Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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Contents

1 | Important System Parameters and their effect on the 5G Networks Performance

In previous chapters we understood the downlink data communication in 5G networks. 5G networks are designed to adapt to changing conditions and meet the quality of services requirements for diverse use-cases. The primary cetegorization of user equipment are **e**nhanced **m**obile **b**road**b**and (eMBB), **u**ltra-**r**eliable **l**ow **l**atency **c**ommunication (uRLLC), and **m**assive **m**achine **t**ype **c**ommunication (mMTC). However, there many use-cases which are have intermediate QoS requirements to these use-cases such as vehicle to everything (V2X) networks, extended reality devices (XR) etc. We will focus primarily on main three use-cases of 5G in this tutorial.
These three use-cases has very different QoS requirements. The eMBB primarily focus on delivering very the data-rate or network/user-perceived throughput. Whereas, the uRLLC aims to deliver highly reliable communication reacting very quickly ensured by very low end to end latency. On the other hand, mMTC is designed to serve massive number of devices constrained in power, complexity and cost which can connect to the network simultaneously requiring small data communications with clement latency requirements.
This tutorial will introduce the users to some very important physical layer parameters which allows the network meet the requirements of all these use-cases. We will discuss these parameters in detail and demonstrate how these parameters influences the network performance. Furthermore, the tutorial will exhibit the fundamental limitations on selection of these parameters and their dependency of the other system aspects

1.1 | What is Flexible numerology?

5G is designed to support diverse use-cases and flexible numerology plays a crucial part in it. The large subcarrier spacing results in shorter sample period and hence short **OFDM** symbols periods and slot duration which are crucial for low latency.
Furthermore, the wider subcarrier spacing are robust to carrier frequency offsets and Doppler frequency offsets making them desirable for low cost receivers and high mobility scenarios. On the other hand, the low subcarrier spacing are particularly useful in rich scattering and large cell deployments. 5G networks supports, 7 numerology as shown in table 1.1 till release 18 for frequency range 1 (FR1, less than 5.4 GHz), frequency range 2 (FR2) and frequency range 2-2 (above 52.6 GHz).

Table 1.1: Supported transmission numerologies in 5G

μ	$2^\mu \times 15$kHz	Cyclic Prefix	Comments
0	15 kHz	Normal	FR1
1	30 kHz	Normal	FR1
2	60 kHz	Normal, extended	FR1/FR2
3	120 kHz	Normal	FR2
4	240 kHz	Normal	FR2 (only for SSB)
5	480 kHz	Normal	FR2-2
6	960 kHz	Normal	FR2-2

1.2 | What is Frame structure?

The frame structure is the organization of radio frames as a unit of time resource in 5G. Each radio unit consists of multiple slots which contains 14 OFDM symbols as shown in figure [?]. The number of slots in a frame depends in the subcarrier spacing (Δf)/numerology (μ).

$$N_{\text{slot}}^{\text{Frame}} = 2^\mu \times 10 \tag{1.1}$$

1.2.1 | Proof

The number of slots in frame changes with subcarrier spacing purely due to variation in sample duration with subcarrier spacing. The sample duration in 5G systems is

$$T_s = \frac{1}{\Delta f \times N_{\text{FFT}}} \tag{1.2}$$

where, the $\Delta f = 2^\mu \times 15000$ relates the subcarrier spacing to numerology. The slot consists of 14 symbols where each symbol contains L_{CP} cyclic prefix samples and N_{FFT} information samples resulting in slot duration ($T_{\text{slot}} = 14 \times (N_{\text{FFT}} + L_{\text{CP}}) \times T_s$) frame duration is 10 ms. Using both these information, the number of slots per frame can be computed as:

$$\begin{aligned}
N_{\text{slot}}^{\text{Frame}} &= \frac{10 \times 10^{-3}}{T_{\text{slot}}} && (1.3)\\
&= \frac{10 \times 10^{-3}}{14 \times (N_{\text{FFT}} + L_{\text{CP}}) \times T_s}\\
&= \frac{10 \times 10^{-3} \times \Delta f \times N_{\text{FFT}}}{14 \times (N_{\text{FFT}} + L_{\text{CP}})}\\
&= \frac{10 \times 10^{-3} \times 2^\mu \times 15000 \times N_{\text{FFT}}}{14 \times (N_{\text{FFT}} + L_{\text{CP}})}\\
&= 2^\mu \times 10 \times 10^{-3} \times \left(\frac{15000 \times N_{\text{FFT}}}{14 \times (N_{\text{FFT}} + L_{\text{CP}})}\right)\\
&= 2^\mu \times 10 \times 10^{-3} \times \frac{1}{\bar{T}_{\text{slot}}} && (1.4)\\
&= 2^\mu \times 10 \times 10^{-3} \times \frac{1}{10^{-3}} && (1.5)\\
&= 2^\mu \times 10 && (1.6)
\end{aligned}$$

In equation 1.5, $\bar{T}_{\text{slot}}$ is the slot duration for 15 kHz subcarrier spacing which is 1 ms.
Note: In eMBB, the transmission time interval (TTI) is typically is equal to slot-duration. On the other hand, the same for uRLLC can be 2, 4 or 7 OFDM symbol. The TTI provides a time framework within which the scheduler operates, making dynamic decisions on resource allocation and scheduling based on the specific requirements of the network, services, and users. The relationship between TTI and the scheduler is crucial for optimizing the use of available resources, meeting quality of service objectives, and adapting to varying network conditions.

1.3 | Impact of parameters on network performance

This section will discuss all the physical layer parameters which influences the network's performance. These parameters are:

- System bandwidth
- Modulation order and code-rate (MCS)
- MIMO: Number of antennas at the transmitter and receiver
- Transmit power
- Subcarrier spacing

1.3.1 | Impact of bandwidth

The bandwidth represents the frequency resources available at the network for communication. The higher bandwidth offers increased resource elements (REs), where each RE is capable of carrying one symbol (denoting a bit of information based on the modulation order) worth of information, resulting in increases information rate. The transmission bandwidth is limited by the maximum bandwidth of the SDR. The higher bandwidth increases the complexity of decoding resulting in higher power consumption. However, the higher bandwidth often require large transport block length pushing the LDPC to operate in asymptotic limit which improve the error correction capability of the LDPC codes. The opposite phenomenon takes place for small resource allocations which degrades the performance of LDPC codec.

1.3.2 | Impact of Modulation Order and Code-rate

The modulation order and code rate are the most important parameters from the network adaptation perspective. These parameters are derived from MCS table using the modulation and code-rate (MCS) index. The parameter is computed by scheduler and configured to the UE either via RRC signalling or DCI using PDCCH. MCS-index helps the scheduler establish a trade-off between the data-rate and reliability based on the channel conditions.
The modulation order control the symbol mapping which maps a group of bits to a complex symbols. As mentioned in previous sub-section, one symbol is carried by a RE. Higher the modulation order more the number of bits mapped to a single RE, hence higher data-rate provided suitable channel conditions. However, if the propagation conditions are harsh higher modulation order might result in high block rates resulting in lower reliability.
On the other hand, the code-rate is controlled by rate-matcher (bit-selection) and LDPC channel codec. Both these modules lies with upper physical layer of physical downlink shared channel (PDSCH). Both these modules control the amount of redundancy, parity bits, introduced in the information bits systematically. Higher code-rate improves the network throughput but offers a poor error correction capability which might result in lower reliability.

1.3.3 | Impact of Transmit Power (P_t)

The transmit power boosts the signal to make it suitable for long-distance transmission. Each modulation order requires a certain minimum link quality (signal to noise ratio (SNR)) to decode the transmit data accurately. The SNR is defined by

$$\rho = \frac{P_{\mathrm{t}}}{N_0} \tag{1.7}$$

where the power of the noise generatedby the receiver is parameterized by,

$$N_0 = \frac{K_{\mathrm{B}} * T * B}{N_{\mathrm{F}}} \tag{1.8}$$

where the K_{B} is Bolzmann constant, T is temperature, B is bandwidth and N_{F} defines the noise figure that parameterize the quality of the receiver. Higher transmit power improves the SNR which improves the decodability of a data transmitted using MCS index. However, beyond a certain point increasing the transmit power doesn't improve the system performance until either the transmit encodes the data with higher the MCS index or receiver supports required noise figure and receives a strong signal.
Note: Transmitting high power without adapting the modulation order, code-rate and tranmission-rank results in poor energy efficiency.

1.3.4 | Impact of MIMO

5G systems are designed to support multiple antenna are the transmitter and receiver. Multiple antennas can be used to transmit either multiple copies of the same data (spatial diversity) or transmit distinct data through each antenna (spatial multiplexing).

- **MIMO: Spatial Multiplexing**:
  - In spatial multiplexing, multiple data streams are transmitted simultaneously using multiple antennas at the transmitter. Each antenna sends a different stream of data, and the signals traverse multiple spatial paths to reach the antennas at the receiver.
  - The receiver uses its set of antennas to capture and separate the individual data streams. By exploiting the spatial dimension, spatial multiplexing increases the overall data rate of the communication system.
  - Spatial multiplexing is particularly effective in environments with favorable conditions, such as when there is minimal signal interference and a clear line of sight between the transmitter and receiver.
- **MIMO: Spatial Diversity**:
  - Spatial diversity, on the other hand, is focused on improving the reliability and robustness of wireless communication by exploiting multiple spatial paths. This is achieved by transmitting the same data over multiple antennas with the goal of increasing the chances that at least one of the signals will reach the receiver with sufficient quality.

- In spatial diversity, each antenna serves as an independent communication channel, and the receiver combines the signals received from different antennas. This helps mitigate the effects of fading, signal attenuation, and other forms of interference.
- Spatial diversity is particularly useful in environments where signal reflections, diffraction, and scattering are prevalent, leading to variations in signal strength at the receiver.

In summary, spatial multiplexing and spatial diversity are both techniques employed in MIMO systems to enhance wireless communication performance:

- **Spatial Multiplexing**: Increases data throughput by transmitting multiple data streams simultaneously over different spatial paths.
- **Spatial Diversity**: Improves reliability and robustness by using multiple antennas to transmit the same data over independent spatial paths, mitigating the effects of fading and signal variations.

Both techniques can be used together in a MIMO system to achieve even greater improvements in data rates and reliability, depending on the specific characteristics of the communication environment.

1.3.5 | Impact of subcarrier spacing

The subcarrier spacing is an important parameter for consideration in system design. For a constant bandwidth, the amount of time-frequency resources for communication doesn't change irrespective of the value of the subcarrier spacing. The higher subcarrier spacing reduces the number of subcarriers/resource elements (REs) available per OFDM symbols but increases the number of OFDM symbols available per frame proportionally. On the other hand, the number of REs per OFDM symbols reduces for smaller numerologies but small duration increases. However, the smaller numerology are more susceptible to carrier frequency offset and Doppler frequency offset. Hence, the network performance improves for devices with higher mobility or unstable clocks. However, such networks have small coverage footprints.

1.4 | Results

The general simulation parameters are given in table 1.2 below:

Table 1.2: Parameters for performance evaluations

Parameters	Value
Carrier frequency (f_c)	1000 MHz
Bandwidth (B)	30 MHz
FFT size (N_{FFT})	1024
subcarrier spacing (Δf)	30 KHz
Numbers of RBs (N_{RB})	85
Numbers of batches ($N_{\text{slot}}^{\text{PDSCH}}$)	7
Numbers of base station (N_{BS})	1
PDSCH mapping type	"mapping type B"
maxLength (single or double DMRS)	"len1"
startSymbol (OFDM start symbol)	0
configurationType	"Configuration-type-1"
dmrsTypeAPosition	"pos2"
dmrsAdditionalPosition	"pos2"
rank	1
mcsIndex	0
mcsTable	"pdschTable1"

The above parameters are general parameters and valid for all results unless specified.

Observation-1: *The network's throughput both improves as the bandwidth allocated to a UE increases.*

The emulation in this observation is carried out for transmitter gain of 0 dB and receiver gain of 60 dB, for transmitter receiver distance of 50 cm. The MCS index is set to 15. From table 1.3 it can be clearly observed as the bandwidth increases the throughput increases owing the transmission of higher numbers of Resource Blocks (RBs). In other words the higher bandwidth allows transmission of larger chunks of data. The numbers of RBs available at BS for data transmission for a specific system bandwidth is determined from *TimeFrequency5GParameters* module in 5G-Toolkit, which returns the numbers of RBs for the input bandwidth.

Table 1.3: Performance analysis of PDSCH for different bandwidths.

Bandwidth (in MHz)	Numbers of Resource Blocks (RBs)	Throughput	BLER	BER
10	24	12.768 Mbps	0	0
15	38	20.174 Mbps	0	0
20	51	26.894 Mbps	0	0
30	78	41.244 Mbps	0	0

Observation-2: *The network's throughput increases with MCS-Index till the link-budget is adequate to decode the information symbols accurately and code-rate can correct the errors in the decoded information.*

From Table 1.4, for MCS index (I_{MCS}) 0 and 4 (both QPSK), the throughput increases due to the higher code rate, rising from 0.117 to 0.300. This increase allows the BS to reduce redundant bits, replacing them with information bits. Similarly, transitioning from $I_{\text{MCS}} = 4$ to $I_{\text{MCS}} = 10$ improves network performance by using higher modulation, allowing twice the bits to be packed in the same bandwidth. However, increasing the MCS index to 25 (from PDSCH table 4) leads to performance degradation due to an inadequate link budget to support very high modulation orders (Q_m) and code rates (r). This results in the receiver being unable to decode the densely packed information, resulting in 0 Mbps throughput.

Table 1.4: KPIs for different mcs index in PDSCH.

MCS Parameters			Throughput	Spectral Efficiency	BLER
I_{MCS}	Q_{m}	r	η	r/B	p_{B}
0 (QPSK)	2	0.117	4.438 Mbps	0.1479 bits/sec/Hz	0
4 (QPSK)	2	0.300	11.2 Mbps	0.373 bits/sec/Hz	0
10 (16 QAM)	4	0.332	24.654 Mbps	0.821 bits/sec/Hz	0
24 (64 QAM)	6	0.753	0 Mbps	0 bits/sec/Hz	1

Observation-3: *Increasing transmitter power improves networks performance for coverage constrained UEs. For UEs with strong links, increasing transmit power doesn't offer any performance gains instead it degrades the energy efficiency.*

The emulations carried out below considers mcs index 9. The tables below shows the throughput and BLER for fixed receiver gain of 60 dB. For distance of 1m, -20 dB of transmitter gain is required to get BLER of 0, whereas for shorter distance of 0.1m, -30 dB of transmitter gain is enough for BLER to be 0. Since, the throughput remains constant despite the increase in transmit power the energy efficiency reduces The energy efficiency is given by,

$$\begin{aligned}\text{Energy Efficiency}(\zeta) &= \frac{\text{Throughput}}{\text{Total Power}} \\ &= \kappa \times \frac{\text{Throughput}}{\text{Tx-Rx Gain}}\end{aligned}$$

where, Tx-Rx Gain (G_{o}) = Transmitter PA gain (G_{tx}) + Receiver LNA gain (G_{rx}). The EE vs Tx-Rx Gain curve is shown in figure 1.1. The EE for total power of 30 dB, 40 dB and 50 dB are 0.1095, 0.0876, 0.073. Thus, despite increasing the transmission power, EE decreases thus wasting the useful power.

Table 1.5: Energy efficiency (ζ) for different transmitter and receiver gain for $I_{\text{MCS}} = 9$.

Transmitter gain	Receiver gain	Tx-Rx gain	Distance (m)	Throughput	BLER	ζ
-28 dB	60 dB	32 dB	1 m	0 Mbps	1	0
-27 dB	60 dB	33 dB	1 m	0 Mbps	1	0
-26 dB	60 dB	34 dB	1 m	0 Mbps	1	0
-25 dB	60 dB	35 dB	1 m	3.521 Mbps	0.857	0.1006
-24 dB	60 dB	36 dB	1 m	7.044 Mbps	0.714	0.195
-23 dB	60 dB	37 dB	1 m	19.371 Mbps	0.214	0.523
-22 dB	60 dB	38 dB	1 m	22.893 Mbps	0.0714	0.587
-21 dB	60 dB	39 dB	1 m	24.654 Mbps	0	0.616
-20 dB	60 dB	40 dB	1 m	24.654 Mbps	0	0.616
-19 dB	60 dB	41 dB	1 m	24.654 Mbps	0	0.601
-15 dB	60 dB	45 dB	1 m	24.654 Mbps	0	0.493
-10 dB	60 dB	50 dB	1 m	24.654 Mbps	0	0.493
-35 dB	60 dB	25 dB	0.1 m	0 Mbps	1	0
-34 dB	60 dB	26 dB	0.1 m	17.61 Mbps	0.285	0.677
-33 dB	60 dB	27 dB	0.1 m	22.893 Mbps	0.071	0.847
-31 dB	60 dB	29 dB	0.1 m	22.893 Mbps	0.071	0.789
-30 dB	60 dB	30 dB	0.1 m	24.654 Mbps	0	0.821

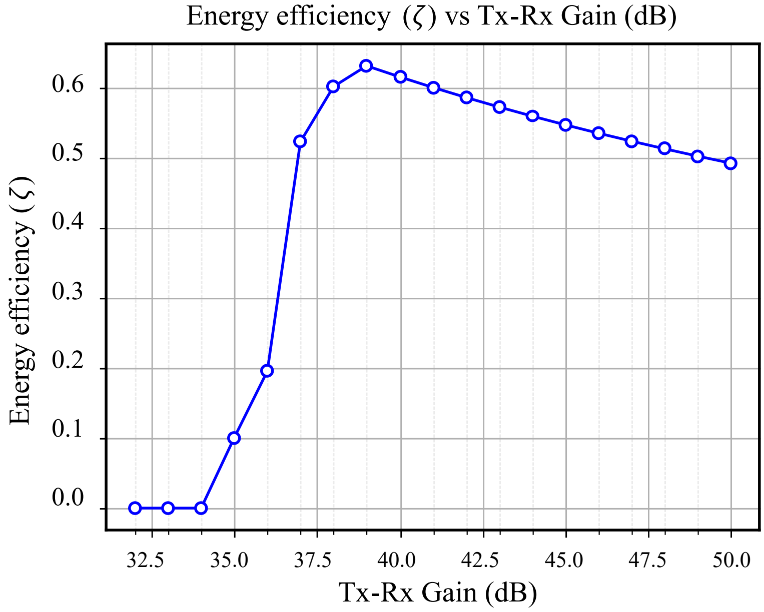

Figure 1.1: Energy Efficiency vs Total Power at distance of 1m.

Observation-4: *Higher order MIMO improves the reliability when configured for* ***spatial diversity*** *and offers higher data-rate when configured for* ***spatial multiplexing****. MIMO can be used either for providing higher reliability (spatial diversity) or higher data rate (spatial multiplexing).*

In table 1.6 the key performance indicators (KPIs) of SISO (1 X 1) and MIMO (2 X 2) with spatial multiplexing (SM) and spatial diversity (SD) are given. It can be noted from table 1.6 that as MCS index increases, the throughput and BLER improves and then starts to deteriorates after certain MCS index. For SISO the maximum throughput is achieved at MCS index of 20, afterwards the BLER starts to increase and becomes 1 at MCS index of 24. For SM MIMO, the BLER becomes 1 at MCS index of 24.

FOr SM MIMO the peak throughput of 117.4 Mbps is achieved thus providing higher throughput, whereas for SD MIMO the BLER does not go to 1 even for MCS index of 28 thus providing higher reliability.

Table 1.6: Performance comparison of SISO, MIMO(SM) and MIMO(SD) systems.

MCS Parameters			SISO		MIMO(SM)		MIMO(SD)	
I_{MCS}	Q_{m}	r	Throughput	BLER	Throughput	BLER	Throughput	BLER
0	2	0.117	4.438 Mbps	0	8.75 Mbps	0	4.438 Mbps	0
20	6	0.553	62.748 Mbps	0	117.488 Mbps	0.063	62.748 Mbps	0
23	6	0.702	3.758 Mbps	0.952	4.098 Mbps	0.974	78.918 Mbps	0
24	6	0.753	0 Mbps	1	0 Mbps	1	84.294 Mbps	0
28	6	0.925	0 Mbps	1	0 Mbps	1	18.57 Mbps	0.821

Observation-5: *Higher subcarrier spacing (Δf) improves the network performance for lower end receiver and mobile users.*

The above experiment is carried out for mcs index 4 with a distance between transmitter and receiver SDR at 1m. The size of FFT for 15 KHz and 30 KHz are 2048 and 1024 respectively. As observed from table 1.7 as the subcarrier spacing increases there is small change in throughput and spectral efficiency. The numbers of RBs is determined from TimeFrequency5GParameters, which returns the numbers of RBs for each configuration.

Table 1.7: Variation on Performance with subcarrier spacing (Δf) for MCS index of 4.

(Δf)	Numbers of RBs	Throughput	Spectral Efficiency	BER	BLER
15 KHz	160	10.535 Mbps	0.351 bits/sec/Hz	0	0
30 KHz	78	10.304 Mbps	0.343 bits/sec/Hz	0	0

1.5 | Exercise

1. Prove the following relation for the number of slots in a frame.

$$N_{\text{slot}}^{\text{Frame}} = 2^{\mu} \times 10$$

2. Prove that the duration of the slot for any numerology μ, with normal cyclic prefix, is 2^{μ} fraction of 1 ms where T_{s} is the sample duration.

$$\sum_{i=0}^{i=13} (N_{\text{FFT}} + L_{\text{CP}}[i]) \times T_{\text{s}} = 2^{\mu} \times 10^{-3}$$

   Hint: Use 3GPP TS 38.211 section 5.3.1 for length of the cyclic prefix (CP).

3. Find the throughput and block-rate error (BLER) for the following modulation-order and code-rates.

   [a] MCS-index = 0, SNR = 10 dB.
   [b] MCS-index = 5, SNR = 10 dB.
   [c] MCS-index = 10, SNR = 10 dB.
   [d] MCS-index = 15, SNR = 10 dB.
   [e] MCS-index = 20, SNR = 10 dB.
   [f] MCS-index = 24, SNR = 10 dB.
   [g] MCS-index = 28, SNR = 10 dB.

4. Find the best modulation-order and code-rate (MCS) index and the corresponding throughput for the following system parameters,

   [a] $P_{\text{t}} = 43\text{dBm}$, bandwidth = 10MHz at temperature = 300°C.

[b] $P_t = 53\text{dBm}, \text{bandwidth} = 80\text{MHz}$ at temperature $= 300°\text{C}$.

[c] $P_t = 46\text{dBm}, \text{bandwidth} = \ \ 2\text{MHz}$ at temperature $= 300°\text{C}$.

5. (MIMO) Find the best rank, modulation-order and code-rate (MCS) index and the corresponding throughput for the following system parameters,

   [a] $P_t = 43\text{dBm}, \text{bandwidth} = 10\text{MHz}$ at temperature $= 300°\text{C}$.

   [b] $P_t = 53\text{dBm}, \text{bandwidth} = 80\text{MHz}$ at temperature $= 300°\text{C}$.

   [c] $P_t = 46\text{dBm}, \text{bandwidth} = \ \ 2\text{MHz}$ at temperature $= 300°\text{C}$.

2 | References