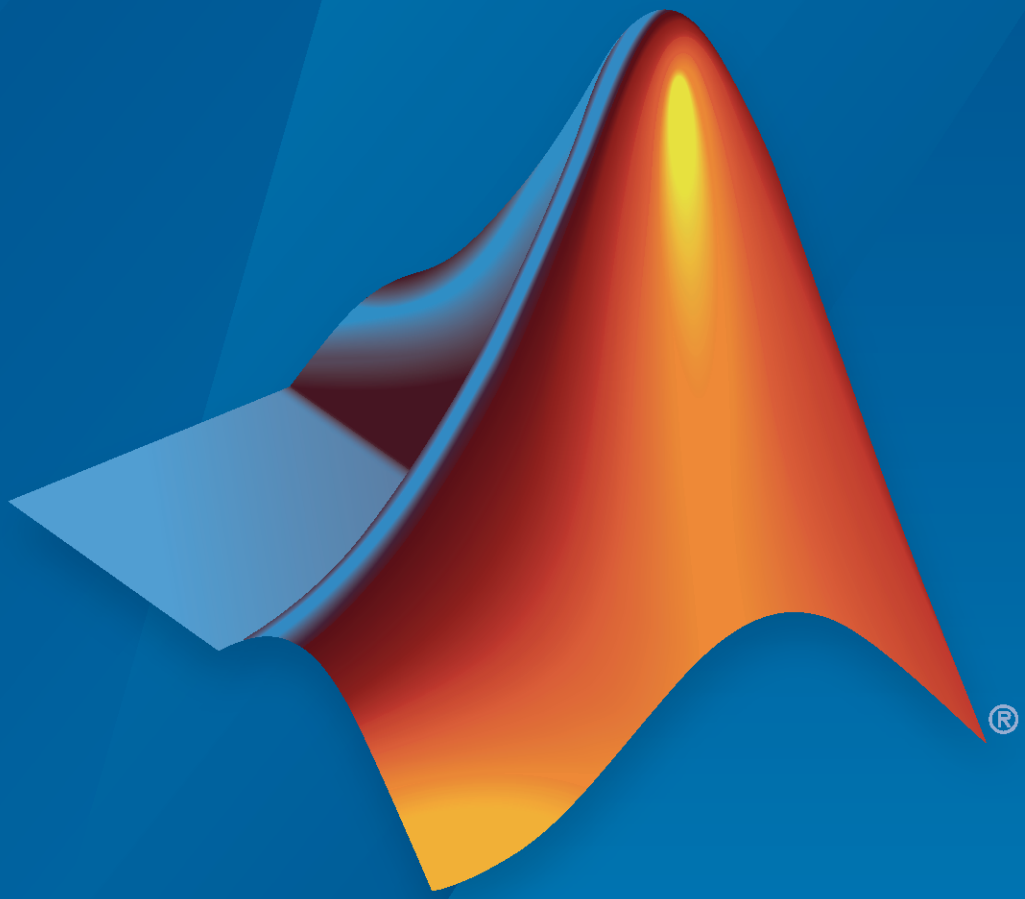
LTE Toolbox™

Getting Started Guide



MATLAB®

R2020a

MathWorks®

How to Contact MathWorks

Latest news: `www.mathworks.com`

Sales and services: `www.mathworks.com/sales_and_services`

User community: `www.mathworks.com/matlabcentral`

Technical support: `www.mathworks.com/support/contact_us`

Phone: 508-647-7000

The MathWorks, Inc.
1 Apple Hill Drive
Natick, MA 01760-2098

LTE Toolbox™ Getting Started Guide

Trademarks

MATLAB and Simulink are registered trademarks of The MathWorks, Inc. See `www.mathworks.com/trademarks` for a list of additional trademarks. Other product or brand names may be trademarks or registered trademarks of their respective holders.

Patents

MathWorks products are protected by one or more U.S. patents. Please see `www.mathworks.com/patents` for more information.

Revision History

September 2013	Online only	Revised for Version 1.0 (Release 2013b)
March 2014	Online only	Revised for Version 1.1 (Release 2014a)
October 2014	Online only	Revised for Version 1.2 (Release 2014b)
March 2015	Online only	Revised for Version 2.0 (Release 2015a)
September 2015	Online only	Revised for Version 2.1 (Release 2015b)
March 2016	Online only	Revised for Version 2.2 (Release 2016a)
September 2016	Online only	Revised for Version 2.3 (Release 2016b)
March 2017	Online only	Revised for Version 2.4 (Release 2017a)
September 2017	Online only	Revised for Version 2.5 (Release 2017b)
March 2018	Online only	Revised for Version 2.6 (Release 2018a)
September 2018	Online only	Revised for Version 3.0 (Release 2018b)
March 2019	Online only	Revised for Version 3.1 (Release 2019a)
September 2019	Online only	Revised for Version 3.2 (Release 2019b)
March 2020	Online only	Revised for Version 3.3 (Release 2020a)

Contents

1 Getting Started with LTE Toolbox Software

2 High-Level Examples

Getting Started with LTE Toolbox Software

LTE Toolbox Product Description

Simulate, analyze, and test the physical layer of LTE and LTE-Advanced wireless communications systems

LTE Toolbox provides standard-compliant functions and apps for the design, simulation, and verification of LTE, LTE-Advanced, and LTE-Advanced Pro communications systems. The toolbox accelerates LTE algorithm and physical layer (PHY) development, supports golden reference verification and conformance testing, and enables test waveform generation.

With the toolbox you can configure, simulate, measure, and analyze end-to-end communications links. You can also create and reuse a conformance test bench to verify that your designs, prototypes, and implementations comply with the LTE standard.

Using LTE Toolbox with RF instruments or hardware support packages, you can connect transmitter and receiver models to radio devices and verify your designs via over-the-air transmission and reception.

Key Features

- Standard-compliant models for LTE, LTE-Advanced, and LTE-Advanced Pro
- Link-level transmit and receive processing functions, and support for uplink, sidelink, and downlink transmission modes 1 to 10
- Reference designs, including narrowband Internet-of-Things (NB-IoT), cellular vehicle-to-everything (C-V2X), and coordinated multipoint (CoMP)
- Test model (E-TM) and reference measurement channel (RMC) for LTE, LTE-A, and UMTS waveform generation
- Waveform transmission and reception with radio devices and instruments for over-the-air testing
- System and control parameter recovery from captured signals, including cell identity, MIB, and SIB1
- Channel estimation, synchronization, MIMO receiver functions, and propagation channel models

What Is LTE?

In this section...

Long-Term Evolution

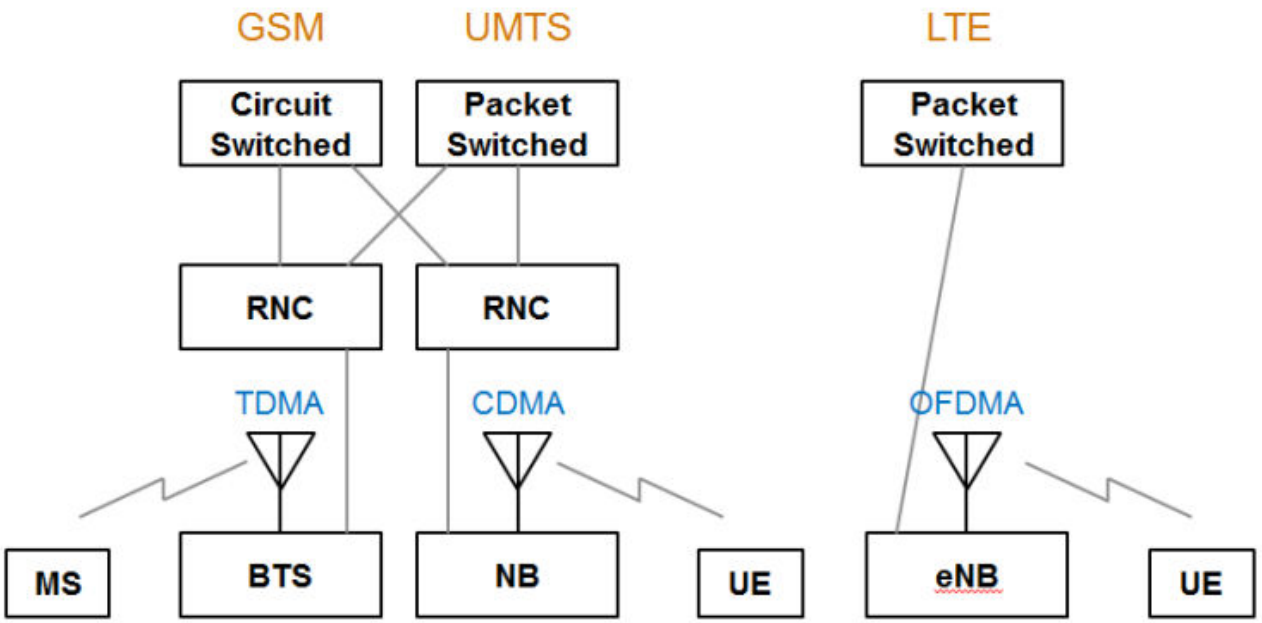
Long-Term Evolution (LTE) is the air interface supporting fourth generation cellular networks. LTE is specifically designed for packet data communications, where the emphasis of the technology is high spectral efficiency, high peak data rates, low latency, and frequency flexibility. The LTE specifications were developed by the Third Generation Partnership Project (3GPP).

GSM and UMTS are the predecessors of the LTE air interface and are referred to as second generation (2G) and third generation (3G) technologies, respectively. GSM was developed as a circuit switched network meaning that radio services are configured at the user’s request and resources remain allocated until terminated by the network controller. This type of operation is well suited to supporting voice calls. Eventually, GSM was enhanced to support low data rate services with packet switching capability but data rates were limited by GSM’s air interface, time division multiple access (TDMA). In TDMA, each user is assigned to a particular channel (frequency band) and time slot which serves to limit capacity as the channel spacing is only 200 kHz.

UMTS uses code division multiple access (CDMA) as its air interface. In CDMA, active users transmit simultaneously over the allocated bandwidth, typically 5 MHz. Signals are separated from each other by the use of orthogonal variable spreading factor (OVSF) spreading codes. The advantage of OVSF codes is that resources can be allocated asymmetrically among the active users. UMTS supports both circuit switched services for voice calls and packet switched for data sessions. Due to its larger bandwidth and superior spectral efficiency, UMTS can support higher data rates than GSM.

Unlike GSM and UMTS, LTE is a purely packet switched network in which both voice and data services are carried by IP. LTE uses orthogonal frequency division multiple access (OFDMA) in which the spectrum is divided into resource blocks (RB) that are composed of twelve 15 kHz subcarriers. By dividing the spectrum in such a way, complicated equalizers are no longer necessary to mitigate frequency selective fading. LTE supports higher order modulation schemes up to 64-QAM along with bandwidth allocations that can be as large as 20 MHz. In addition, LTE makes use of MIMO so that very high theoretical data rates can be achieved (75 Mbps in the uplink and 300 Mbps in the downlink for Release 8).

Second and third generation cellular networks consist of an interface to the public telephone or IP network, a radio network controller (RNC) that allocates radio resources among the users, a base station (referred to as a Node B in UMTS) that transmits and receives signals to and from the users, and user devices (MS for GSM and UE for UMTS). The LTE access network is similar with the exception that the RNC functionality has been pushed down into the enhanced Node B (eNB). The flatter architecture reduces the time required to establish data services resulting in lower latency. The architecture is shown below.

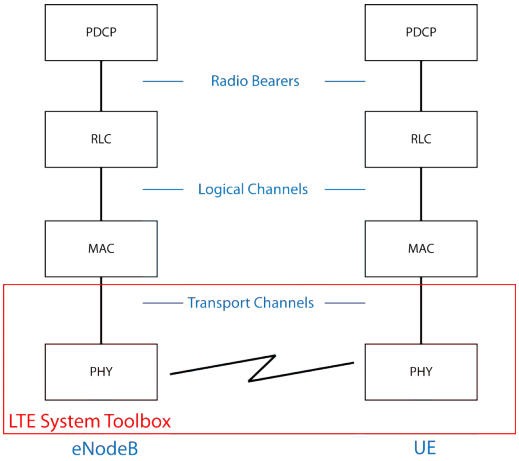


LTE Physical Layer

The LTE radio access network is comprised of the following protocol entities.

- Packet Data Convergence Protocol (PDCP)
- Radio Link Control (RLC)
- Medium Access Control (MAC)
- The Physical Layer (PHY)

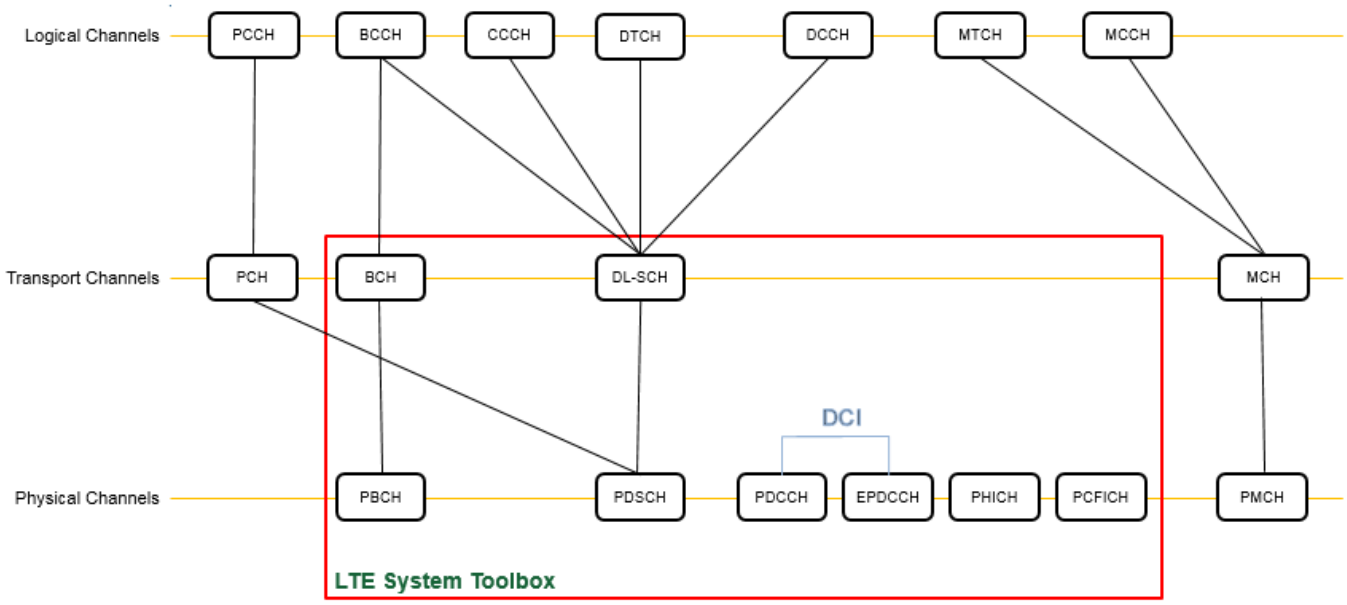
The first three protocol entities handle tasks such as header compression, ciphering, segmentation and concatenation, and multiplexing and demultiplexing. The physical layer handles coding and decoding, modulation and demodulation, and antenna mapping. The figure shows the delineation between the physical layer and higher layers.



LTE Toolbox focuses on the physical layer, which is highlighted in red in the preceding figure. It also supports interfacing with portions of the RLC and MAC layers, which are highlighted in blue. The primary features of the LTE physical layer are OFDM modulation, including the time-frequency structure of the resource blocks, adaptive modulation and coding, hybrid-ARQ, and MIMO.

Downlink Channel Mapping

System downlink data follows the indicated mapping between logical channels, transport channels, and physical channels. The red outline contains LTE Toolbox downlink functionality for physical channels, transport channels, and control information.

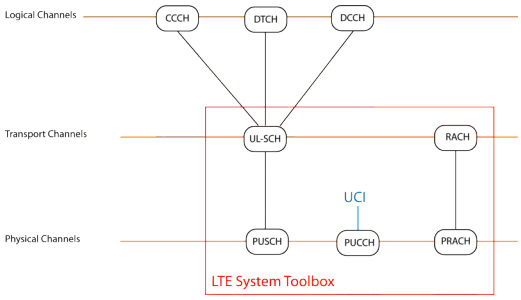


For more information, see “Downlink Channels” or the specific channel category of interest:

- “Physical Signals”
- “Physical Channels”
- “Control Information”
- “Transport Channels”

Uplink Channel Mapping

System uplink data follows the indicated mapping between logical channels, transport channels, and physical channels. The red outline contains LTE Toolbox uplink functionality for physical channels, transport channels, and control information.

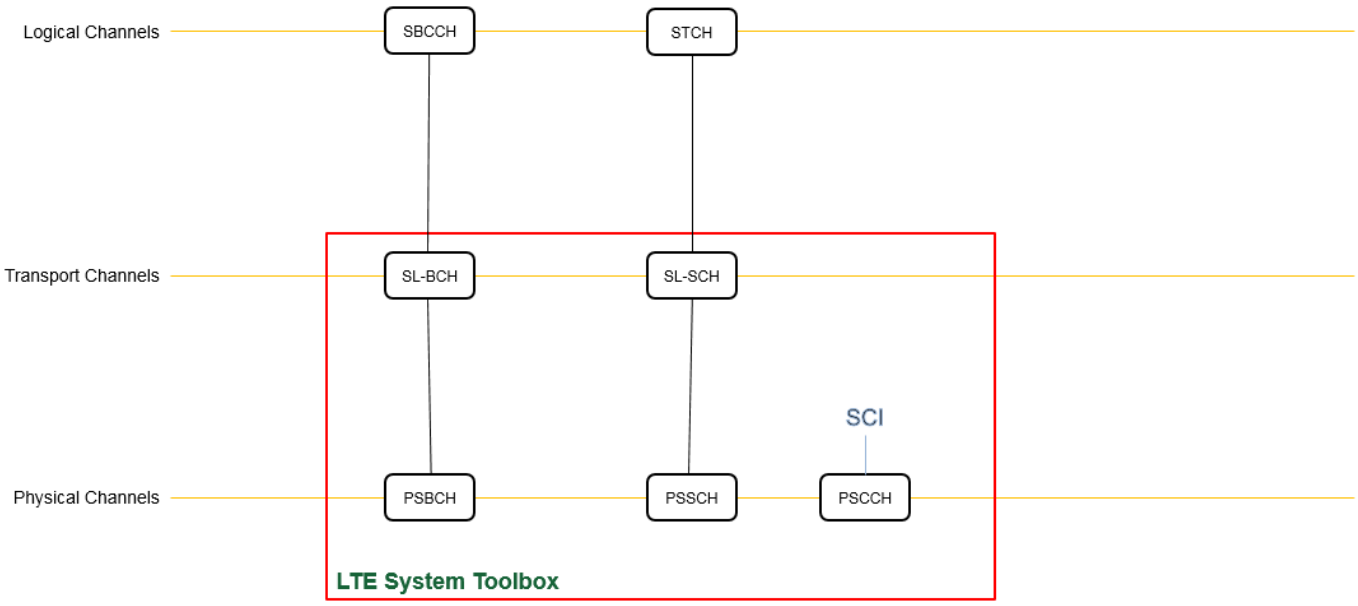


For more information, see “Uplink Channels” or the specific channel category of interest:

- “Physical Signals”
- “Physical Channels”
- “Transport Channels”
- “Control Information”

Sidelink Channel Mapping

System sidelink data follows the indicated mapping between logical channels, transport channels, and physical channels. The red outline contains LTE Toolbox sidelink functionality for physical channels, transport channels, and control information.



For more information, see “Sidelink Channels” or the specific channel category of interest:

- “Physical Signals”
- “Physical Channels”
- “Transport Channels”
- “Control Information”

References

[1] Nohrborg, Magdalena, for 3GPP. *LTE* https://www.3gpp.org/technologies/keywords-acronyms/98-lte.

[2] Dahlman, E., Parkvall, S., and Sköld, J.. *4G LTE / LTE-Advanced for Mobile Broadband*. Kidlington, Oxford: Academic Press, 2011. pp. 112–118.

LTE-Advanced Functionality

In this section...

The LTE Toolbox supports enhancements to the LTE Release 8 and 9 offerings. LTE-Advanced builds upon these earlier releases. A brief description of significant Release 9 updates is provided here prior to discussing the LTE-Advanced functionality. 3GPP defines LTE-Advanced functionality in Releases 10, 11, and 12 of the LTE Standard.

Release 9 Positioning Reference Signal

Release 9 defines several changes to the provision for positioning within the LTE standard. These changes, which enable the network to compute the position of the UE, include:

- UE reception of a new downlink positioning reference signal (PRS) transmitted by the eNodeB.
- Transmission of the time difference of arrival to the eNodeB as a measurement.

LTE Toolbox supports the PRS with the `ltePRS` and `ltePRSIndices` functions.

To learn how to use the PRS to perform time-difference of arrival (TDOA) position estimation, see "Time Difference Of Arrival Positioning Using PRS".

Release 9 Dual-Layer UE-Specific Beamforming

Release 9 provides a dual-layer UE-specific beamforming mode. It defines two UE-specific reference signals (antenna ports 7 and 8). Two independent streams of data can be sent, one on each layer. These streams of data can be to a single UE (one rank 2 transmission) or to two UEs (two rank 1 transmissions).

LTE Toolbox supports the antenna port 5, 7, and 8 reference signals with the `lteDMRS` and `lteDMRSIndices` functions. These functions support the transmission of UE-specific reference signals for Release 8, 9 and 10. The particular UE-specific reference signals created are controlled by the transmission scheme parameter, `TxScheme`. For Release 9, you have the option to set `TxScheme` to these transmission schemes.

Parameter Setting	Description
`'Port7-8'`	Release 9 single-antenna port, port 7 (if `NLayers`=1) Release 9 dual layer transmission, ports 7 and 8 (if `NLayers`=2)
`'Port8'`	Single-antenna port, port 8

PDSCH transmissions, associated with antenna ports 7 and 8 (or any transmission scheme), can be made using the `ltePDSCH` and `ltePDSCHIndices` functions. These functions accept settings for the `TxScheme` parameter as described in the preceding table.

The UE-specific beamforming of the reference signals and PDSCH transmission is specified by the parameter `W` provided to `lteDMRS` and `ltePDSCH`. The `lteDMRSIndices` and `ltePDSCHIndices` functions use the `NTxAnts` parameter to specify the number of transmission antennas. See the function reference pages for details.

At the receiver, `ltePDSCHDecode` decodes PDSCH transmissions made on ports 7 and 8, under the assumption that the input will be equalized back to the transmission layers. Hence, no deprecoding is required. This behavior is consistent with the operation of `lteDLChannelEstimate`, which cannot assume knowledge of the UE-specific beamforming used at the transmitter when it produces the channel matrices between transmission layers and receive antennas. Therefore, the MMSE equalization carried out within `ltePDSCHDecode` outputs the PDSCH layers, which are then layer demapped, demodulated, and descrambled to produce soft bit estimates.

Note Several other functions are aware of the transmission scheme and process signals in compliance with Release 9 UE-specific beamforming, including `lteDLDeprecode`, `lteDLPrecode`, `lteDLSCH`, `lteDLSCHDecode`, `lteRateMatchTurbo`, and `lteRateRecoverTurbo`.

Release 9 transmissions on antenna ports 7 and 8 are associated with DCI Format 2B, which is supported by the `lteDCI`, `lteDCIDecode`, `lteDCIInfo`, `ltePDCCHSearch`, and `lteDCIResourceAllocation` functions.

Release 10 Downlink Enhanced MIMO

Release 10 provides a further extension to downlink UE-specific beamforming with reference signals (antenna ports) for up to 8 layers. These reference signals are called demodulation reference signals (DM-RS) in the standard. To support channel estimation for up to 8 layers (noting the cell-specific reference signals support only 4 antenna ports) a new channel state information reference signal (CSI-RS) set has been added, with 8 antenna ports specifically designed for CSI estimation.

The DM-RS antenna ports are numbers 7 through 14, with ports 7 and 8 being compatible with the dual-layer UE-specific beamforming capability of Release 9. LTE Toolbox supports these reference signals with the `lteDMRS` and `lteDMRSIndices` functions. These functions support the transmission of UE-specific reference signals for Release 8, 9 and 10. The particular UE-specific reference signals created are controlled by the transmission scheme parameter, `TxScheme`. For Release 10, you have the option to set `TxScheme` to this transmission scheme.

Parameter Setting	Description
`'Port7-14'`	Release 10 up to 8-layer transmission, ports 7–14 (`NLayers`=1...8)

PDSCH transmissions, associated with antenna ports 7 through 14 (or any transmission scheme), can be made using the `ltePDSCH` and `ltePDSCHIndices` functions. These functions accept settings for the `TxScheme` parameter as described in the preceding table.

The UE-specific beamforming of the reference signals and PDSCH transmission is specified by the parameter `W` provided to `lteDMRS` and `ltePDSCH`. The `lteDMRSIndices` and `ltePDSCHIndices` functions use the `NTxAnts` parameter to specify the number of transmission antennas. See the function reference pages for details.

At the receiver, `ltePDSCHDecode` decodes PDSCH transmissions made on ports 7 through 14, under the assumption that the input will be equalized back to the transmission layers. Hence, no deprecoding is required. This behavior is consistent with the operation of `lteDLChannelEstimate`, which cannot assume knowledge of the UE-specific beamforming used at the transmitter when it produces the channel matrices between transmission layers and receive antennas. Therefore, the MMSE equalization carried out within `ltePDSCHDecode` outputs the PDSCH layers, which are then layer demapped, demodulated, and descrambled to produce soft bit estimates.

For PMI feedback, `lteDLChannelEstimate` can optionally perform channel estimation against the CSI-RS. To do so, set the `Reference` parameter to `'CSIRS'`. Then, provide this channel estimate to `ltePMISelect` to perform PMI selection based on the codebook for CSI reporting, which is implemented using the `lteCSICodebook` function.

Note Several other functions are aware of the transmission scheme and process signals in compliance with Release 10, including `lteDLDeprecode`, `lteDLPrecode`, `lteDLSCH`, `lteDLSCHDecode`, `lteRateMatchTurbo`, and `lteRateRecoverTurbo`.

Release 10 transmissions on antenna ports 7 through 14 are associated with DCI Format 2C, which is supported by the `lteDCI`, `lteDCIDecode`, `lteDCIInfo`, `ltePDCCHSearch`, and `lteDCIResourceAllocation` functions.

Release 10 Uplink MIMO

Release 10 supports uplink MIMO, with 2 codewords transmitted on up to 4 layers on 4 antennas for the PUSCH. LTE Toolbox supports uplink MIMO similar to how it supports downlink MIMO, using cell arrays to represent multiple codeword vectors, and using multiple column matrices to represent multiple layers and transmission antennas.

Uplink MIMO transmission is provided by the `ltePUSCH` and `lteULSCH` functions. In the receiver, the timing offset function, `lteULFrameOffset`, searches its input across all configured DM-RS signals. By default, `lteULChannelEstimate` provides channel estimates to the precoded DM-RS signals, or transmission antennas, and `ltePUSCHDecode` uses knowledge of the precoding matrices used to perform MIMO equalization. Alternatively, you can configure `lteULChannelEstimate` to provide channel estimates to the DRS layers. To do so, set the `Reference` parameter to `'Layers'`. In this case, `ltePUSCHDecode` equalizes back to transmission layers.

The `ltePUSCHPrecode` and `ltePUSCHDeprecode` functions perform MIMO precoding and deprecoding for the PUSCH.

The `lteLayerMap` and `lteLayerDemap` functions provide support for the uplink and downlink.

The `lteACKDecode`, `lteACKEncode`, `lteRIDecode`, and `lteRIEncode` functions support the increased number of bits that can be coded in Release 10.

To learn how to create and simulate an uplink MIMO PUSCH performance test, see “Release 10 PUSCH Multiple Codeword Transmit and Receive Modeling”.

Release 10 Spatial Orthogonal Resource Transmit Diversity (SORTD)

Release 10 incorporates spatial orthogonal resource transmit diversity (SORTD) transmission on the PUCCH and SRS channels. SORTD transmits independent versions of an encoded and modulated signal on each transmission antenna by using a different orthogonal resource for each transmission antenna. For the PUCCH, the different orthogonal resources are different PUCCH resource indices, $n1_{\mathrm{PUCCH}}$, $n2_{\mathrm{PUCCH}}$, and $n3_{\mathrm{PUCCH}}$. For the SRS, the different orthogonal resources are different reference signal cyclic shifts, *alpha*.

SORTD transmission is supported by the `ltePUCCH1`, `ltePUCCH1DRS`, `ltePUCCH1DRSIndices`, `ltePUCCH1Indices`, `ltePUCCH2`, `ltePUCCH2DRS`, `ltePUCCH2DRSIndices`, `ltePUCCH2Indices`, `lteSRS`, and `lteSRSIndices` functions.

For PUCCH formats 1 and 2 and their DM-RS signals, specify SORTD using the `ResourceIdx` parameter, For Release 10 this parameter is a vector of indices, rather than a scalar index as for Release 8. For the SRS, specify SORTD using the `NTxAnts` parameter.

In the receiver, the timing offset functions, `lteULFrameOffsetPUCCH1` and `lteULFrameOffsetPUCCH2`, search their input across all configured DM-RS signals. The channel estimators, `lteULChannelEstimatePUCCH1` and `lteULChannelEstimatePUCCH2`, make a channel estimate against all DM-RS signals, or transmission antennas. If using a pilot averaging frequency window size, orthogonal despreading of different DM-RS signals is supported. The pilot averaging frequency window size is always a multiple of 12.

Release 10 PUCCH Format 3

Release 10 introduces a new PUCCH format, format 3, designed to transmit a large number of ACK indications in a single subframe. The LTE Toolbox implements PUCCH format 3 with the `ltePUCCH3`, `ltePUCCH3Decode`, `ltePUCCH3DRS`, `ltePUCCH3DRSIndices`, `ltePUCCH3Indices`, `ltePUCCH3PRBS`, `lteULChannelEstimatePUCCH3` and `lteULFrameOffsetPUCCH3` functions.

Release 11 Enhanced Physical Downlink Control Channel (EPDCCH)

Release 11 introduces the Enhanced Physical Downlink Control Channel, EPDCCH, which is designed to achieve improved spectral reuse of control channel resources. It supports CoMP, downlink MIMO, beamforming and frequency domain inter-cell interference coordination (ICIC). LTE Toolbox implements EPDCCH with the `lteEPDCCH`, `lteEPDCCHIndices`, `lteEPDCCHDMRS`, `lteEPDCCHDMRSIndices`, and `lteEPDCCHPRBS` functions.

Coordinated multipoint (CoMP) operation in LTE Release 11 takes advantage of low latency and high capacity backhaul between base stations within a cooperating set. For a demonstration of CoMP in a dynamic point selection (DPS) scheme, see “CoMP Dynamic Point Selection with Multiple CSI Processes”.

Release 12 Carrier Aggregation

Release 12 introduced intersite carrier aggregation to coordinate the capabilities and backhaul of adjacent cells. For a demonstration on how to create a signal covering multiple LTE carriers using

carrier aggregation, see “Release 12 Downlink Carrier Aggregation Waveform Generation, Demodulation and Analysis”.

Release 12 Alternative Codebook

Release 12 introduced an alternative codebook for channel state information reporting. For more information, see `lteCSICodebook`.

Representing Resource Grids

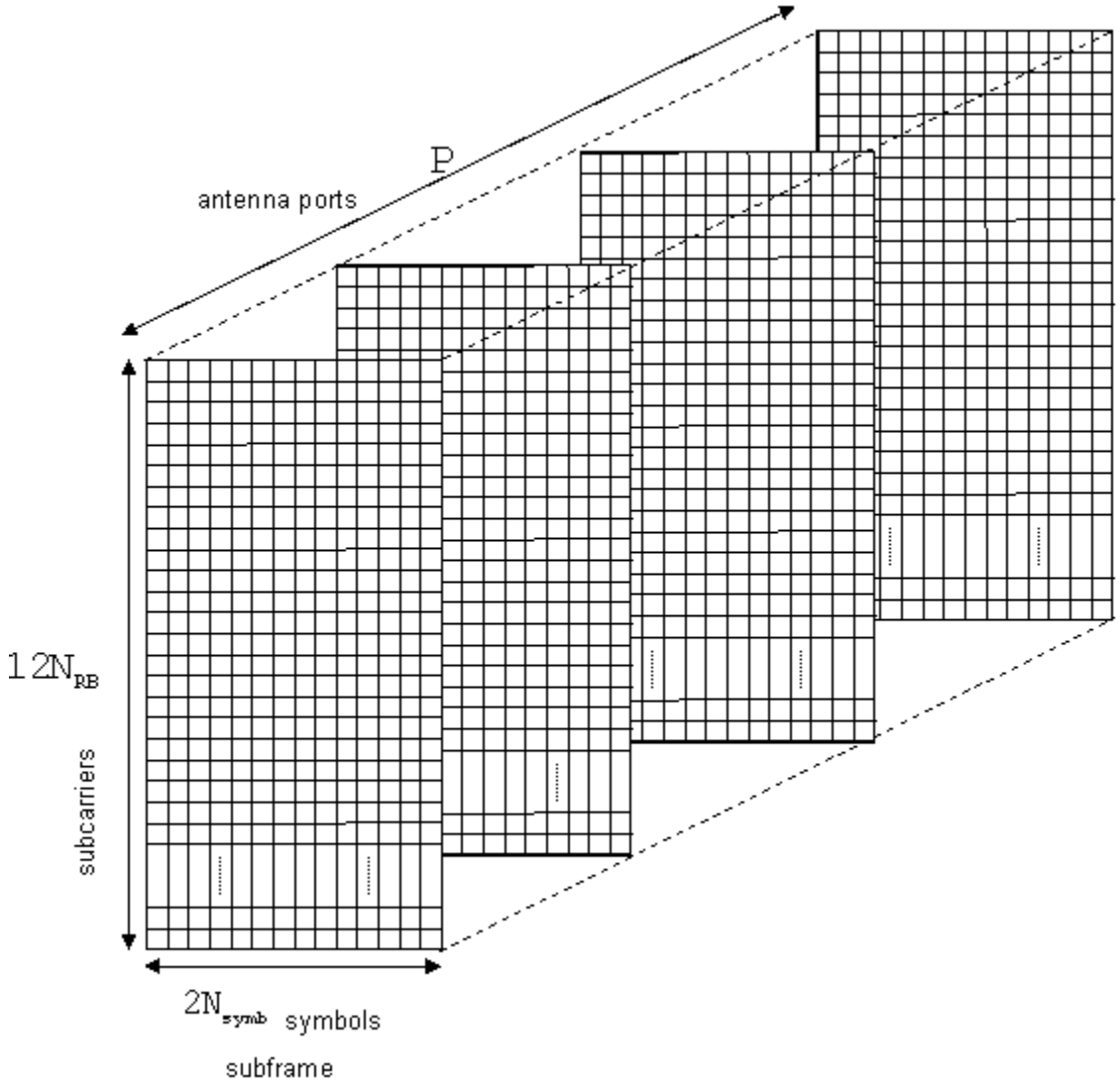
In this section...

Overview

This section describes the data structures used to represent the resource grid in the LTE Toolbox.

Multidimensional Arrays

Before OFDM modulation (IFFT), the physical channels and signals in LTE are mapped to different portions of the resource grid. LTE Toolbox represents the resource grid as a multidimensional array.



The rows of this array represent the subcarrier. The columns map the OFDM or SC-FDMA symbols in the downlink and uplink, respectively. The third dimension or plane represents the antenna ports. In the LTE Toolbox, the resource grid spans a subframe in the time-domain, instead of a slot. Hence, the documentation uses the term subframe resource grid. The size of this multidimensional array is $12N_{RB}\times 2N_{symb}\times P$, where N_{RB} is the number of resource blocks spanning the available bandwidth, N_{symb} is the number of OFDM, or SC-FDMA in the uplink, symbols per slot, and P is the number of antenna ports. Therefore, the resource grid represents a subframe,two slots, and whole bandwidth since there are 12 subcarriers per resource block. For the single antenna case, you can work with a two-dimensional array of size $12N_{RB}\times 2N_{symb}$.

Creating an Empty Resource Grid

Create an empty downlink resource grid using two different methods. Valid and equivalent subframe resource grids can be created using the `lteDLResourceGrid` function or the MATLAB® `zeros` function.

Initialize required parameters

Create the parameter structure for normal cyclic prefix, nine downlink resource blocks, and one transmit antenna. Also define seven symbols per slot for use in the `zeros` function only.

```
enb.CyclicPrefix = 'Normal';
enb.NDLRB = 9;
enb.CellRefP = 1;
noSymbolsSlot = 7;
```

Create two empty resource grids

Create an empty subframe resource grid, using each method.

```
resourceGrid1 = lteDLResourceGrid(enb);
resourceGrid2 = zeros(enb.NDLRB*12, noSymbolsSlot*2, enb.CellRefP);
```

Confirm the grids are equal

Compare the two grid variables for equality using the MATLAB `isequal` function.

```
isequal(resourceGrid1,resourceGrid2)
```

```
ans = logical
   1
```

Both approaches generate the same result. Use either approach to create an empty downlink resource grid. Similarly, an empty uplink resource grid could be created using `lteULResourceGrid` function or the MATLAB `zeros` function.

See Also

`isequal` | `lteDLResourceGrid` | `lteResourceGrid` | `lteULResourceGrid` | `zeros`

Related Examples

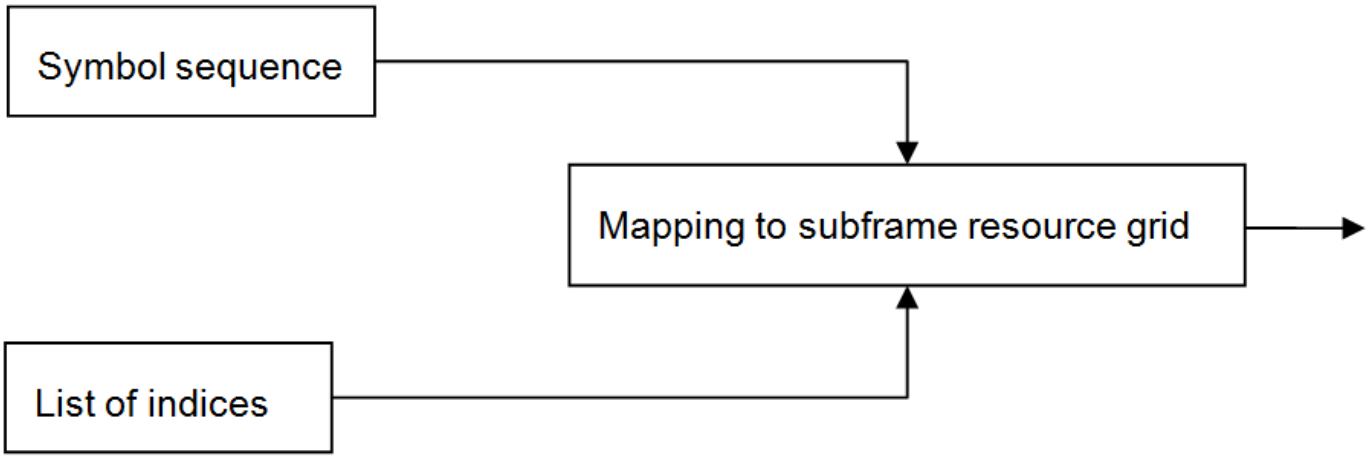
- “Resource Grid Indexing” on page 1-16

Resource Grid Indexing

In this section...

Overview

The LTE Toolbox provides facilities to generate sequences of symbols corresponding to the physical channels and signals. Indices for the mapping of these sequences to the resource grid are also generated. For convenience, the LTE Toolbox uses the MATLAB® linear indexing style to represent these indices.



Subframe Resource Grid Size

Before applying OFDM modulation (IFFT), the physical channels and signals in LTE are mapped to different portions of the subframe resource grid. The subframe resource grid is represented in the LTE Toolbox as a multidimensional array of the following size.

$$12N_{RB} \times 2N_{symb} \times P$$

In the preceding expression, N_{RB} is the number of resource blocks spanning the available bandwidth, N_{symb} is the number of OFDM (or SC-FDMA in the uplink) symbols per slot, and P is the number of antenna ports. Therefore, the resource grid represents a subframe (two slots) and whole bandwidth,

since there are 12 subcarriers per resource block. For the single antenna case, a resource grid can be a two-dimensional matrix of the following size.

$$12N_{RB} \times 2N_{symb}$$

Creating an Empty Resource Grid

Create an empty downlink resource grid using two different methods. Valid and equivalent subframe resource grids can be created using the `lteDLResourceGrid` function or the MATLAB® `zeros` function.

Initialize required parameters

Create the parameter structure for normal cyclic prefix, nine downlink resource blocks, and one transmit antenna. Also define seven symbols per slot for use in the `zeros` function only.

```
enb.CyclicPrefix = 'Normal';
enb.NDLRB = 9;
enb.CellRefP = 1;
noSymbolsSlot = 7;
```

Create two empty resource grids

Create an empty subframe resource grid, using each method.

```
resourceGrid1 = lteDLResourceGrid(enb);
resourceGrid2 = zeros(enb.NDLRB*12, noSymbolsSlot*2, enb.CellRefP);
```

Confirm the grids are equal

Compare the two grid variables for equality using the MATLAB `isequal` function.

```
isequal(resourceGrid1,resourceGrid2)
```

```
ans = logical
   1
```

Both approaches generate the same result. Use either approach to create an empty downlink resource grid. Similarly, an empty uplink resource grid could be created using `lteULResourceGrid` function or the MATLAB `zeros` function.

Resource Grid Indexing

Generate a reference signal and map it to an empty resource grid for the single antenna case. The LTE Toolbox(TM) has been designed to facilitate the mapping of physical channels and signals in the resource grid.

Set up the cell-wide settings. Create a structure and specify the cell-wide settings as its fields.

```
enb.CyclicPrefix = 'Normal';
enb.NDLRB = 6;
enb.CellRefP = 1;
enb.NCellID = 1;
enb.NSubframe = 0;
```

```
enb.DuplexMode = 'FDD';
antPort = 0;
```

The `enb` structure now contains the parameters required by the functions to be called next.

Use `lteDLResourceGrid` to create an empty subframe resource grid, then populate it with reference symbols. To do so, call the `lteCellRSIndices` and `lteCellRS` functions.

```
resourceGrid = lteDLResourceGrid(enb);
ind = lteCellRSIndices(enb,antPort);
rs = lteCellRS(enb,antPort);
resourceGrid (ind) = rs;
```

A call to the function `lteCellRSIndices` generates a list of indices identifying to where the reference signal is to be mapped, whereas the call to `lteCellRS` generates the reference signal symbols.

Linear Indices and Subscripts

Generate indices in linear and subscript form. All of the LTE Toolbox index generation functions can produce either linear or subscript formats by setting the appropriate options string. The default is linear indexing style, which allows access to any element of a matrix with a single index value. Subscripted matrix element indexing is also available. Using subscripted indexing on a 2-D matrix, you can access each element with a set of two elements representing the row and column equivalents.

Note, the linear indexing style allows you to conveniently map the reference sequence symbols to the appropriate location in the resource grid with just one line of code. Mapping reference symbols to the resource grid using subscripted indices would require more finesse.

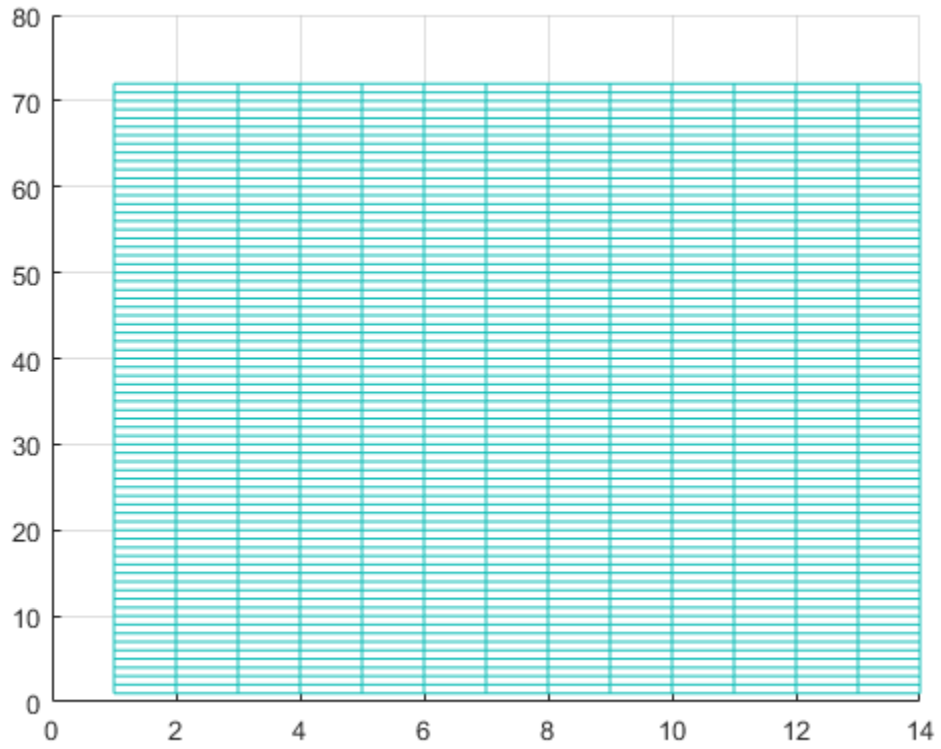
Create a structure specifying the cell-wide settings as its fields. Assign zero as the antenna port number.

```
enb.CyclicPrefix = 'Normal';
enb.NDLRB = 6;
enb.CellRefP = 1;
enb.NCellID = 1;
enb.NSubframe = 0;
enb.DuplexMode = 'FDD';

antPort = 0;
```

The `enb` structure now contains the parameters required by the functions to be called next.

Use `lteDLResourceGrid` to create an empty subframe resource grid and `lteCellRS` to create reference signal symbols. View the empty resource grid.

```
resourceGrid = lteDLResourceGrid(enb);
rs = lteCellRS(enb,antPort);
mesh(abs(resourceGrid))
view(2)
```



After the indices are generated and the reference symbols are mapped to the resource grid, the resource grid is replotted to show the reference symbol mapping.

Generate linear indices. Since linear indexing is the default, the following two calls are equivalent.

```
ind_lin = lteCellRSIndices(enb,antPort);
ind_lin = lteCellRSIndices(enb,antPort,'ind')
```

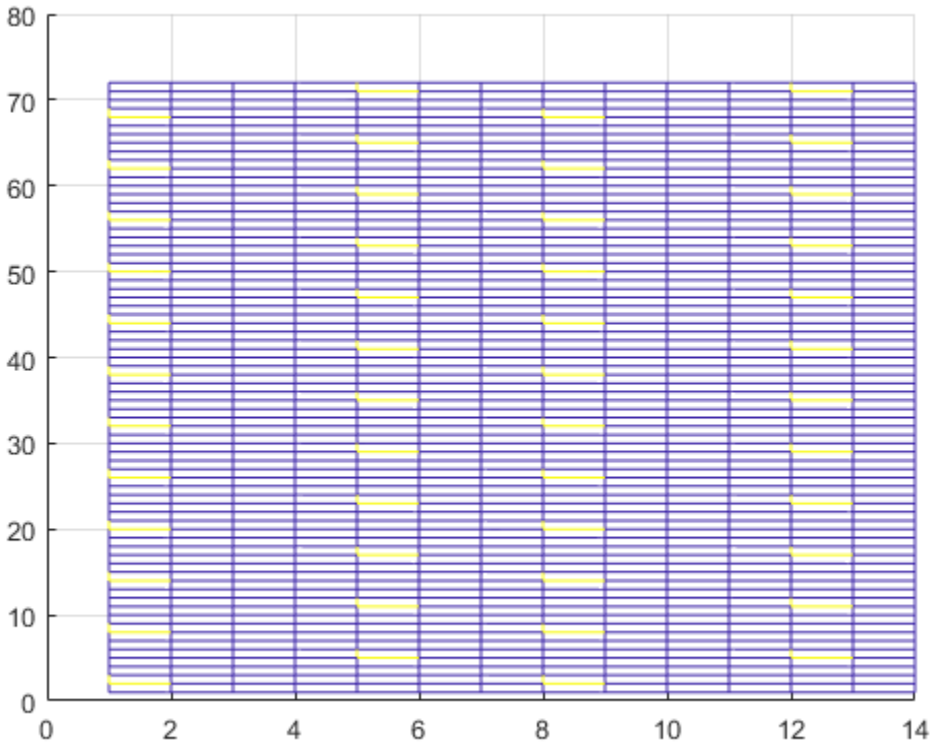
```
ind_lin = 48x1 uint32 column vector

    2
    8
   14
   20
   26
   32
   38
   44
   50
   56
    ⋮
```

Mapping the reference signal symbols to the resource grid using linear indices, `ind_lin`, simply requires you to assign the reference signal symbols to the resource grid indicating the active indices.

```
resourceGrid(ind_lin) = rs;
```

Replotting the resource grid shows the reference symbols active for the cell-wide settings assigned in `enb`.

```
figure
mesh(abs(resourceGrid))
view(2)
```



Alternatively, generate indices in subscript form by providing the `'sub'` option string for `lteCellRSIndices`.

```
ind_sub = lteCellRSIndices(enb,antPort,'sub')
```

```
ind_sub = 48x3 uint32 matrix

    2     1     1
    8     1     1
   14     1     1
   20     1     1
   26     1     1
   32     1     1
   38     1     1
   44     1     1
   50     1     1
   56     1     1
    ⋮
```

In this case, the output argument, `ind_sub`, is a [subcarrier, OFDM symbol, antenna port] matrix format of the resource grid. These indices are calculated for antenna port 0.

Converting Between Linear Indices and Subscripts

Conversion between linear indices and subscripts can be achieved using the MATLAB `ind2sub` and `sub2ind` functions. Alternatively, all index generation functions in the LTE Toolbox can produce both formats.

Multi-Antenna Linear Indices

Generate indices in multi-antenna linear form. This form is a variant of the MATLAB® linear indexing style in which the indices corresponding for each antenna port are in a different column. However, all indices are still in linear form. Several toolbox functions return indices in multi-antenna linear form.

To illustrate this, call the function `ltePDSCH` for the four antenna case.

```
enb.CellRefP = 4;
enb.CFI = 1;
enb.NCellID = 1;
enb.NSubframe = 0;
enb.NDLRB = 6;
enb.CyclicPrefix = 'Normal';
enb.DuplexMode = 'FDD';

pdsch.TxScheme = 'TxDiversity';
pdsch.Modulation = 'QPSK';
pdsch.RNTI = 1;
pdsch.PRBSet = (0:5).';

data = ones(768,1);
symb = ltePDSCH(enb,pdsch,data);
size(symb)

ans = 1×2

   384     4


symb(1:10,:)

ans = 10×4 complex

  -0.5000 - 0.5000i   0.0000 + 0.0000i  -0.5000 - 0.5000i   0.0000 + 0.0000i
   0.5000 - 0.5000i   0.0000 + 0.0000i  -0.5000 + 0.5000i   0.0000 + 0.0000i
   0.0000 + 0.0000i  -0.5000 - 0.5000i   0.0000 + 0.0000i   0.5000 - 0.5000i
   0.0000 + 0.0000i  -0.5000 - 0.5000i   0.0000 + 0.0000i  -0.5000 + 0.5000i
   0.5000 - 0.5000i   0.0000 + 0.0000i   0.5000 + 0.5000i   0.0000 + 0.0000i
  -0.5000 + 0.5000i   0.0000 + 0.0000i   0.5000 + 0.5000i   0.0000 + 0.0000i
   0.0000 + 0.0000i   0.5000 + 0.5000i   0.0000 + 0.0000i  -0.5000 + 0.5000i
   0.0000 + 0.0000i   0.5000 + 0.5000i   0.0000 + 0.0000i   0.5000 - 0.5000i
  -0.5000 - 0.5000i   0.0000 + 0.0000i   0.5000 + 0.5000i   0.0000 + 0.0000i
  -0.5000 + 0.5000i   0.0000 + 0.0000i  -0.5000 + 0.5000i   0.0000 + 0.0000i
```

The output argument, `symb`, is a matrix with four columns, in which each column corresponds to each antenna port.

In a similar format, generate the indices for the PDSCH by calling `ltePDSCHIndices`.

```
pdschIndices = ltePDSCHIndices(enb,pdsch,pdsch.PRBSet);
size(pdschIndices)
```

```
ans = 1×2

   384     4
```

```
pdschIndices(1:10,:)
```

```
ans = 10x4 uint32 matrix

    145   1153   2161   3169
    146   1154   2162   3170
    147   1155   2163   3171
    148   1156   2164   3172
    149   1157   2165   3173
    150   1158   2166   3174
    151   1159   2167   3175
    152   1160   2168   3176
    153   1161   2169   3177
    154   1162   2170   3178
```

Again, each column corresponds to each of the four antenna ports. The concatenation of all four columns produces a column vector of indices using the MATLAB linear indexing style.

Index Base

Generate either zero-based or one-based indices. All mapping operations in the LTE technical specification (TS) documents refer to zero-based indexing. However, MATLAB® indices must be one-based. LTE Toolbox™ generates one-based indices by default, but you can generate zero-based indices by setting the appropriate options string.

Create a cell-wide setting structure and assign an antenna port number.

```
enb.NDLRB = 6;
enb.NCellID = 1;
enb.CyclicPrefix = 'Normal';
enb.DuplexMode = 'FDD';

antPort = 0;
```

Since one-based indexing is the default, you can generate one-based indices by specifying the `'1based'` flag or leaving it out.

```
ind = lteCellRSIndices(enb,antPort);
ind = lteCellRSIndices(enb,antPort,'1based');
```

Generate zero-based indices by specifying the `'0based'` flag.

```
ind = lteCellRSIndices(enb,antPort,'0based');
```

Resource Blocks

The 3GPP documents describes a *resource block* to be a group of resource elements spanning 12 consecutive subcarriers in the frequency domain and one slot in the time domain. For processing efficiency, the LTE Toolbox™, operates on a subframe (two timeslot) basis and describes a *resource block pair* to represent 12 consecutive subcarriers spanning in the frequency domain and one subframe (two slots) in the time domain. For example, the command `ltePDSCHIndices` uses the parameter `PRBSet` to define the set of physical resource block (PRB) indices for a subframe of data.

Create the cell-wide settings structure and define the `PDSCH` configuration.

```
enb.CellRefP = 4;
enb.CFI = 1;
enb.NCellID = 1;
enb.NSubframe = 0;
enb.NDLRB = 6;
enb.CyclicPrefix = 'Normal';
enb.DuplexMode = 'FDD';

pdsch.TxScheme = 'TxDiversity';
pdsch.Modulation = 'QPSK';
pdsch.RNTI = 1;
pdsch.PRBSet = (0:5).';
```

Create a set of PDSCH PRB indices for the initialized configuration.

```
pdschIndices = ltePDSCHIndices(enb,pdsch,pdsch.PRBSet);
size(pdschIndices)
```

```
ans = 1×2

   384     4
```

```
pdschIndices(1:10,:)
```

```
ans = 10x4 uint32 matrix

    145   1153   2161   3169
    146   1154   2162   3170
    147   1155   2163   3171
    148   1156   2164   3172
    149   1157   2165   3173
    150   1158   2166   3174
    151   1159   2167   3175
    152   1160   2168   3176
    153   1161   2169   3177
    154   1162   2170   3178
```

```
pdsch
```

```
pdsch = struct with fields:
      TxScheme: 'TxDiversity'
    Modulation: 'QPSK'
          RNTI: 1
```

```
        PRBSet: [6x1 double]
```

`pdsch.PRBSet` can be either a column vector or a two-column matrix. If you provide a column vector, the resource allocation is the same in both slots of the subframe, which means the set of resource indices applies to both subframe time slots. On the other hand, if you provide a two-column matrix, the PRB indices refer to each slot individually.

See Also

`lteCellRS` | `lteCellRSIndices` | `lteDLResourceGrid` | `ltePDSCH` | `ltePDSCHIndices` | `zeros`

Related Examples

- “Parameterization” on page 1-25

Parameterization

In this section...

Some of the functions in the LTE Toolbox require a large number of parameters. To simplify the process, the LTE Toolbox groups relevant parameters together into structures.

Parameter Structures

Consider, as an example, the task of generating PCFICH symbols and mapping indices. For this task, you can call the functions `ltePCFICH`, and `ltePCFICHIndices`. The `ltePCFICH` function also requires `cw`, an input bit vector. For this input, you can call the `lteCFI` function. All three functions require a parameter structure, `enb`, that represents the eNodeB cell-wide settings.

The function `ltePCFICH` requires `enb` to have at least the following fields.

- `NCellID` — Physical layer cell identity
- `CellRefP` — Number of cell-specific reference signal antenna ports. Valid values are 1, 2, and 4.
- `NSubframe` — Subframe number

In comparison, the function `ltePCFICHIndices` requires `enb` to have at least the following fields.

- `NCellID` — Physical layer cell identity
- `NDLRB` — Number of downlink resource blocks

Finally, the function `lteCFI` only requires `enb` to have one field, `CFI`. In all cases, if additional fields are present and not required, the function ignores them.

Create a Cell-Wide Settings Structure

This example shows how to create a cell-wide settings structure. In particular, you can create a parameter structure, `enb`, that has all the fields required by the `lteCFI`, `ltePCFICH`, and | `ltePCFICHIndices` functions.

Create a new parameter structure, `enb`, with only one field, `CFI`.

```
enb.CFI = 1;
```

Create a 32-element bit vector, `cw`, representing the rate 1/16 block encoding of the control format indicator (CFI) value. To do so, call the `lteCFI` function. Provide `enb` as an input argument.

```
cw = lteCFI(enb);
```

Add additional fields to the parameter structure, `enb`.

```
enb.NCellID = 0;
enb.CellRefP = 1;
```

```
enb.NSubframe = 0;
enb.NDLRB = 9;
```

Generate the PCFICH complex symbols by calling the `ltePCFICH` function, providing the `enb` structure and the `cw` bit vector as input arguments.

```
sym = ltePCFICH(enb,cw);
```

Although `ltePCFICH` does not require that `enb` have the `NDLRB` field, this does not cause a problem. In this case, the function ignores any non-required fields.

Generate the PCFICH mapping indices by calling the `ltePCFICHIndices` function, providing the `enb` structure as an input argument.

```
ind = ltePCFICHIndices(enb);
```

Although `ltePCFICHIndices` does not require the `enb.NSubframe` field, it does not cause a problem. The function ignores any fields that it does not require.

You can remove fields from a structure using the MATLAB® `rmfield` function but, as shown, removing the field is not necessary.

Cell-Wide Parameters

Many functions in the LTE Toolbox require a parameter structure called `enb`. This parameter represents the eNodeB, or cell-wide, settings which are common to all user equipments (UEs) in the cell. This structure can include the following fields, which are among the most common.

- `NCellID` — Physical layer cell identity
- `CellRefP` — Number of cell-specific reference signal antenna ports. Valid values are 1, 2, and 4.
- `CyclicPrefix` — Length of cyclic prefix. Valid values are `'Normal'` and `'Extended'`.
- `NSubframe` — Subframe number
- `NDLRB` — Number of downlink resource blocks

Different functions require different fields. Not all functions that require the `enb` structure need all the fields listed above. Some functions require only a subset of those listed above. In this case, any non-required fields are ignored.

When optional parameter fields are not specified, a function in the LTE Toolbox may assume default settings. In this case, the toolbox produces warning messages to specify the default values that it is using. You may control these warnings using the `lteWarning` function.

Optional Output Formats

This example shows how to pass optional inputs to certain functions to change the output format provided from the function.

Create a new parameter structure, `enb`.

```
enb.NCellID = 0;
enb.CellRefP = 1;
enb.NSubframe = 0;
```

```
enb.NDLRB = 9;
enb.Ng = 'Sixth';
```

For example, consider the case where a list of indices for a certain physical channel is generated using `ltePCFICHIndices`.

The input argument, `enb`, is a structure with the appropriate fields. By default, these indices are one-based, as opposed to the zero-based indices specified in the technical specification (TS) documentation.

```
ind = ltePCFICHIndices(enb);
firstIndex = ind(1)
```

```
firstIndex = uint32
    2
```

Change the base number used in the index generation by providing an additional optional input argument. Specify `'0based'` to generate zero-based indices or `'1based'` to generate one-based indices.

```
ind = ltePCFICHIndices(enb, '0based');
firstIndex_0based = ind(1)
```

```
firstIndex_0based = uint32
    1
```

```
ind = ltePCFICHIndices(enb, '1based');
firstIndex_1based = ind(1)
```

```
firstIndex_1based = uint32
    2
```

The first index generated when no optional argument is provided matches the first index when `'1based'` is specified. The optional input is not required. If you do not specify an optional input, the function uses the default value.

Specify multiple output format options for a function by providing a cell array input argument, `opts`.

```
opts = {'sub', '1based', 'reg'};
pcfichInd = ltePCFICHIndices(enb, opts)
```

```
pcfichInd = 4x3 uint32 matrix

    1    1    1
   25    1    1
   55    1    1
   79    1    1
```

The generated PCFICH indices are in subscript indexing style, one-based, and refer to resource element groups. The cell array of options that you specify indicates the format for the returned indices.

Varying the order of the `opts` cell entries produces the same result.

```
opts = {'1based', 'sub', 'reg'};
pcfichInd = ltePCFICHIndices(enb, opts)
```

```
pcfichInd = 4x3 uint32 matrix

    1    1    1
   25    1    1
   55    1    1
   79    1    1
```

The order in which you provide the `opts` inputs is not relevant. Both cases produce the same values in the output argument, `pcfichInd`.

See Also

`lteCFI` | `ltePCFICH` | `ltePCFICHIndices` | `lteWarning` | `rmfield`

Related Examples

- “LTE Parameterization for Waveform Generation and Simulation”
- “UL-SCH Parameterization” on page 1-29

UL-SCH Parameterization

In this section...

A number of the uplink shared channel (UL-SCH) and PUSCH related functions offer two different ways of parameterizing multiple codewords in the UL-SCH or PUSCH-specific parameter structure. As with many functions in the LTE Toolbox, the parameters associated with codewords can be combined together in the individual fields of a single scalar (1-by-1) structure. However, many UL-SCH-specific functions also allow each codeword to be defined by separate independent elements of a (1-by-2) structure array. This feature offers additional flexibility and results in more compact code when explicit fine-grained parameterization of the individual processing steps is required.

Set UL-SCH Parameters in Scalar Structure

This example shows how to parameterize an UL-SCH or PUSCH-specific parameter structure using two different representations. Consider creating a parameter structure for the `lteULSCHDeinterleave` function.

When UCI is being transmitted on the UL-SCH, the deinterleaving and UCI demultiplexing operations require explicit knowledge of number of control channel symbols within the codeword. For example, for a single LTE Release 8 codeword, the UL-SCH specific parameters can be defined by a scalar (1-by-1) structure.

```
ulsch1.Modulation = 'QPSK';
ulsch1.QdCQI = 4;
ulsch1.QdRI  = 2;
ulsch1.QdACK = 2;
```

In this case, there are four CQI, two RI, and two HARQ-ACK symbols within the QPSK-modulated codeword.

When moving to a full LTE-Advanced uplink transmission, you must consider a second possible codeword and the impact of the additional PUSCH layering. This layering can be achieved either by adding values in the structure field values above or by using a 1-by-2 element structure array to define the codeword pair. For example, transmit a second 16-QAM-modulated codeword also, which now carries the CQI and both codewords are sent on a total of three spatial layers.

```
ulsch2.Modulation = {'QPSK','16QAM'};
ulsch2.NLayers = 3;
ulsch2.QdCQI = [0,4];
ulsch2.QdRI  = 2;
ulsch2.QdACK = 2;
```

Since the CQI should only be transmitted on one of the codewords (the second one here) this symbol allocation is signaled by setting ulsch2.QdCQI = [0,4].

You must explicitly specify some parameters for each codeword. However, in general, when using a single 1-by-1 structure for multi-codeword parameterization, scalar parameter field values are assigned to all codewords. The structure `ulsch2` sets the number of RI and HARQ-ACK coded modulation symbols per layer per codeword to two. Make this number of symbols explicit for each codeword by defining the `QdRI` and `QdACK` fields as 1-by-2 vectors.

```
ulsch2.QdRI  = [2,2];
ulsch2.QdACK = [2,2];
```

One special case is the parameter field which controls the number of spatial layers, `NLayers`, which has slightly different semantics. If this field value is scalar, it defines the total number of layers across all codewords. Following the LTE standard formulae, when you set the total number of layers to three, the LTE Toolbox™ partitions one layer for the first codeword and two layers for the second codeword. Make this layer allocation per codeword explicit by defining the `NLayers` field as a 1-by-2 vector.

```
ulsch2.NLayers = [1,2];
```

In summary, you can write the overall parameter structure by declaring all of the parameter fields at once.

```
ulsch2.Modulation = {'QPSK','16QAM'};
ulsch2.NLayers = [1,2];
ulsch2.QdCQI = [0,4];
ulsch2.QdRI  = [2,2];
ulsch2.QdACK = [2,2];
```

This structure is equivalent to the ones created earlier.

Set UL-SCH Parameters in Structure Array

This example shows how to parameterize an UL-SCH or PUSCH-specific parameter structure using two different representations. Consider creating a parameter structure for the `lteULSCHDeinterleave` function.

When UCI is being transmitted on the UL-SCH, the deinterleaving and UCI demultiplexing operations require explicit knowledge of number of control channel symbols within the codeword. For example, for a single LTE Release 8 codeword, the UL-SCH specific parameters can be defined by a scalar (1-by-1) structure.

```
ulsch1.Modulation = 'QPSK';
ulsch1.QdCQI = 4;
ulsch1.QdRI  = 2;
ulsch1.QdACK = 2;
```

The UL-SCH-specific structure also allows each codeword to be defined by separate, independent elements of a 1-by-2 structure array. In this case, the important distinction is that no parameter field values are implicitly shared between the codewords. Each field value applies only to the codeword associated with that structure array element. For example, redefine the single codeword structure by creating a new 1-by-2 structure array containing two identical elements.

```
ulsch2(1:2) = ulsch1
```

```
ulsch2=1×2 struct array with fields:
    Modulation
    QdCQI
    QdRI
    QdACK
```

Update only the parameters which are different for each codeword.

```
ulsch2(1).QdCQI = 0;
ulsch2(2).Modulation = '16QAM';
```

Add the explicit number of layers per codeword parameter, `NLayers`, to the elements of the structure array.

```
[ulsch2.NLayers] = deal(1,2);
```

View the first element of the final `ulsch2` structure array.

```
ulsch2(1)
```

```
ans = struct with fields:
    Modulation: 'QPSK'
         QdCQI: 0
          QdRI: 2
         QdACK: 2
       NLayers: 1
```

View the second element of the final `ulsch2` structure array.

```
ulsch2(2)
```

```
ans = struct with fields:
    Modulation: '16QAM'
         QdCQI: 4
          QdRI: 2
         QdACK: 2
       NLayers: 2
```

Both of these forms of UL-SCH parameter representation can be used in many of the UL-SCH- and PUSCH-related functions. In additional, the `lteULSCHInfo` function can return its output structure in either form:

- To receive a structure array, set the second element of the 1-by-2 `opts` cell array to `'cwseparate'`.
- To receive a scalar structure, set it to `'cwcombined'`.

See Also

`lteULSCHDeinterleave` | `lteULSCHInfo`

Related Examples

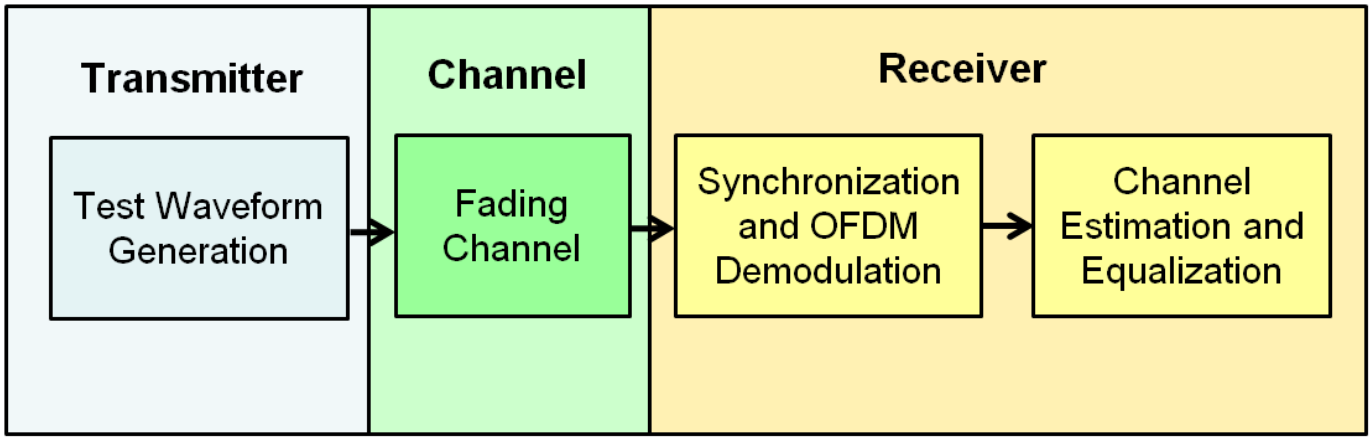
- “Parameterization” on page 1-25

High-Level Examples

Transmit-Receive Chain Processing

Transmit-Receive Chain

This example shows how to implement an LTE transmit and receive chain, as shown in this figure.

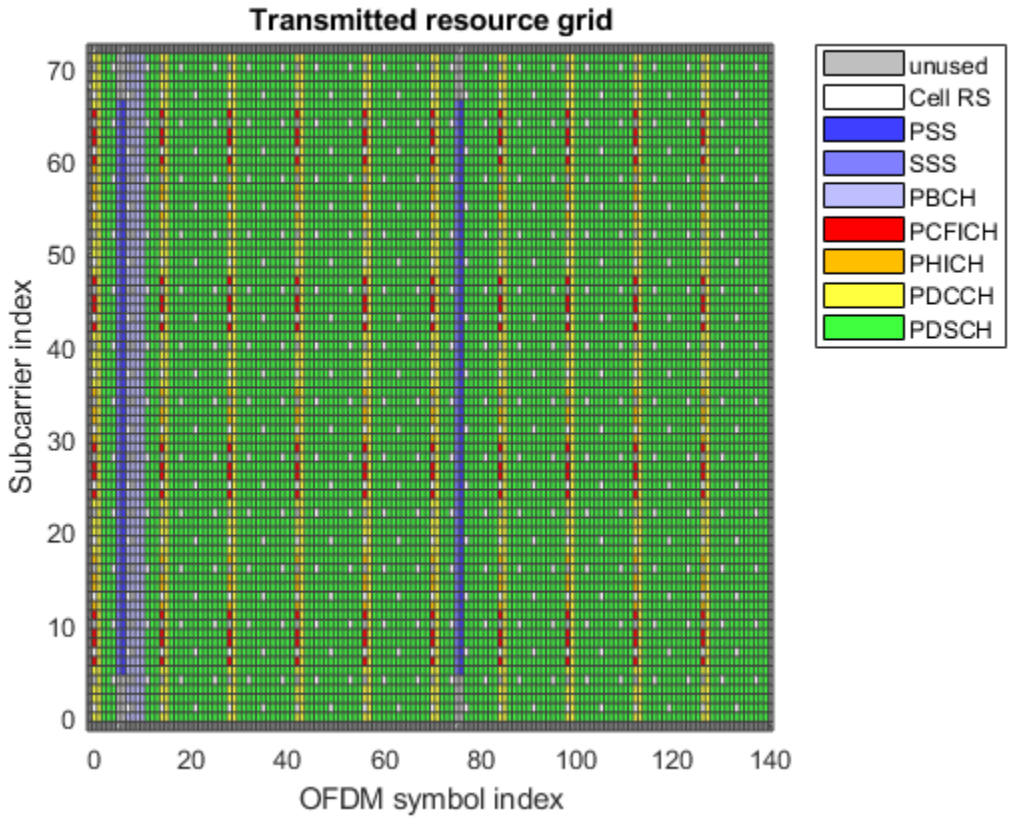


Generate an E-UTRA test model (E-TM) configuration. Use this configuration to generate the waveform and populate the resource grid.

```
enb = lteTestModel('1.1','1.4MHz');
[txwave,txgrid,info] = lteTestModelTool(enb);
```

Plot a graphical representation of the transmit resource grid.

```
figure('Color','w');
helperPlotTransmitResourceGrid(enb,txgrid);
```



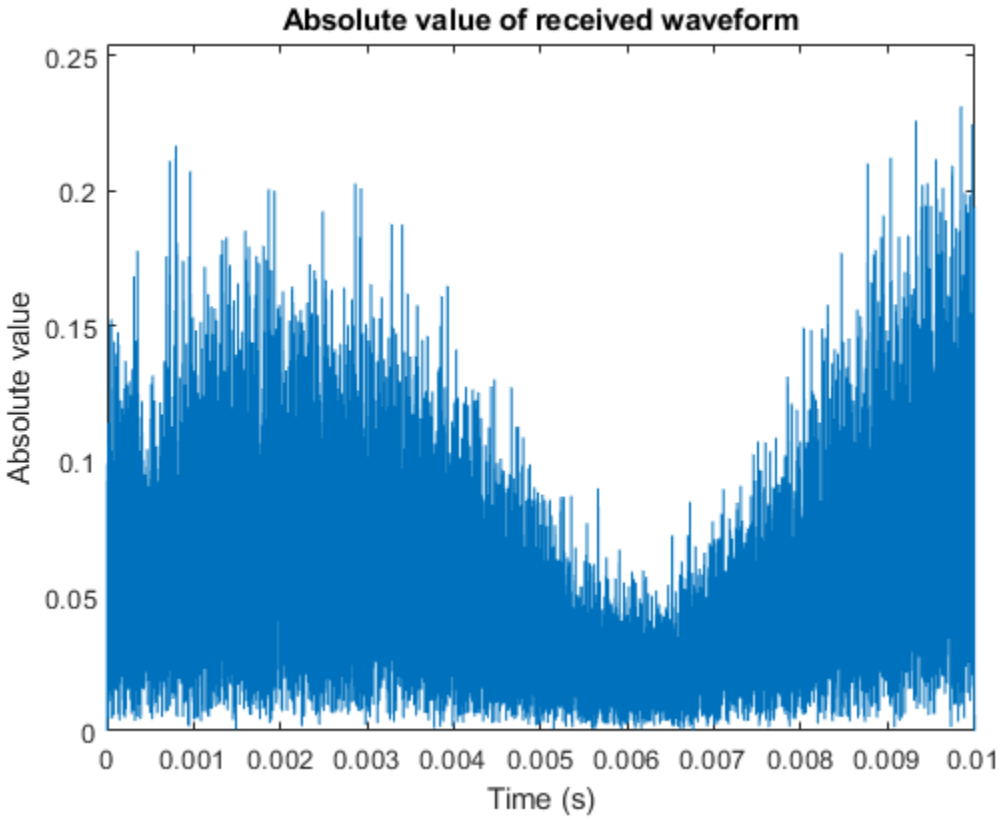
The figure shows a resource grid populated with E-TM 1.1 resource elements.

Simulate transmission through a fading channel propagation model.

```
channel.ModelType = 'GMEDS';
channel.DelayProfile = 'EVA';
channel.DopplerFreq = 70;
channel.MIMOCorrelation = 'Medium';
channel.NRxAnts = 1;
channel.InitTime = 0;
channel.InitPhase = 'Random';
channel.Seed = 17;
channel.NormalizePathGains = 'On';
channel.NormalizeTxAnts = 'On';
channel.SamplingRate = info.SamplingRate;
channel.NTerms = 16;
rxwave = lteFadingChannel(channel,[txwave;zeros(25,1)]);
```

Plot the time-varying power of the received waveform.

```
figure('Color','w');
helperPlotReceiveWaveform(info,rxwave);
```



This plot shows the waveform power variation over time.

Perform frame synchronization.

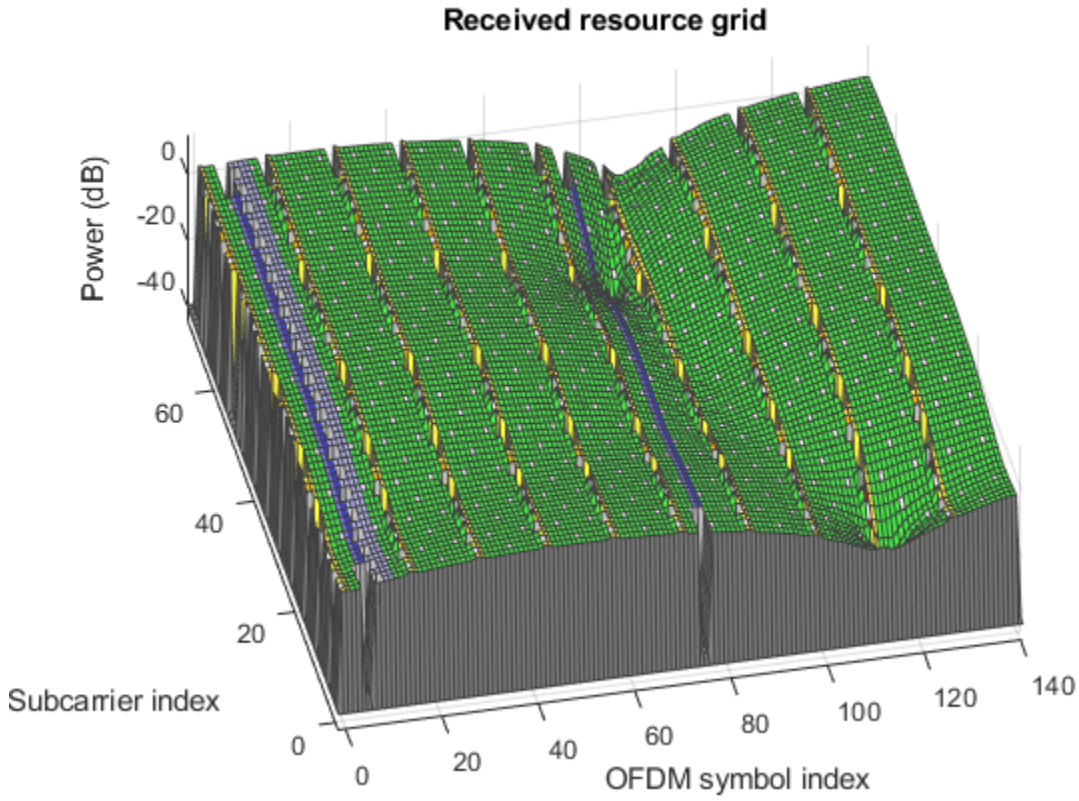
```
offset = lteDLFrameOffset(enb,rxwave);
rxwave = rxwave(offset:end,:);
```

Perform OFDM demodulation.

```
rxgrid = lteOFDMDemodulate(enb,rxwave);
```

Create a surface plot showing the power of the received grid for each subcarrier and OFDM symbol.

```
figure('Color','w');
helperPlotReceiveResourceGrid(enb,rxgrid);
```



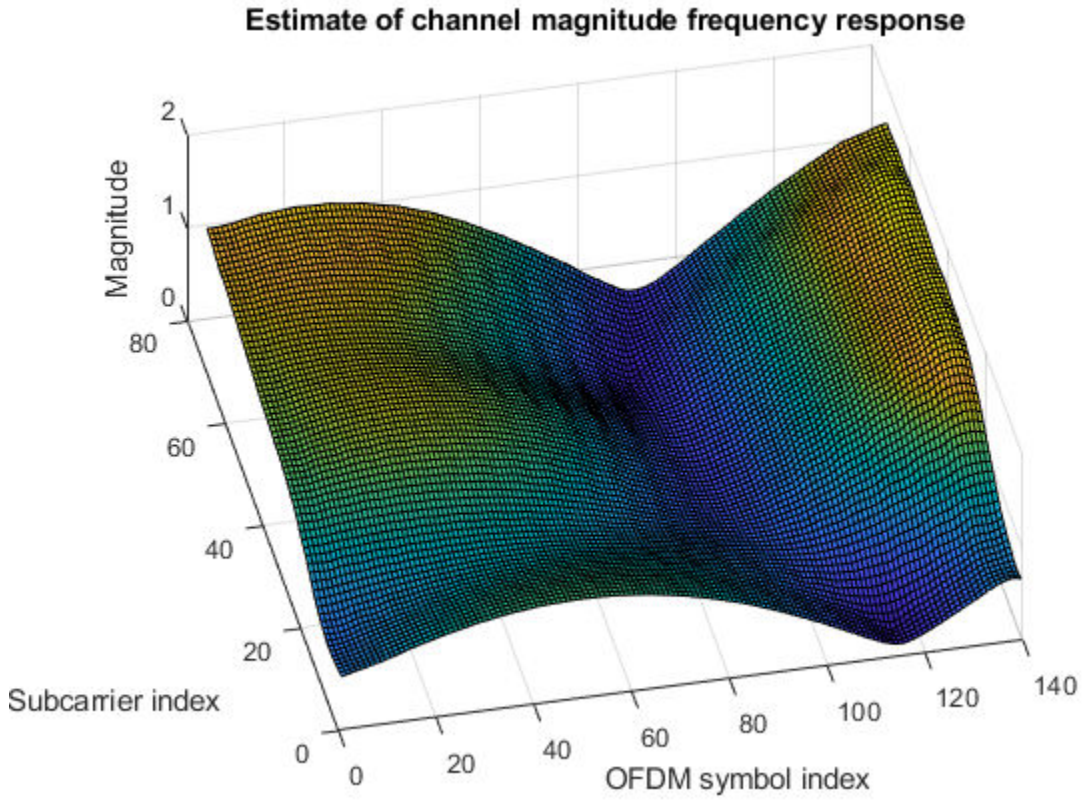
This plot shows the received grid power.

Estimate the channel and noise.

```
cec.PilotAverage = 'UserDefined';
cec.FreqWindow = 9;
cec.TimeWindow = 9;
cec.InterpType = 'Cubic';
cec.InterpWindow = 'Centered';
cec.InterpWinSize = 3;
[hest,nest] = lteDLChannelEstimate(enb,cec,rxgrid);
```

Create a surface plot showing the magnitude of the channel estimate for each OFDM symbol across the subcarriers.

```
figure('Color','w');
helperPlotChannelEstimate(hest);
```



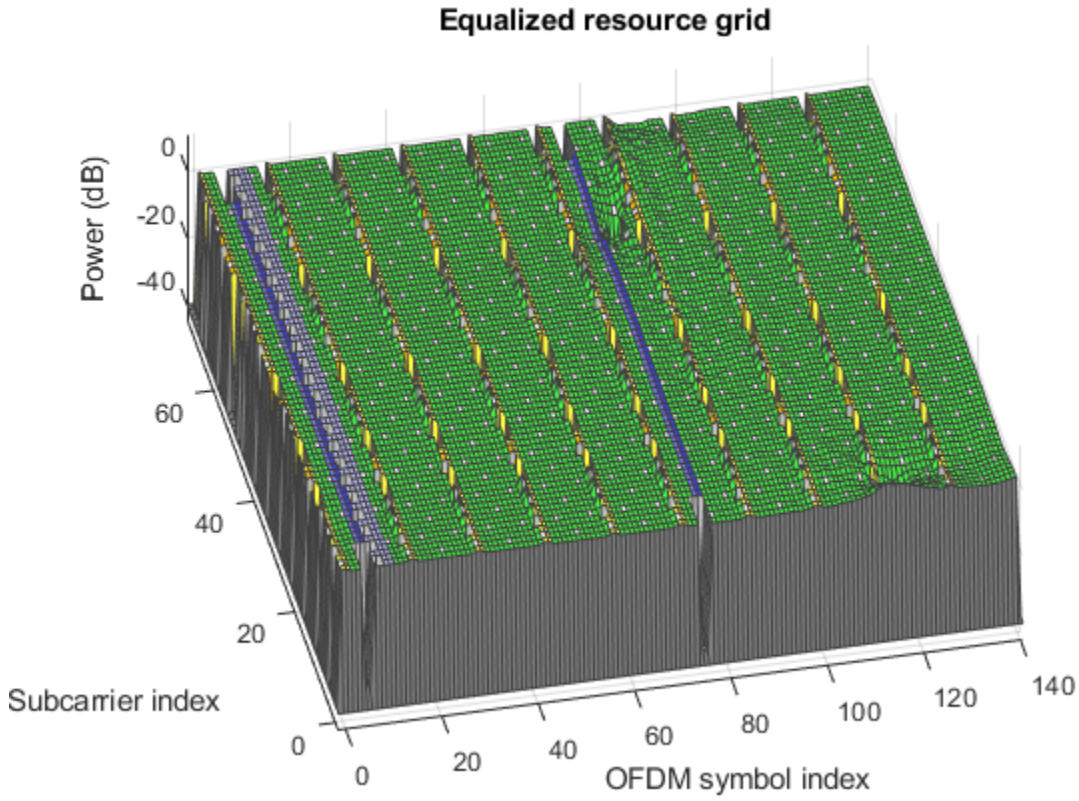
This figure shows an estimate of channel magnitude frequency response.

Finally, perform minimum mean-square error (MMSE) equalization on the received grid.

```
eqgrid = lteEqualizeMMSE(rxgrid,hest,nest);
```

Create a surface plot of the power of the equalized resource grid, in dB.

```
figure('Color','w');
helperPlotEqualizedResourceGrid(enb,eqgrid);
```



As can be seen the equalization flattened the power response across the resource grid.

See Also

`lteDLChannelEstimate` | `lteDLFrameOffset` | `lteEqualizeMMSE` | `lteFadingChannel` | `lteOFDMDemodulate` | `lteTestModel` | `lteTestModelTool`

Related Examples

- “Generate a Test Model”
- “Simulate Propagation Channels”
- “Find Channel Impulse Response”

More About

- “Propagation Channel Models”
- “Channel Estimation”