LTE/LTE-Advanced PHY Layer Coding Rate Based Performance Verification

This paper addresses the measurement needs and test challenges for LTE and LTE-Advanced mobile devices. In particular, it focuses on verifying user equipment (UE) receiver and transmitter implementation and characterizing its performance which is not fully specified in 3GPP test requirements but is expected to be in compliance. 3GPP defines the detailed implementation of the LTE radio technologies and derived UE test specifications that must be met universally by chipset providers and mobile device providers. Protocol implementation, radio resource management and radio conformance test are governed by certification labs to ensure the UE released to the network will perform according to acceptable minimum requirements. However, large portion of implementations of the chipset resource scheduling mathematically specified and implemented changes according to numerous varying factors that are complex and time consuming to be fully tested. Characterizing of receiver performance is generally covered in 3GPP test requirements, with limited pre-defined emulation conditions. This paper recommends comprehensive LTE UE receiver and transmitter performance verification with varying code rate to allow robust verification of the receiver implementation for operation on the real world.

Keywords: *LTE, LTE-Advanced, comprehensive LTE UE receiver, 3GPP, PHY Layer coding.*

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Introduction

Mobile devices, commonly known as UE supporting LTE are becoming common in recent years as network providers race to provide faster data rate to attract ever demanding consumers. Increasing demand to take advantage of these fast networks drove the market adoption of high-end mobile devices with embedded LTE chipsets.

Driven by the ever-increasing hunger for throughput and limitation of carrier frequency spectrum governed by each specific country; the push to aggregate multiple frequencies within and/or across bands with different combinations of allocated bandwidth led to greater demands for power efficiency, sensitivity, spectral purity and process scheduling of the wireless chipset.

The following sections describe high-level LTE radio technology fundamentals required to help understand the importance of verifying the receiver and transmitter resource allocation based on coding rate which also indirectly, helps verifying all major factors in the UE receiver and transmitter implementation.

LTE radio bandwidth

Initial LTE wireless technology defined by 3GPP introduced a set of frequency bandwidth that allows scalable deployment of LTE with a range of transmission bandwidth. It includes 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz frequency domain bandwidth which allows scalability according to the radio spectrum availability. With the recent introduction of release 10 3GPP specifications, carrier aggregation between combinations of these transmission bandwidths were made available up to 100MHz aggregated bandwidth with 5 component carriers (CC) to achieve peak data rate of 1Gbps Although release 10 defined the signaling for up to 5 CC, test requirements are only defined for up to 2 CC so far.

Downlink / uplink modulation

The LTE technology uses Orthogonal Frequency Division Multiplexing (OFDM) modulation with 15 kHz subcarriers spacing on the downlink. 7.5 kHz subcarriers spacing is also defined in the LTE standards for Multimedia Broadcast Multicast Service Single Frequency Network (MBSFN). With standard OFDM, subcarrier allocations are fixed for each user and are more susceptible to narrowband interference. With Orthogonal Frequency Division Multiple Access (OFDMA), subcarriers can be allocated dynamically among different users of the channel. OFDMA also allows non-contiguous allocation of subcarriers for a single user.

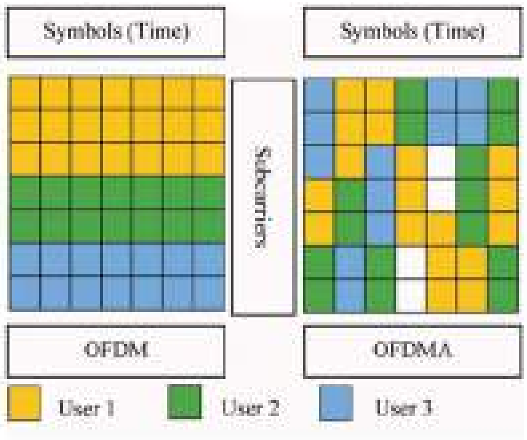

Figure 1. OFDM versus OFDMA allocation

The LTE uplink however uses Single-Carrier Frequency Division Multiple Access (SC-FDMA) modulation to reduce Peak-to-Average Power Ratio and only the subcarrier spacing of 15kHz is used. The detail behind the using SC-FDMA is beyond the scope of this paper.

Downlink resources

A resource element (RE) is the smallest unit in the physical layer that occupies one OFDM symbol in time domain and one subcarrier in the frequency domain. A physical resource block (RB) consists of $N^{DL}_{symb} \times N^{RB}_{sc}$ resource elements, corresponding to one slot in time domain and $N^{RB}_{sc} \times \Delta f$ in frequency domain. Table 1 below shows the values for the downlink resource parameters.

A normal cyclic prefix configuration has 84 resource elements per slot; in FDD single 10 ms frame (10 subframes or 20 slots) structure has total of 1680 RE/RB. However, not all RE is allocated for physical downlink shared channel (PDSCH). Some RE needs to be allocated to carry control information including physical downlink control channel (PDCCH), physical control format indicator channel (PCFICH) and physical hybrid automatic repeat request indicator channel (PHICH); allocation ranges from 1 to 4 symbols.

Table 1

Downlink resource block parameters [1]

Configuration		N_{sc}^{RB}	N_{symb}^{DL}
Normal cyclic prefix	$\Delta f = 15\,\text{kHz}$	12	7
Extended cyclic prefix	$\Delta f = 15\,\text{kHz}$		6
	$\Delta f = 7.5\,\text{kHz}$	24	3

In frequency domain, each RB is spread across 180 kHz with subcarrier spacing depending on the cyclic prefix configuration as shown on the table 1 above. The transmission bandwidth configuration N_{RB} define the maximum number of RB available (minus the guard band) for the different LTE channel shown on Table 2 below.

Table 2

Transmission bandwidth configuration

BWchannel (MHz)	1.4	3	5	10	15	20
N_{RB}	6	15	25	50	75	100

The physical resource block is then mapped to Virtual Resource Block (VRB). Resource allocation is signaled through the PDCCH DCI format indicator to the UE for proper demodulation and decoding. There are three types of resource allocations (RA) defined for LTE. For more details of these RA types, refer to TS36.213 Section 7.1.6 [2].

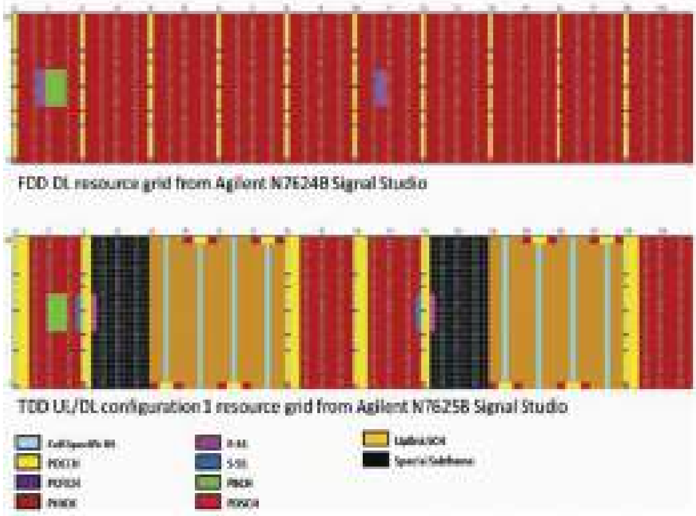

Figure 2. FDD and TDD resource grid

Uplink resources

The resource grid of the uplink is similar to that of the downlink. However, the modulation scheme used for the uplink transmission is based on SC-FDMA. Both normal cyclic prefix and extended cyclic prefix are available.

Figure 3. FDD UL resource grid

The physical uplink shared channel (PUSCH) can be completely switched off and physical uplink control channel (PUCCH) will be used to carry hybrid automatic repeat request (HARQ) information to report reception of the downlink data being successfully or unsuccessfully decoded. When PUSCH is transmitted, PUCCH can be switched off and HARQ information is carried over the PUSCH. Starting from LTE release 10, both PUSCH and PUCCH can also be turned on at the same time.

Synchronization signals

There are two physical synchronization signals transmitted on the eNB downlink mapped to the resource grid occupying central 72 subcarriers on different subframe and slot according to each frame structure type.

Primary synchronization signal (P-SS) is transmitted on the last OFDM symbol in slots 0 and 10 of the FDD frame structure; on the third OFDM symbol in slots 2 and 12 of the TDD frame structure. While 72 subcarriers are occupied on the resource grid, only central 62 subcarriers are modulated using the Zadoff-Chu sequence; three distinctive root sequence indices are used to separate 504 unique physical layer identities into 168 unique physical cell-identity group. Secondary synchronization signal (S-SS) is then used to further identify the specific identity group out of the 168 unique identity groups. SSS is transmitted on slots 0 and 10 of the FDD frame structure and slots 1 and 11 of the TDD frame structure. S-SS is modulated using BPSK modulation scheme.

In the terms of resource element; P-SS and S-SS used up 288 REs on each radio frame. Figure 2 above shows the P-SS and S-SS resource allocation in FDD and TDD frames.

Cell broadcast channel

The physical broadcast channel (PBCH) is the physical channel that carries the broadcast channel transport channel (BCH). The BCH carries the master information block (MIB) to be decoded by each UE in the cell. The PBCH is modulated with QPSK on the center 62 subcarriers (6 RBs) on subframe 0 and span 4 symbols. In the terms of resource elements, it uses 72 RE on each radio frame.

The system information block (SIB) messages are however been carried on the PDSCH through the DL-SCH transport channel. The FDD and TDD downlink fixed reference channel (FRC) used for RF conformance always reserved subframe 5 so that no data payload is carried on this subframe. In an actual network, this subframe can carry data payload in the RBs that are not allocated for SIB transmissions.

Reference signals

3GPP TS 36.211 [1] defined six types of reference signals listed in table 3 below. Reference signals in general are used for channel estimation and equalization. The only mandatory downlink reference signal is the CRS.

Table 3

Types of downlink reference signal

Reference signal	3GPP	CP and Δf
Cell specific (CRS)	Rel. 8	Normal CP and Extended CP with $\Delta f = 15$ kHz only
MBSFN RS	Rel. 8	Extended CP with $\Delta f = 7.5$ kHz only
UE Specific (DM-RS)	Rel. 8	Normal CP and Extended CP
Positioning Reference Signal (PRS)	Rel. 9	Normal CP and Extended CP with $\Delta f = 15$ kHz only
CSI-RS	Rel. 10	Normal CP and Extended CP with $\Delta f = 15$ kHz only

However, the number of RE allocated for the RS varies depending on the number of antennas used in the transmission. Figure 4 below shows that 8 REs are allocated for each subframe for each antenna when two antennas are used for transmission. Notice that there are 8 REs reserved ("Not Used") for the first antenna where those 8 REs are used on the same location of the second antenna and vice versa.

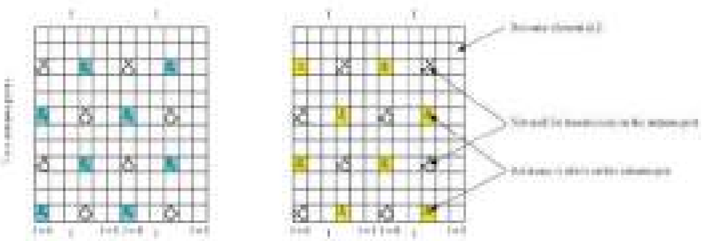

Figure 4. Downlink CRS mapping in normal CP with two antennas [1]

Two uplink reference signals are also defined. The Demodulation Reference Signal (DM-RS) associated to PUSCH and PUCCH and the optional Sounding Reference Signal (SRS). The DM-RS for PUSCH takes up 12 RE/RB on the 4th symbol of normal CP and on the 3rd symbol of extended CP on each slot. The number of RE/RB occupied by DM-RS for PUCCH depends on the PUCCH format as shown in the Table 4 below and is defined in 3GPP TS 36.211 Section 5.5.2.2 [1].

Table 4

DM-RS for PUCCH symbols per slot [1]

PUCCH format	Normal cyclic prefix	Extended cyclic prefix
1, 1a, 1b	3	2
2, 3	2	1
2a, 2b	2	N/A

The uplink SRS will occupy 12 RE/RB on the last symbol of each subframe as shown in the Figure 3 above. 12 RE/RB are allocated but the transmission of SRS signal may not occupy all RE/RB.

Downlink transmission mode

There are 9 transmission mode defined as of 3GPP Release 10 as shown in the table 5 below.

Table 5

Transmission Modes [2] [4]

TM	3GPP	Transmission scheme	Description of usage
1	Rel. 8	Single-antenna port	Basic RXD
2	Rel. 8	Transmit diversity	For low SNR condition
3	Rel. 8	Transmit diversity	Fallback mode
3	Rel. 8	Large delay CDD	Increase throughput
4	Rel. 8	Transmit diversity	Fallback mode
4	Rel. 8	Closed-loop spatial multiplexing	Improve throughput
5	Rel. 8	Transmit diversity	Fallback mode
5	Rel. 8	Multi-user MIMO	Improve spectral efficiency
6	Rel. 8	Transmit diversity	Fallback mode
6	Rel. 8	Closed-loop spatial multiplexing using a single transmission layer (beamsteering)	Improve signal robustness
7	Rel. 8	Single-antenna port or Transmit diversity	Fallback mode
7	Rel. 8	Single-antenna port (beamforming)	Improved signal robustness with non-codebook precoding
8	Rel. 9	Single-antenna port or Transmit diversity	Fallback mode
8	Rel. 9	Dual layer transmission (beamforming)	Same as TM7 with increased throughput
9	Rel. 10	Non-MBSFN subframe: Single-antenna port or Transmit diversity. MBSFN subframe: Single-antenna port	Fallback mode
9	Rel. 10	Up to 8 layer transmission (beamforming)	Same as TM8 with improved throughput

With these transmission modes definitions, various antenna configurations and various layers of transmission can be configured to achieve the ideal maximum data throughput operating in different channel conditions, depending on the chipset capabilities. For more explanation of MIMO, multiple layers transmission and codeword, refer to Keysight application note "MIMO in LTE Operation and Measurement - Excerpts on LTE Test"

Digital modulation types

Just like for any other radio technology defined in the 3GPP standards, digital modulation schemes are defined for LTE PDSCH and PUSCH transport channel transmission to carry digital data. QPSK, 16QAM and 64QAM modulation types are defined to transmit 2 bits, 4 bits and 6 bits per symbol respectively. The selection of the modulation type depends greatly on the propagation conditions, resource elements available and the channel quality indicator (CQI), which is part of the channel state information (CSI) reporting.

Downlink PDCCH uses QPSK modulation type to carry control information; while uplink PUCCH uses BPSK and/or QPSK based on the PUCCH format defined in 3GPP TS36.211 section 5.4 to carry control information.

Downlink channel coding rate

The Physical Downlink Shared Channel (PDSCH) transport block size and modulation order map is defined in 3GPP TS 36.213 Section 7.17 [2] as shown in the Table 6 and 7 below.

Table 6

PDSCH MCS to TBS Index [2]

MCS Index I_{MCS}	Modulation Order Q_m	TBS Index I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15
18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	2	reserved
30	4	
31	6	

TBS index points to the set of tables' matrix (*I*TBS, *N*PRB) defined in 3GPP TS36.213 Section 7.1.7.2. It is used to calculate and determine the coding rate that can be applied to transport block without causing decoding error. The UE may skip decoding a transport block in an initial transmission if the effective channel code rate is higher than 0.93 and so the limit of 0.93 is used throughout this paper.

Q_m = bits per symbol

Physical channel bits = $N_{PRB} \times RE_{PDSCH} \times Q_m$

Downlink information bits = TBS(*I*TBS, *N*PRB) + 24 CRC bits

DL Coding Rate is the ratio of downlink information bits to be transmitted and the available physical channel bits per subframe.

Uplink channel coding rate

The Physical Uplink Shared Channel (PUSCH) transport block size and modulation order map are defined in 3GPP TS 36.213 Section 8.6 [2] as shown in the Table 7 below.

Table 7

PUSCH MCS Index to TBS Index [2]

MCS Index I_{MCS}	Modulation Order Q'_m	TBS Index I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	2	10
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	4	16
18	4	17
19	4	18
20	4	19
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	reserved	
30		
31		

Similar to the downlink, TBS index points to the set of tables matrix (*I*TBS, *N*PRB) defined in 3GPP TS36.213 Section 7.1.7.2 and it is used to calculate and determine the coding rate that can be applied to transport block without causing decoding error.

Q_m = bits per symbol

Physical channel bits = $N_{PRB} \times RE_{PUSCH} \times Q_m$

Uplink information bits = TBS(*I*TBS, *N*PRB) + 24 CRC bits

UL Coding Rate is the ratio of uplink information bits to be transmitted and the available physical channel bits per subframe.

The uplink *Qm* will be limited to 4 bit per symbol (16QAM) from IMCS 21 onwards when the UE is not capable of supporting 64QAM transmission on PUSCH. When TTI bundling is used, *Qm* will be clipped to 2 bit per symbol (QPSK).

Putting it all together

In order to help to put the pieces together, let's take a practical approach example of FDD frame structure. A downlink FDD frame structure with normal cyclic prefix configuration has 84 REs per slot, and 168 REs in one subframe (2 slots).

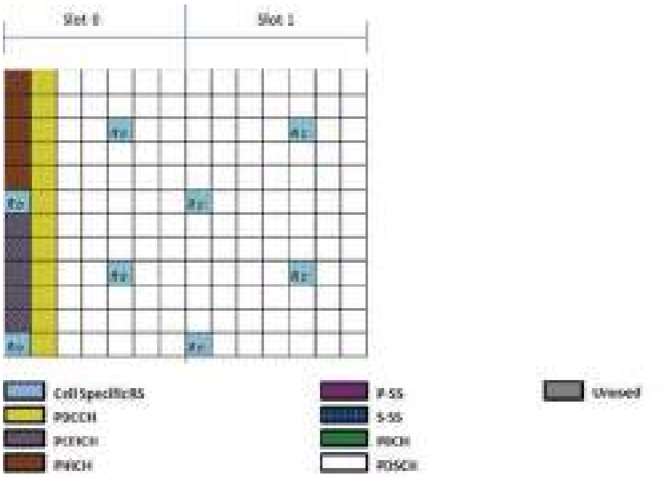

Figure 5. FDD Downlink Single Antenna Normal CP Resource Grid (subframe other than 0 or 5)

However, only 138 RE are allocated to PDSCH when 2 symbols are allocated to PDCCH transmission as shown in Figure 5 above. When 2 antenna ports are used, the number of PDSCH RE is reduced to 132 for each antenna port as shown in Figure 6 below.

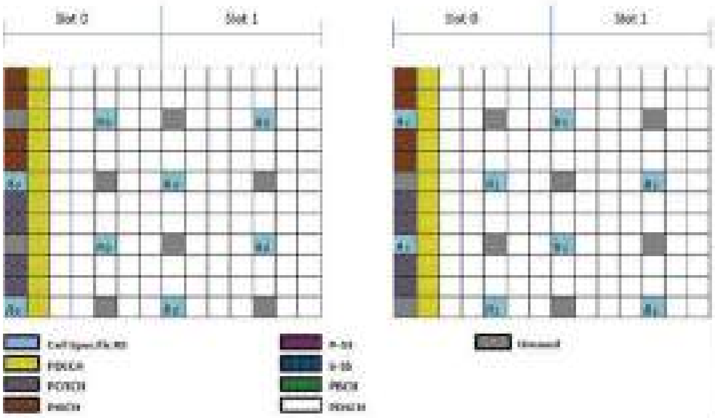

Figure 6. FDD Downlink Dual Antenna Normal CP Resource Grid

On subframe 5 where the resource grid occupies central 72 subcarriers (6 RBs), the P-SS and S-SS takes up 24 REs and with 2 symbols allocated to PDCCH, only 108 REs left for the PDSCH.

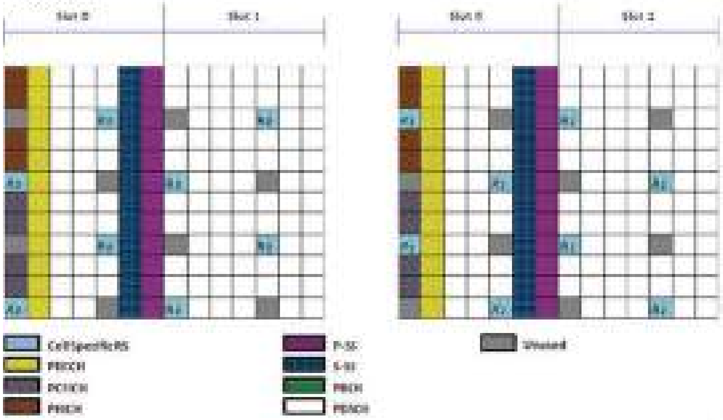

Figure 7. FDD Downlink Dual Antenna Normal CP Resource Grid on subframe 5 in central 6RB

On subframe 0 where the resource grid occupies central 72 subcarriers (6 RBs), the P-SS, S-SS and PBCH takes up 68 REs and with 2 symbols are allocated to PDCCH, only 64 REs are left for the PDSCH as shown in Figure 8 below.

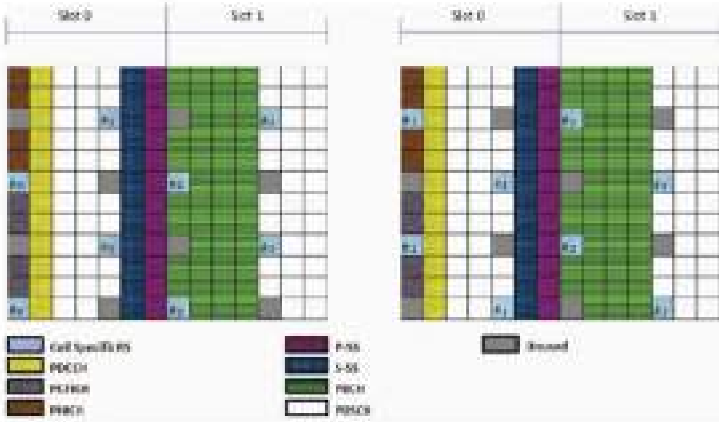

Figure 8. FDD Downlink Dual Antenna Normal CP Resource Grid on subframe 0 in central 6RBs

Table 8

Partial table for transport blocks not mapped to two or more layer spatial multiplexing [2]

N_{PRB}	I_{TBS}								
	6	7	8	9	....	23	24	25	26
1	88	104	120	136	....	552	584	616	712
2	176	224	256	296	....	1128	1192	1256	1480
3	256	328	392	456	....	1736	1800	1864	2216
4	392	472	536	616	....	2280	2408	2536	2984
5	504	584	680	776	....	2856	2984	3112	3752
6	600	712	808	936	....	3496	3624	3752	4392
7	712	840	968	1096	....	4008	4264	4392	5160
8	808	968	1096	1256	....	4584	4968	5160	5992
9	936	1096	1256	1416	....	5160	5544	5736	6712
10	1032	1224	1384	1544	....	5736	5992	6200	7480

Let's take a real scenario in a 10 MHz transmission bandwidth with a UE transmitting at TM4 with 2X2 antenna configuration (2 layer spatial multiplexing with 2 codewords transmission), with 2 symbols allocated to PDCCH and 6 PRBs allocated within the central 72 subcarriers (6 RBs); the number of PDSCH RE/RB for subframe 0 is 64 REs. Even if channel conditions permit a QPSK 2 bits per symbol transmission, putting IMCS of 8 (QPSK), the coding rate will actually exceed 0.93.

SF0 CW0 Code Rate = $(808+24)/(384\times 2) = 1{,}083$.

So, in order to assure the transmission without decoding error, the IMCS has to be reduced to 6 so as to bring the coding rate under 0.93.

SF0 CW0 Code Rate = $(600+24)/(384\times 2) = 0{,}812$.

On the other hand, the PDSCH REs in subframe 5 with the same configuration shows that the coding rate can allows up to IMCS of 25 (64QAM) without exceeding code rate of 0.93.

SF5 CW0 Code Rate = $(3496+24)/(648\times 6) = 0{,}905$.

Other FDD downlink subframes except subframe 0 and 5 allow IMCS up to 28 (64QAM) where TBS is 4392 without exceeding the coding rate of 0.93. Other resources allocated to

DM-RS, PRS and CSI-RS will also affect downlink PDSCH RE availability.

It may be worth noting that the maximum data throughput for the example above is the sum of TBS values for all 10 subframes multiplied by 100. The throughput is therefore $(600+3496)+(4392\times8)\times100$ and equals 3.9232Mbps for each codeword. In this single-user MIMO case, two codewords yield 7.8464Mbps.

The uplink coding rate uses the same computation algorithm except that the allocation of PUSCH, PUCCH and SRS are mapped differently on the resource grid as shown on Figure 9 below.

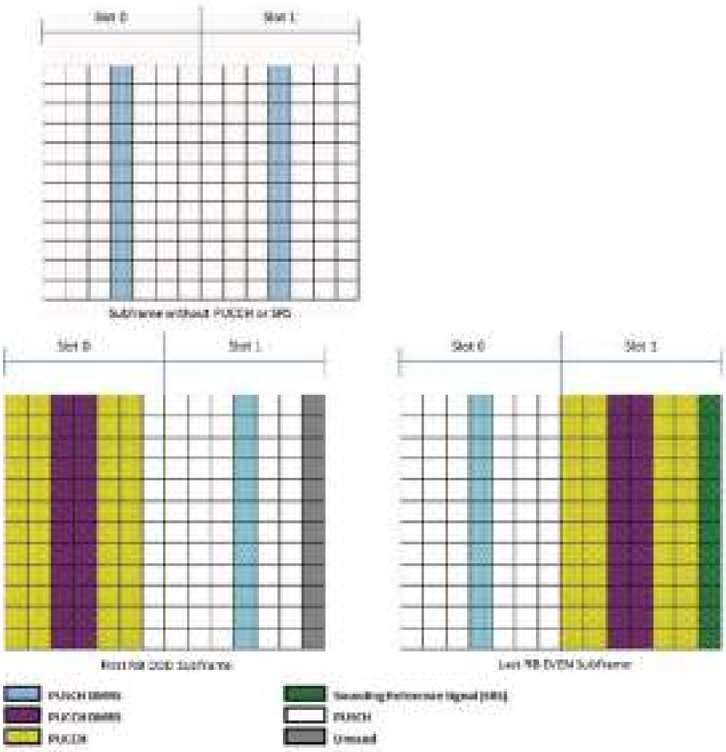

Figure 9. FDD Uplink Single Normal CP Resource Grid

As you may have observed, each subframe is governed by the maximum target coding rate of 0.93 which forces resources allocated for different users to have different coding schemes, modulation types and transport block sizes based on various factors including cyclic prefix, transmission mode, antenna configuration, transmission bandwidth, resource block allocation and number of control channel symbols.

In radio conformance test, target coding rates of 1/6, 1/5, 1/3, 1/2, 2/3 and 3/4 are used and without subframe 5 allocations. With target coding rate of 3/4 or 0.75, the error correction in the data transmission prevents some implementation issues from surfacing and furthermore subframe 5 data coding is not even tested. Although in real world implementation, the environmental effect hardly allows constant coding rate of 0.93, it is crucial to use highest possible coding rate with ideal channel condition in the design verification to minimize error correction that hides the implementation issue on the physical layer and transport layer.

CSI based scheduling

In the non-ideal real world condition, CSI based scheduling is used to dynamically reduce or increase coding rate using UE channel estimation. The channel condition is the determining factor for the CQI table mapping. It ensures optimal modulation type and transport block size are used to carry the required data across the transmission medium, adapting to the environment assessment information feedback through the CSI report. The data rate may be reduced in poor signal-to-noise ratio environment in accordance with the CQI reported based on UE receiver assessment and performance. Lower code rate allows successful decoding of data transmitted with higher redundancy and also effectively reduces overhead for retransmission.

3GPP TS 36.213 Table 7.2.3-1 [2] shows the CQI table and its target code rate. It is shown in table 9 below.

Table 9

CQI Table [2]

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

This table will be offset based on different resource allocations and on UE wideband or narrow band reporting. The algorithm may be optimized by each chipset modem vendor or manufacturer to provide efficient coding rate in dynamic scheduling in the real world.

In order to measure the performance of the dynamic scheduling, Additive White Gaussian Noise (AWGN), Ortogonal Channel Noise Generator (OCNG) and propagation conditions are applied to verify the algorithm implementation.

Implementing code rate based verification

To effectively perform the various combinations of aggregated carriers with different bandwidth allocations, transmission modes and antenna configurations; creating a complex matrix of each possible permutations will allows completeness in verification of various signaling implementation of transport channels and control channels. Verifying the PDCCH, PCFICH, PHICH, PBCH, PDSCH, PUCCH and PUSCH performance under different antenna configurations, transmission modes and bandwidth allocations by allocating desired transport block size and modulation schemes based on maximum target coding rate allowed for a given allocation can be a complex task. Figure 10 below shows an example of flexible RMC configurations provided by the Keysight E7515A UXM wireless test set that helps engineers to graphically setup the resource allocation.

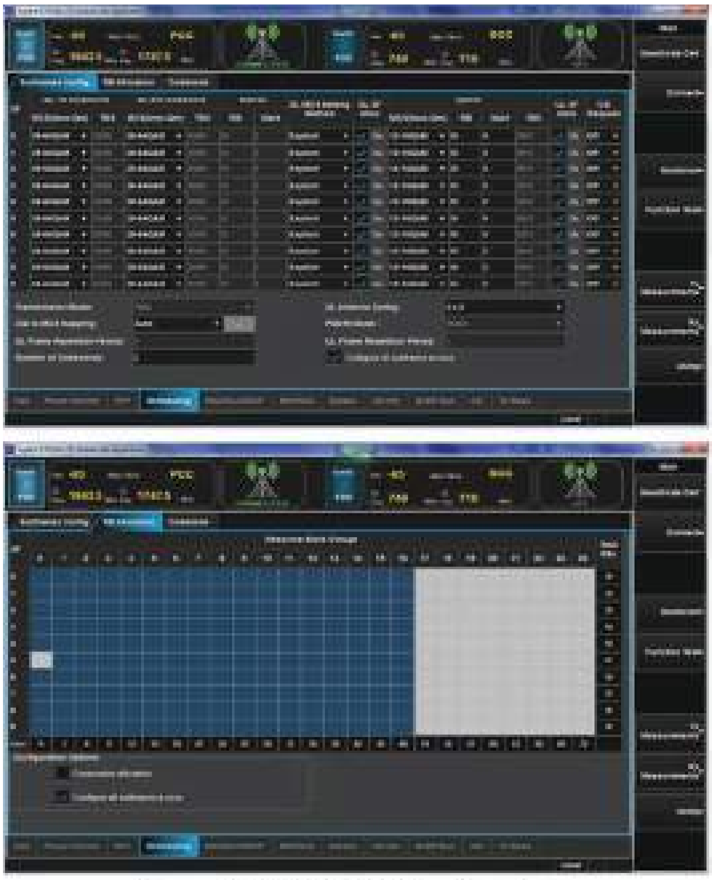

Figure 10. UXM PCC RMC configuration

CSI based scheduling can also be turned on through this user interface for each codeword in each subframe. Adding internal AWGN, OCNG and baseband fading emulation allows receiver performance test with various signal-to-noise ratio classifying how well the UE responds to the dynamic change in code rate and modulation scheme.

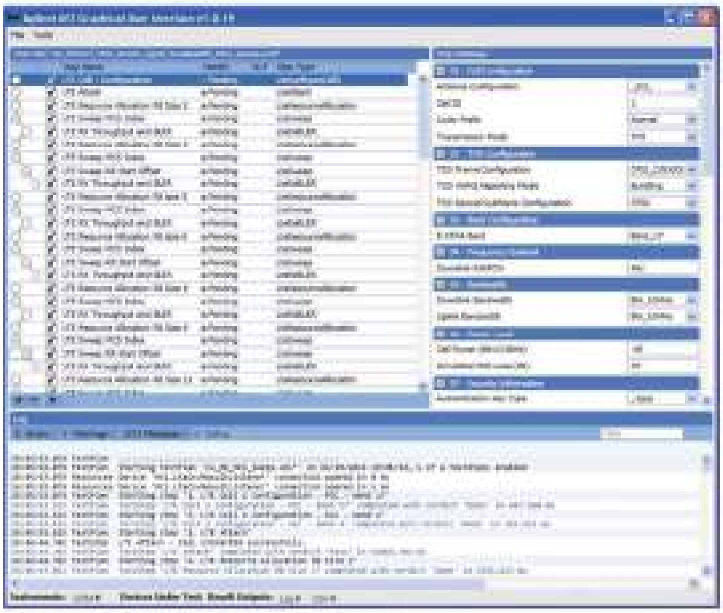

Figure 11. MTI exercising combinations of RB and sweeping of IMCS up to max code rate

Changes of resource allocations can be manually performed by engineer or automatically performed using a software automation tool such as Mobile Test Interface (MTI) software as shown in Figure 11.

The software automatically calculate and limit the valid code rate below 0.93 for each codeword in each subframe making sure the measurements do not cause false failure.

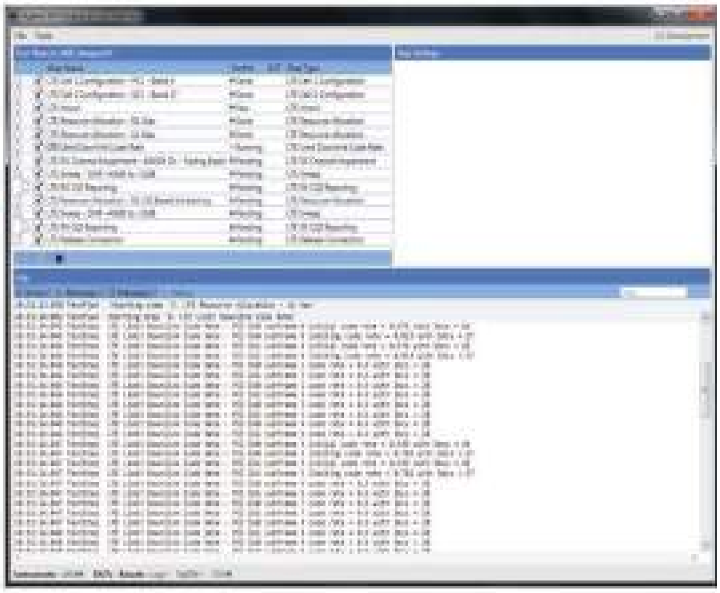

Figure 12. MTI reduces modulation coding scheme to within the allowed code rate for each component carrier

It also effectively reduces human errors by not having to calculate coding rate for thousands of test scenarios.

Summary

In the early stage of the modem chipset protocol layers development, a comprehensive protocol test set is required to allow protocol engineers to construct, edit and customize protocol layers defined in the 3GPP standards but may not be fully implemented in its full extent on the modem.

When the full modem stack is completed, standard 3GPP compliance wireless test set such as the UXM coupled by software automation should be used to make sure that all implementation are in accordance to real network deployment conditions. The LTE/LTE-Advanced PHY layer code rate based performance verification described in this paper helps effectively and completely characterize and verify the UE receiver and transmitter performance with a bottom up approach.

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