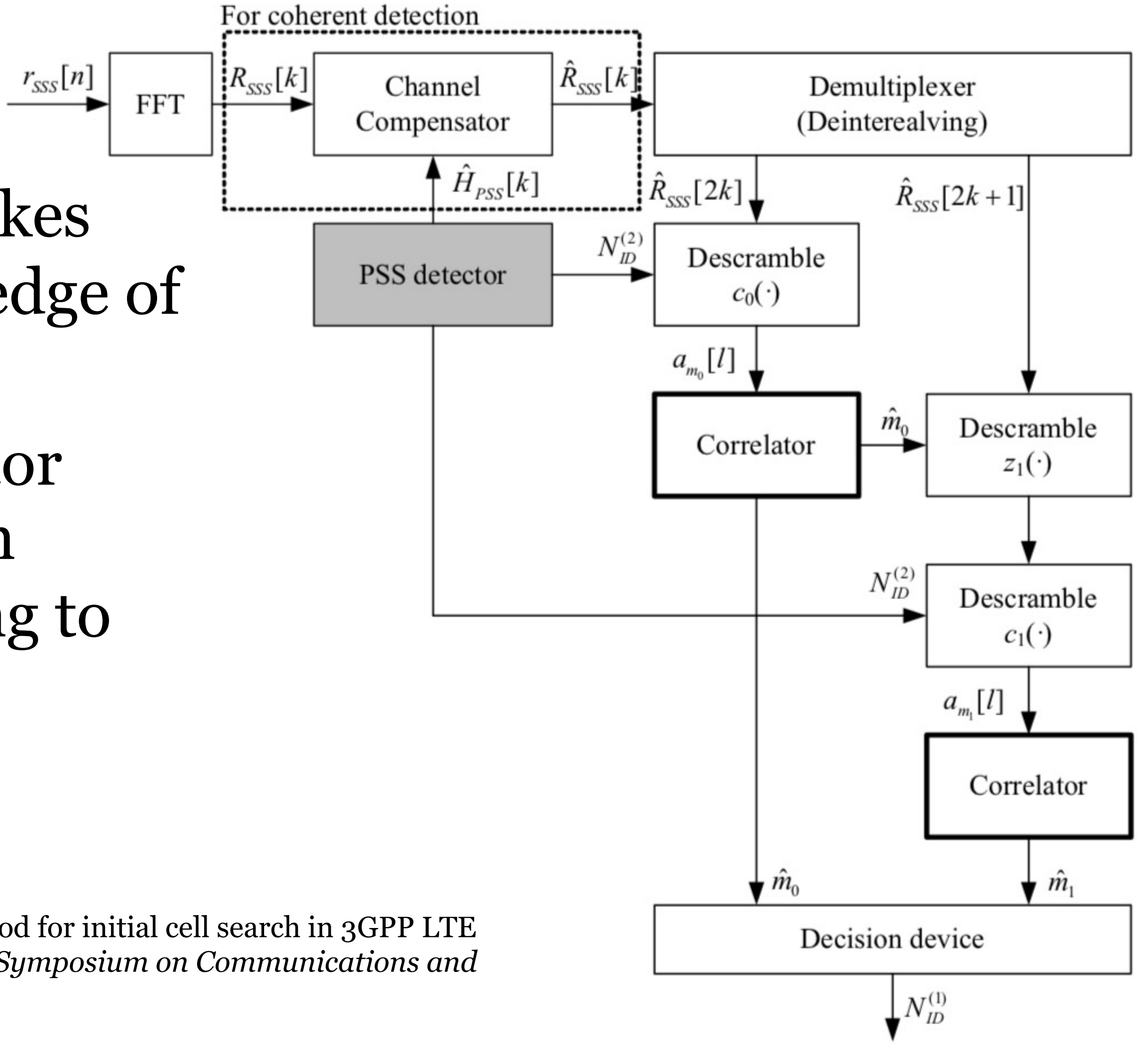


The set of valid combinations of X and Y for SSS1 (as well as for SSS2) are 168, allowing for detection of the physical-layer cell identity

https://www.mathworks.com/help/lte/ug/synchronization-signals-pss-and-sss.html

SSS Detector

- coherent detector takes advantage of knowledge of the channel
- non-coherent detector uses an optimization metric corresponding to the average channel statistics



J. Kim, J. Han, H. Roh and H. Choi, "SSS detection method for initial cell search in 3GPP LTE FDD/TDD dual mode receiver," *2009 9th International Symposium on Communications and Information Technology*, Icheon, 2009, pp. 199-203.

Cell System Information

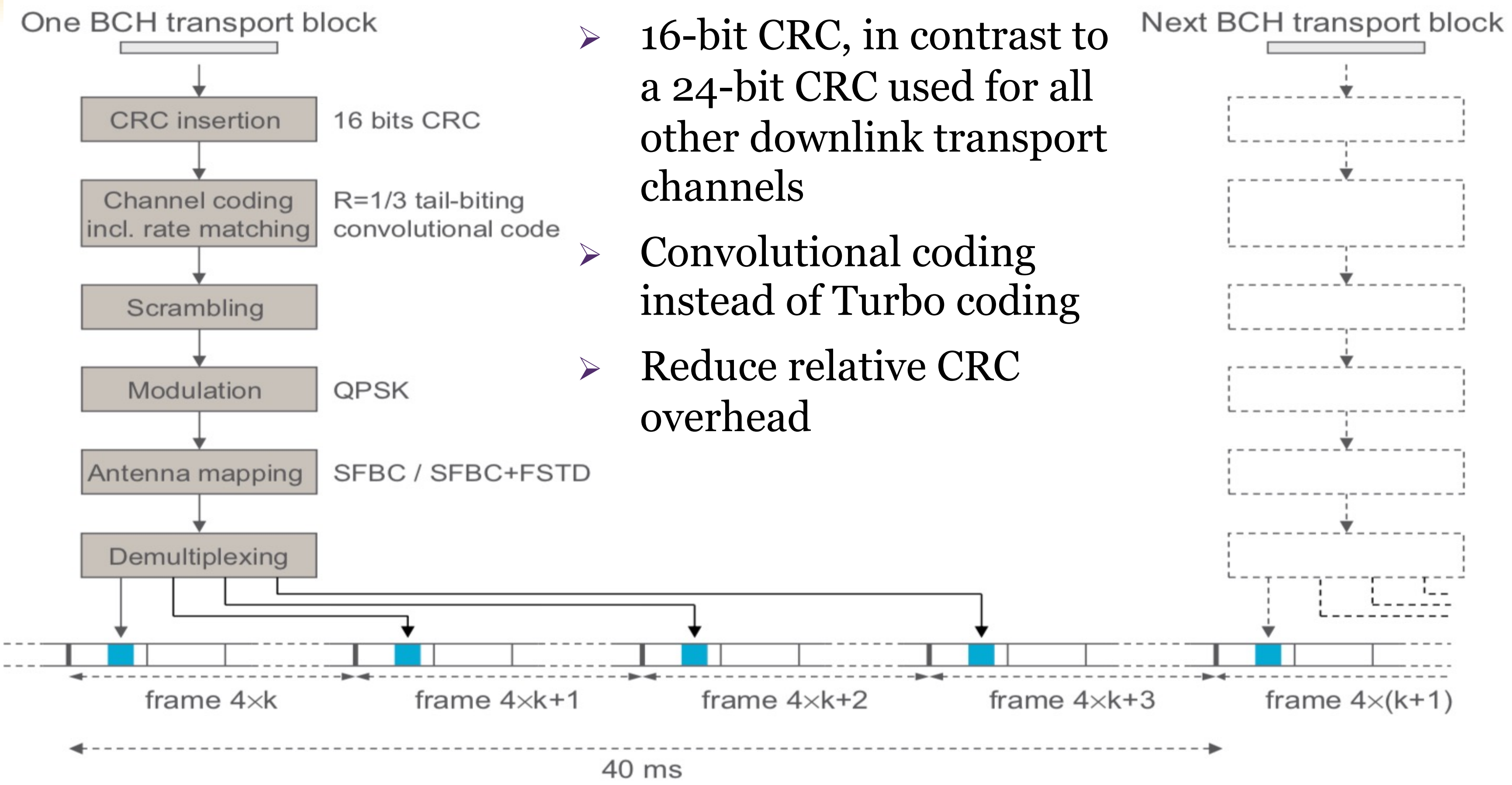
- After achieving synchronization, device has to acquire cell system information
- Two Transport Channels for system information
  - Master information block (MIB) in BCH
  - System information block (SIB) in DL-SCH

MIB

- PBCH is used to transmit
- MIB payload is 24-bit
  - **3 bits** for system bandwidth
  - **3 bits** for PHICH information,
    - 1 bit to indicate normal or extended PHICH
    - 2 bit to indicate the PHICH Ng value
  - **8 bits** for system frame number (0-1023, 2 LSBs not transmitted)
  - **10 bits** are reserved for future use
- Generation Periodicity – 40ms
- Transmission Periodicity – 10ms

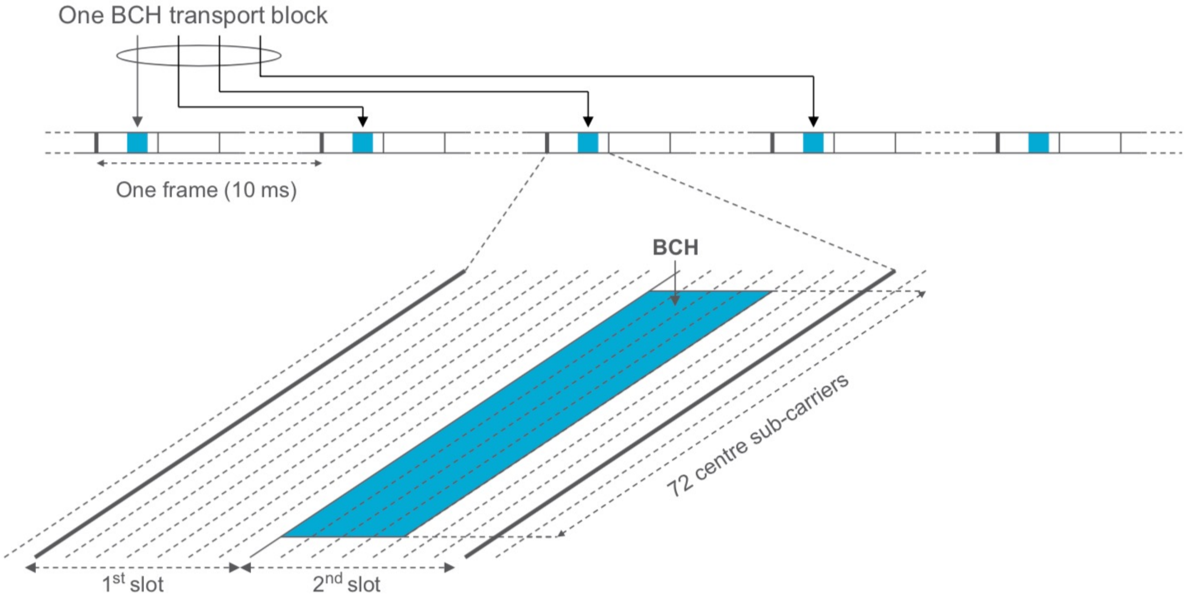
MIB Structure

- 16-bit CRC, in contrast to a 24-bit CRC used for all other downlink transport channels
- Convolutional coding instead of Turbo coding
- Reduce relative CRC overhead



Mapping of MIB → BCH → RB

- Mapped to first subframe of each frame in four consecutive frames.
- BCH is transmitted within the first four OFDM symbols of the second slot of subframe 0 and only over the 72 center subcarriers
- In the case of FDD, BCH follows immediately after the PSS and SSS in subframe 0.

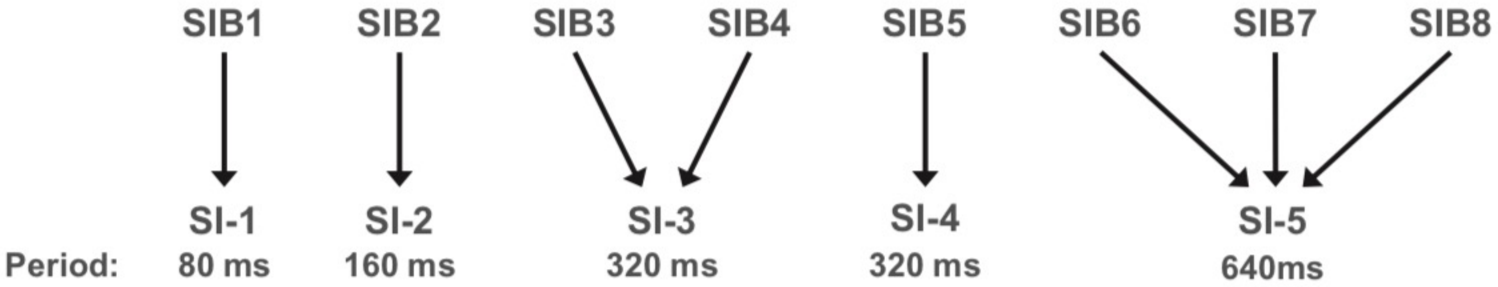


System Information Block

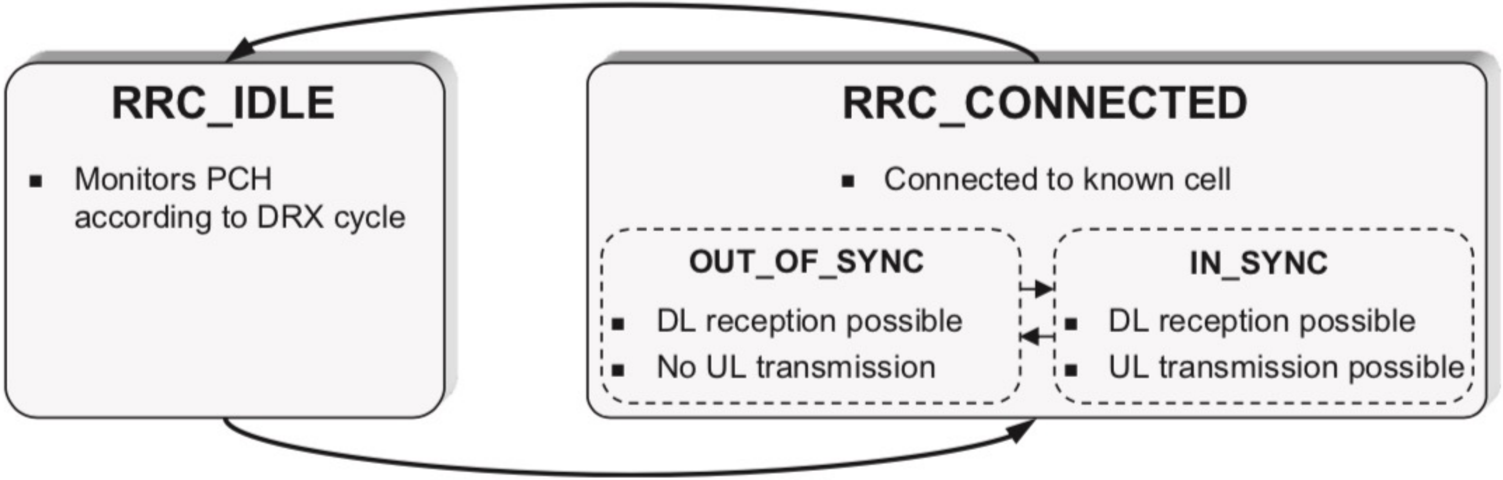
- The SIBs represent the basic system information to be transmitted.
- 3GPP defines 20 different SIBs (SIB1-SIB20)
- SIB1 includes parameters needed to determine if a cell is suitable for cell selection, as well as information about the time-domain scheduling of the other SIBs
- SIB2 includes information that devices need in order to be able to access the cell.
  - This includes information about the uplink cell bandwidth, random-access parameters, and parameters related to uplink power control.

SIB Transmission

- SIBs are mapped to different system-information messages (SIs)
- SIs correspond to the actual transport blocks to be transmitted on DL-SCH
- SIB1 (SI-1) transmitted every 80ms
- SI-1 is transmitted within subframe 1
- Transmission period of higher order SIBs is flexible and vary from one network to another



RRC_Idle to RRC_Connected



PRACH – Physical Random Access Ch

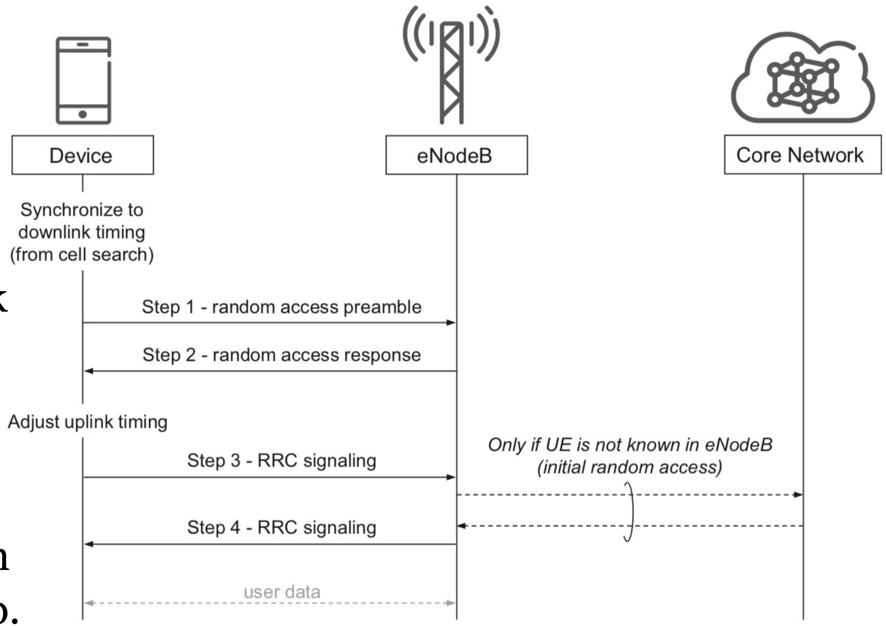
- Scenarios for use
  - A UE in RRC_CONNECTED state
    - not uplink-synchronized, needing to send new uplink data or control information
    - not uplink-synchronized, needing to receive new downlink data, and therefore to transmit corresponding (ACK/NACK) in uplink
    - handing over from its current serving cell to a target cell
    - For positioning purposes, when timing advance is needed
  - A UE in RRC_IDLE state
    - Initial access to convert to RRC_CONNECTED
    - Recovering from radio link failure

Process for Random Access

STEP 1: Random-Access Preamble Transmission → STEP 2: Random-Access Response → STEP 3: Device Identification → STEP 4: Contention Resolution

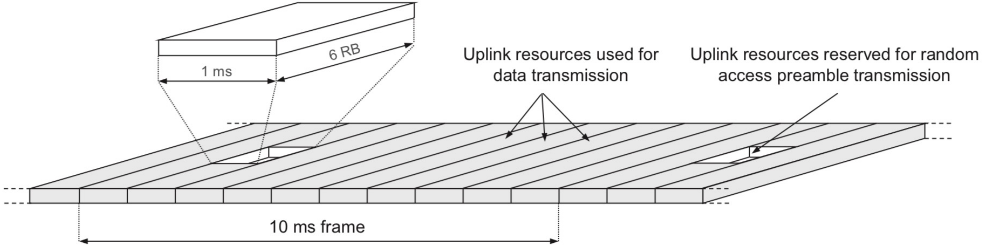
Random Access Preamble

- The device transmits a random-access preamble
  - The network estimates the transmission timing of the device
  - Uplink synchronization is necessary as the device otherwise cannot transmit any uplink data.
- The network transmits timing advance command
  - Adjusts the device transmit timing, based on the timing estimate obtained in the first step.
  - Assigns uplink resources to the device to be used in the third step in the random-access procedure.



PRACH

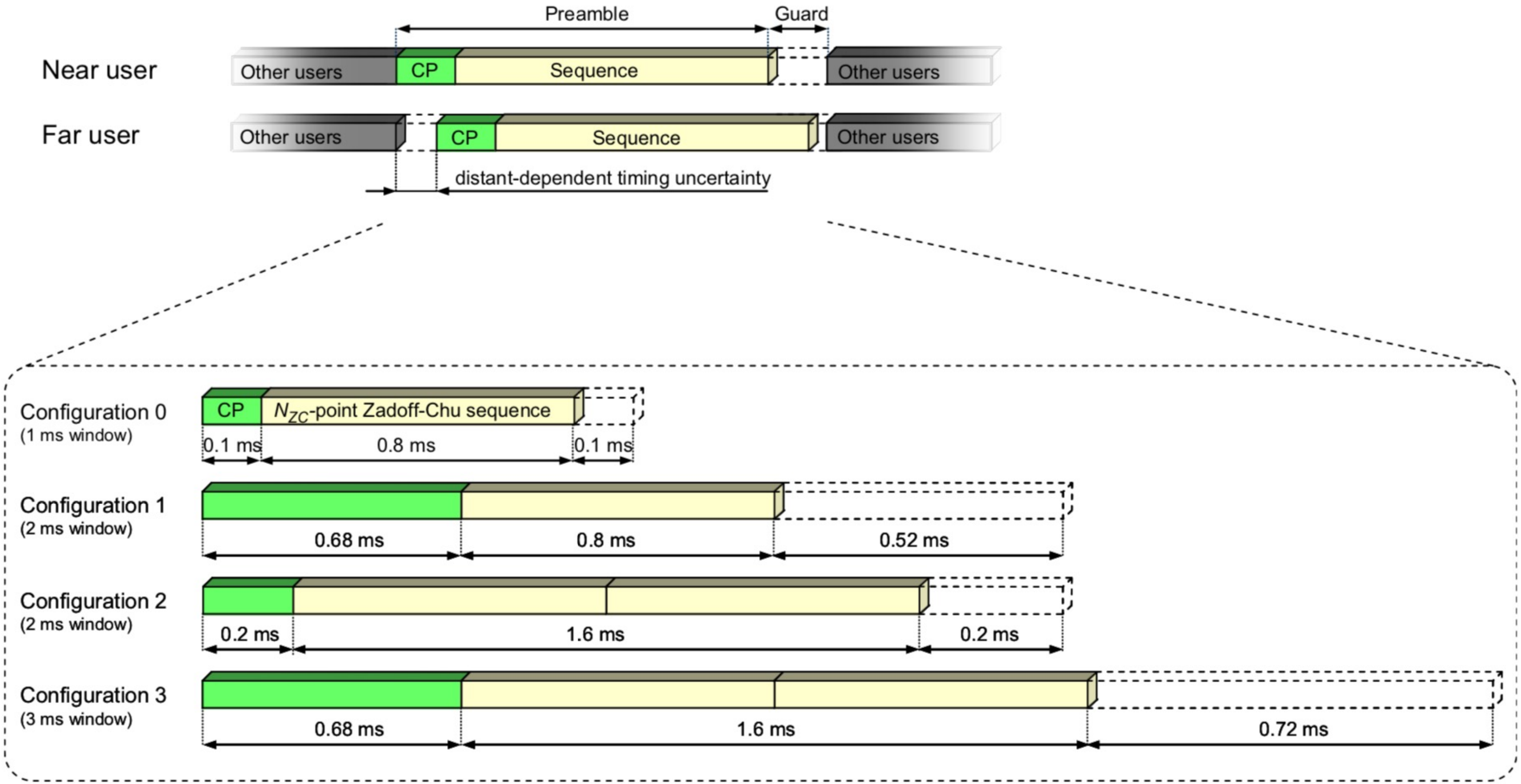
- The RBs in which random access preamble is allowed to be transmitted is known as PRACH.
- The network broadcasts information about PRACH resources in SIB-2.
- PRACH has a bandwidth of 6 RB (1.08MHz).
- The basic random-access resource is 1 ms in duration, but it is also possible to configure longer preambles



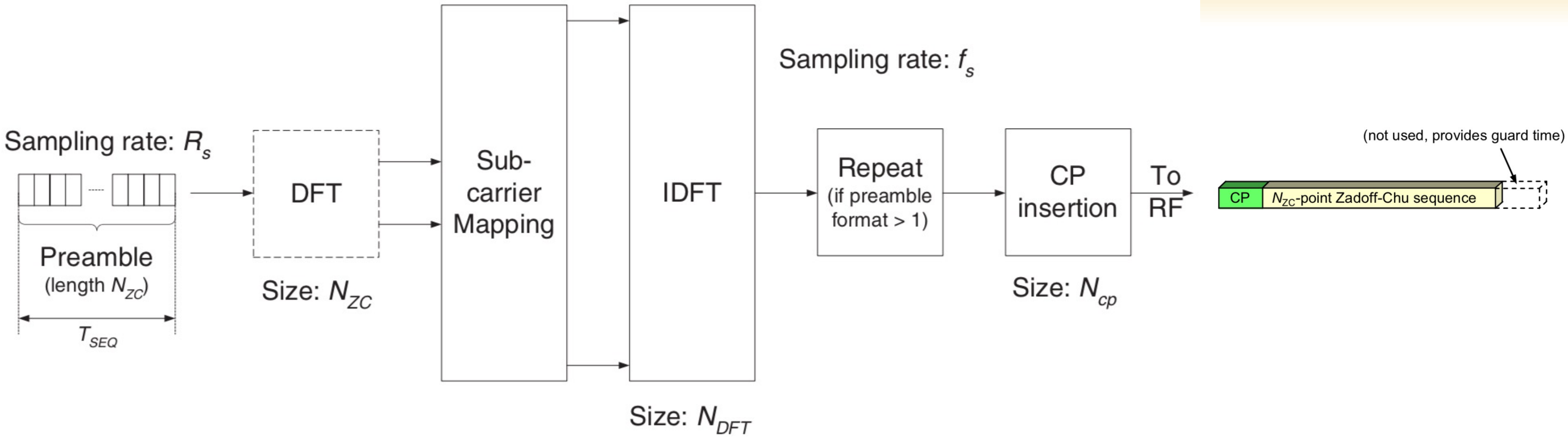
Preamble Structure

- The start of an uplink frame at the device is defined relative to the start of a downlink frame received at the device
- The uplink timing uncertainty is proportional to the cell size and amounts to 6.7 us/km
- the preamble transmission uses a guard period
  - to avoid the data interference at preamble edges
- length of the cyclic prefix is approximately equal to the length of the guard period
- With a preamble sequence length of approximately 0.8 ms, there is 0.1 ms cyclic prefix and 0.1 ms guard time.

Preamble Formats



Preamble Sequence Generation



- Generated from Zadoff-Chu sequence
- From each root, cyclically shifted (in time domain) sequences are obtained

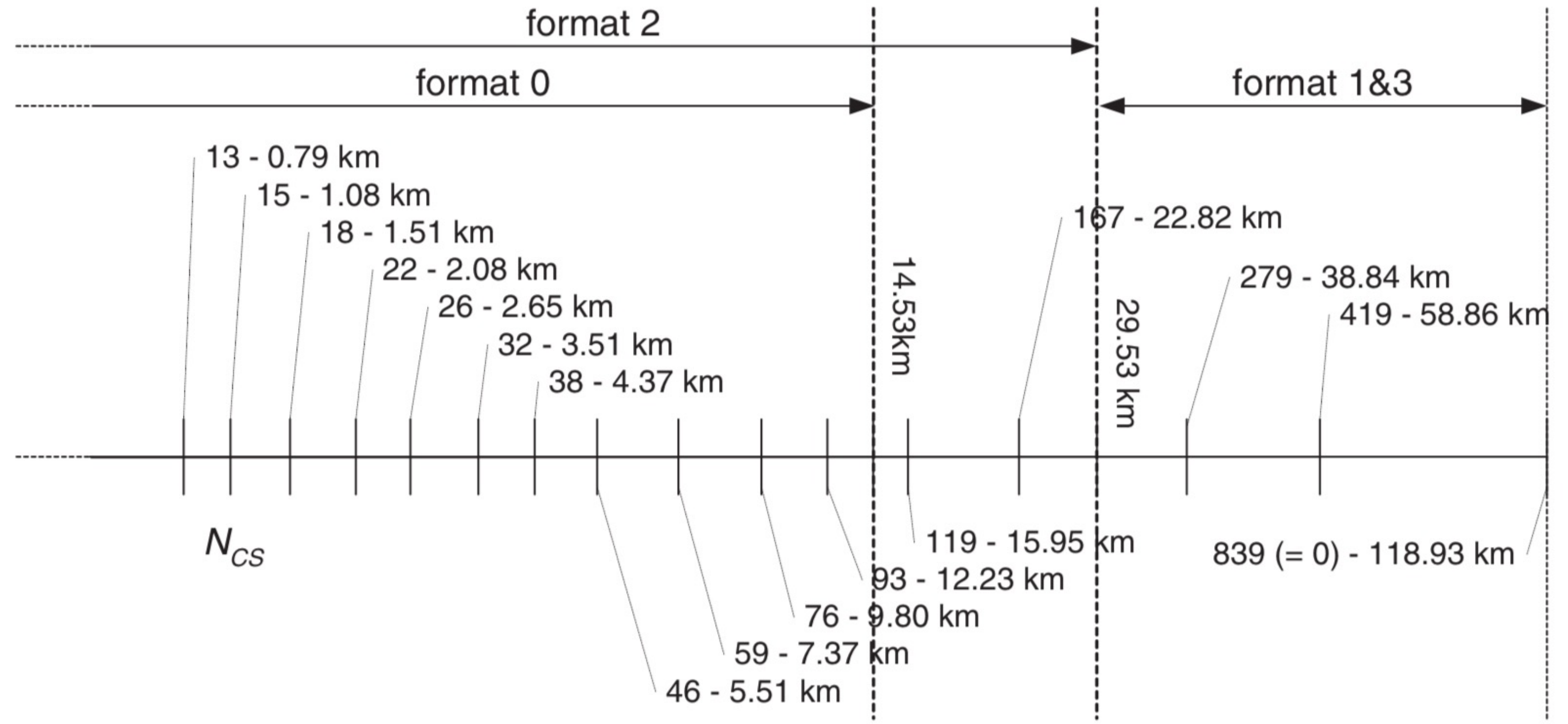
Zadoff Chu Cyclic Shift Restriction

- Due to ideal cross-correlation property, there is no intra-cell interference from multiple random-access attempts using preambles derived from the same Zadoff-Chu root sequence.
- The cross-correlation between different preambles based on cyclic shifts of the same Zadoff-Chu root sequence is zero at the receiver
  - As long as the cyclic shift used when generating the preambles is larger than the maximum round-trip propagation time in the cell plus the maximum delay spread of the channel.
  - To handle different cell sizes, the cyclic shift N_{CS} is signaled as part of the system information.
  - In smaller cells, a small cyclic shift can be configured, resulting in a larger number of cyclically shifted sequences being generated from each root sequence.

Designing N_{CS}

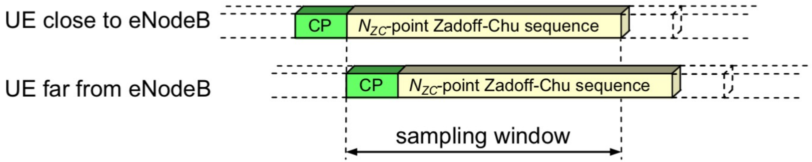
- For cell sizes below 1.5 km, all 64 preambles can be generated from a single root sequence.
- In larger cells, a larger cyclic shift needs to be configured
- To generate the 64 preamble sequences, multiple root Zadoff–Chu sequences must be used in the cell.

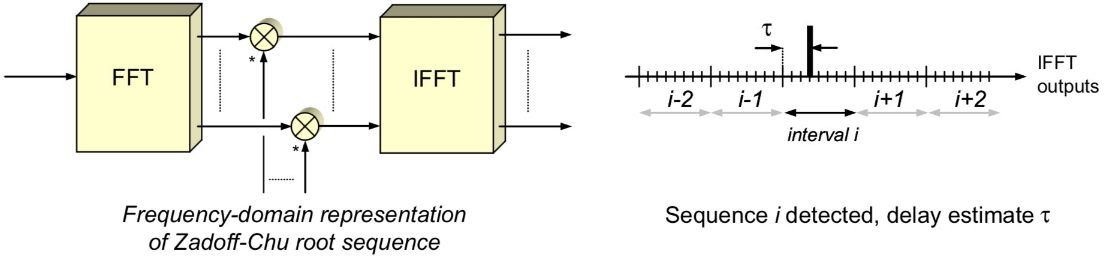
N_{CS} in low speed cells



Preamble Detection

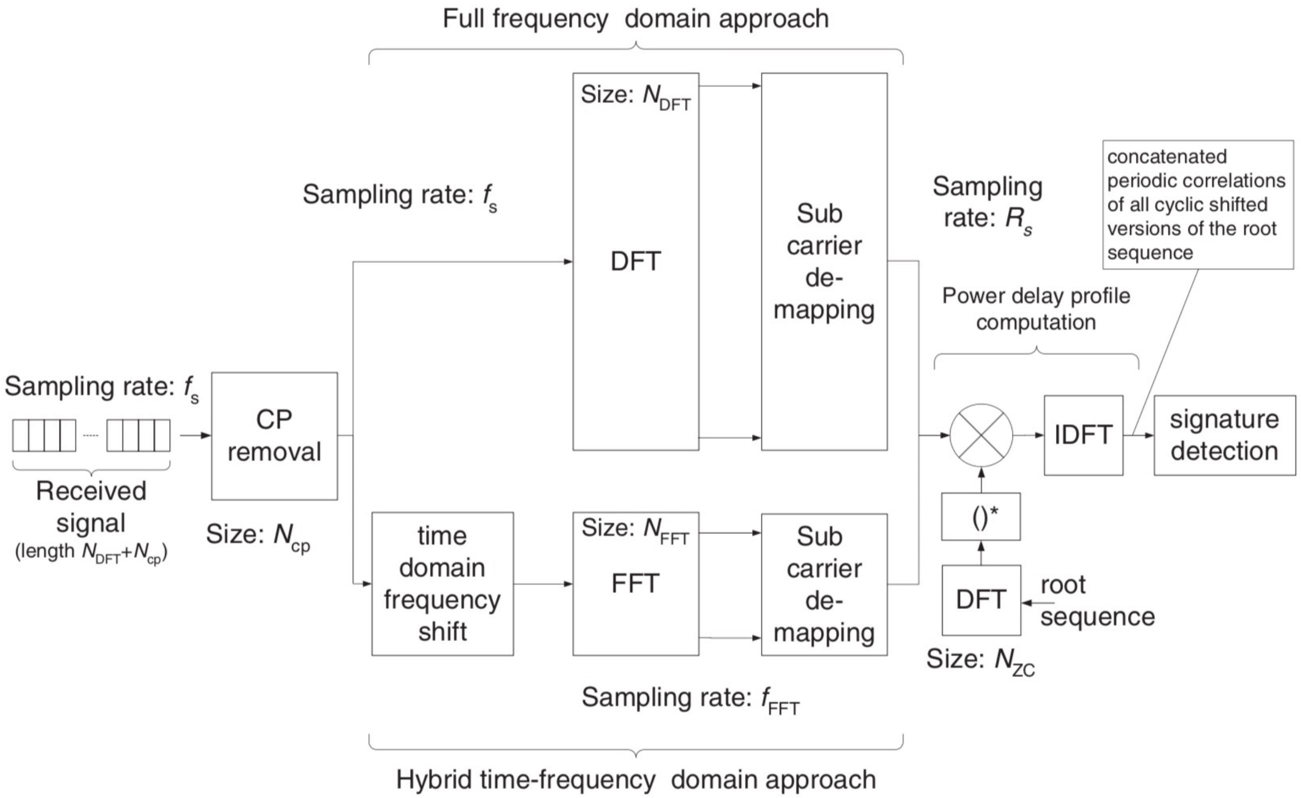
- Converted to frequency domain
- multiplied by the complex-conjugate frequency-domain representation of the root Zadoff-Chu sequence
- result is fed through an IFFT



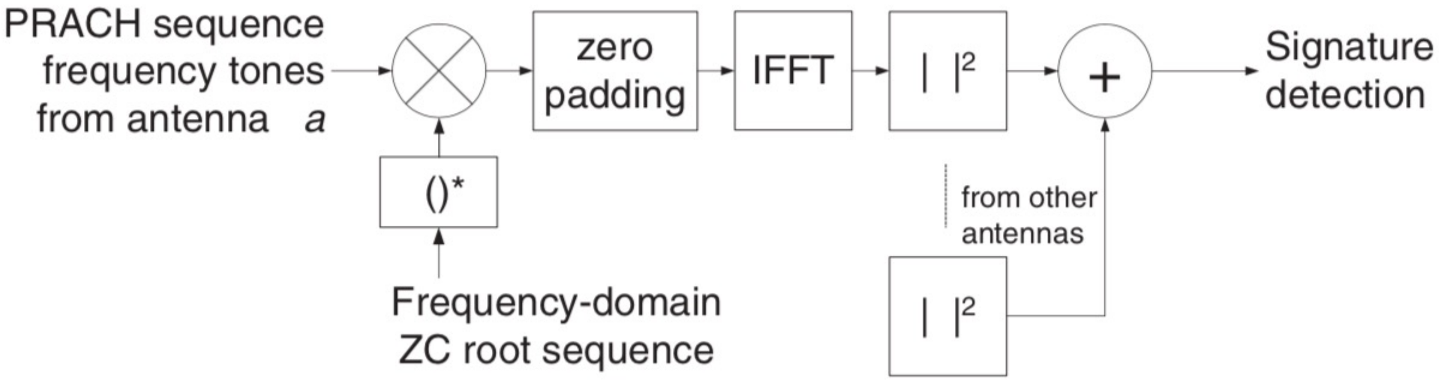


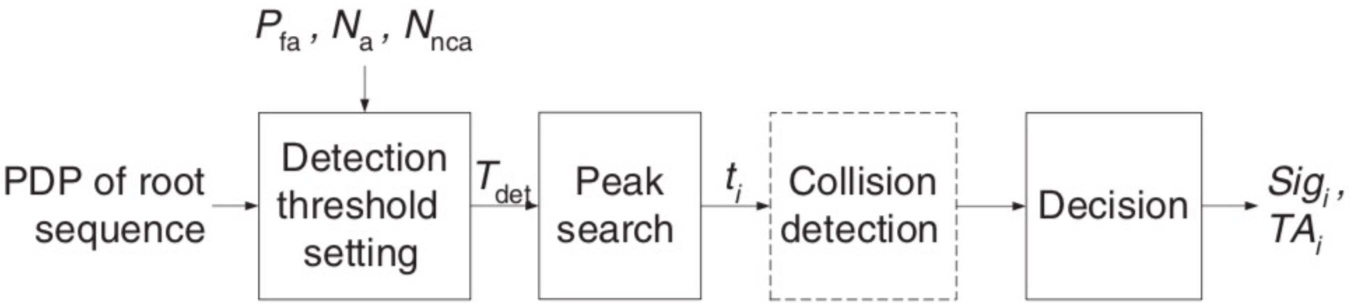
- Time domain output shows which of the shifts of the root Zadoff-Chu sequence has been transmitted and its delay
  - a peak of the IFFT output in interval i corresponds to the i^{th} cyclically shifted sequence and the delay is given by the position of the peak within the interval

PRACH Hybrid Detection

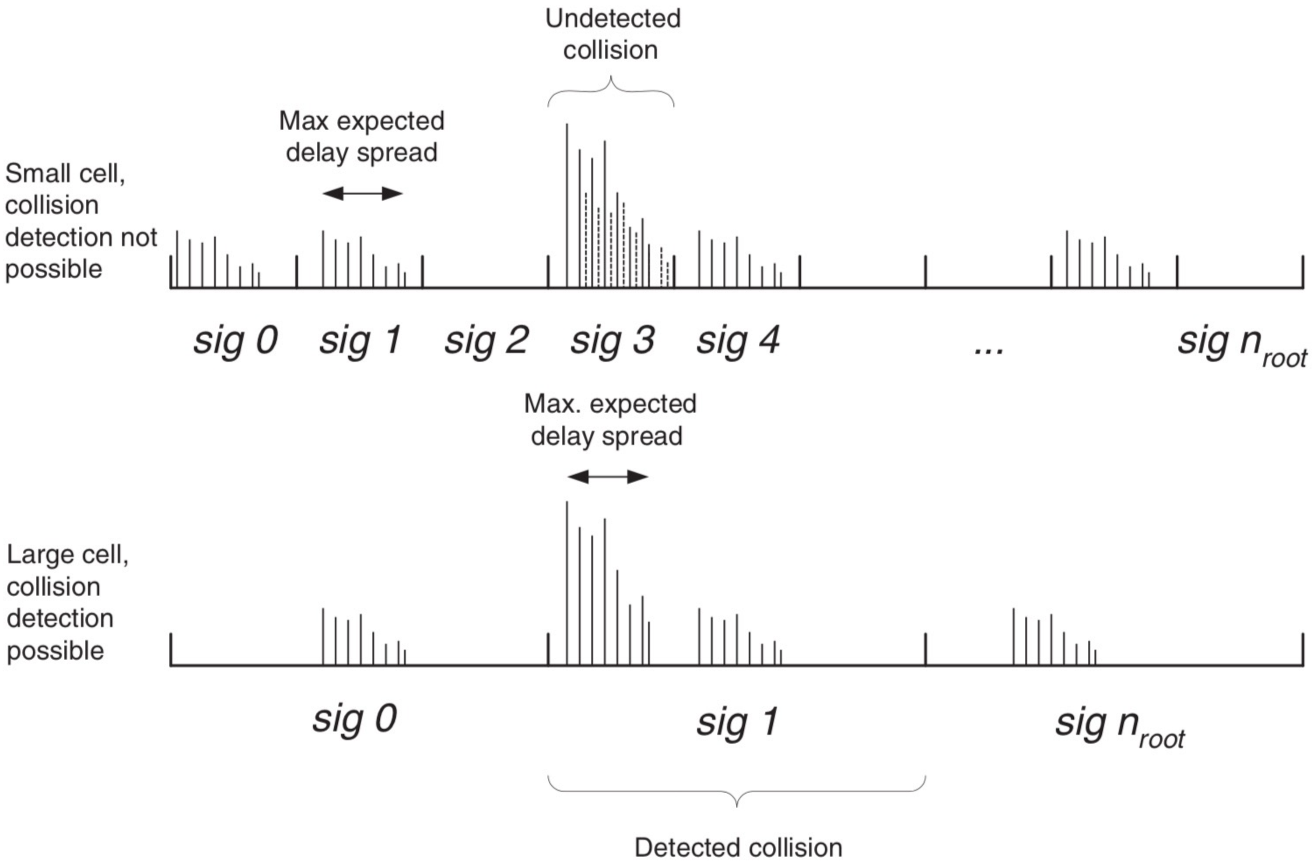


PDP Computation & Detection





Collision Detection



Random Access Response

- In response to the detected random-access attempt, the network will transmit a message on the DL-SCH, containing:
  - The index of the random-access preamble sequences the network detected and for which the response is valid.
  - The timing correction calculated by the random-access-preamble receiver.
  - A scheduling grant, indicating what resources the device should use for the transmission of the message in the third step.
  - A temporary identity, the TC-RNTI, used for further communication between the device and the network.

Multiple Random Access

- As long as the devices that performed random access in the same resource used different preambles, no collision will occur
- From the downlink signaling it is clear to which device(s) the information is related
- There is a certain probability of contention, that is, multiple devices using the same random-access preamble at the same time.
- In this case, multiple devices will respond upon the same downlink response message and a collision occurs.
- Resolving these collisions is part of the subsequent steps

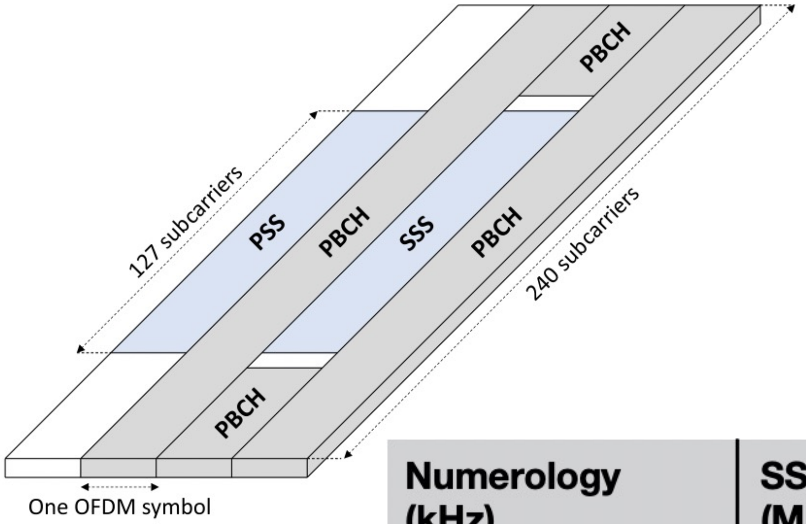
Device Identification

- The device transmits the necessary messages to the eNodeB using the UL-SCH resources assigned in the random-access response
- Transmits the uplink message in the same manner as scheduled uplink data
- Uses TC-RNTI (or C-RNTI is it is already assigned) to respond

Contention Resolution

- If the device already had a C-RNTI assigned
  - Contention resolution is handled by addressing the device on the PDCCH using the C-RNTI
  - Reception of C-RNTI in PDCCH results in successful random access
- If the device does not have a valid C-RNTI
  - The contention resolution message is addressed using the TC-RNTI
  - The device will compare the identity in the message with the identity transmitted
  - Match indicates successful random access
- Devices that do not detect PDCCH transmission with their C-RNTI, or do not find a match between the identity received and identity have failed the random-access procedure and need to restart the procedure from the first step.

Modifications in 5G NR



- PSS & SSS are generated using M-sequence

Numerology (kHz)	SSB Bandwidth[a] (MHz)	SSB Duration (μs)	Frequency Range
15	3.6	≈285	FR1 (<3 GHz)
30	7.2	≈143	FR1
120	28.8	≈36	FR2
240	57.6	≈18	FR2

[a] *The SS-block bandwidth is simply the number of subcarriers used for SS block (240) multiplied by the SS-block subcarrier spacing.*

SS Transmission in 5G NR