OFDM Modulation (OS12)

This component modulates a digital signal into multiple orthogonal sub-carriers.

Ports

Name and description	Port type	Signal type
Input - I 1	Input	M-ary
Input - Q 1	Input	M-ary
Output - I	Output	Electrical
Output - Q	Output	Electrical

Parameters

Main

Name and description	Default value	Default unit	Value range
Number of input ports Define the number of Users for the OFDM modulator	1	-	[1,1000]
Number of subcarriers Number of subcarriers used for transmission by each user	4	-	[1,100e6]
User defined position If True each user can define the position of its initial subcarrier	False	-	True, False
Position array Array containing the initial subcarrier positions for each user	0	-	[0,100e6]
Number of IFFT points Number of points used in the IFFT	64	-	[1,100e6]

Name and description	Default value	Default unit	Value range
Symmetric spectrum Defines if the input vector to the IFFT is constrained to have hermetian symmetry	False	-	True, False
Cyclic prefix Defines which guard period will be used	Symbol extension	-	Symbol extension, Zero values
Number of prefix points Defines the number of points used in the guard period	0	-	[0,100e6]

DAC

Name and description	Default value	Default units	Unit	Value range
Interpolation Defines the type of interpolation that will be used	Cubic	-	-	Linear, Cubic, Step
Smoothing filter Determines whether or not the smoothing filter is enabled	False	-	-	True, False

Simulation

| Name and description	Default value	Default units	Unit	Value range
Sample rate Frequency simulation window	Sample rate	Hz	Hz, GHz, THz	[0,+INF[
Enabled Determines whether or not the component is enabled	True	-	-	True, False

Graphs

Name and description	X Title	Y Title
OFDM FFT	Frequency (Hz)	Amplitude (a.u.)

Technical background

Orthogonal Frequency Division Multiplexing [1] is a multi-carrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. The following diagram describes the different parts of the OFDM modulator component.

Figure 1   OFDM modulator diagram
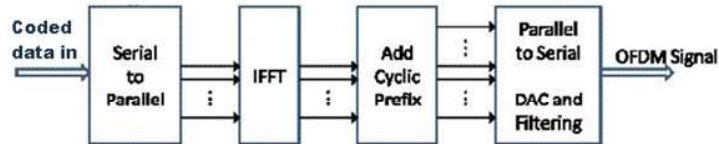
The input data can be in different modulations formats, for example: BPSK, QPSK, QAM, etc. This input serial symbol stream is shifted into a parallel format. Then the data is transmitted in parallel by assigning each symbol to one carrier in the transmission.

After mapping the spectrum, an inverse Fourier transform is used to find the corresponding time waveform. The cyclic prefix (guard period) can then be added to start each symbol.

The component allows the introduction of a cyclic extension of the symbol transmitted or a guard time with zero transmission. The parameter Number of prefix points will define how many points will be used in the guard period.

Different interpolation techniques (Step, Linear, and Cubic) can be used to function as the digital-to-analog converter. After the DAC, the parallel data is shifted back into the serial symbol stream. An internal smoothing filer is applied depending on whether the parameter "Smoothing filter" is enabled or not.

The figure below presents an example of OFDM transmitter using the OFDM modulator.

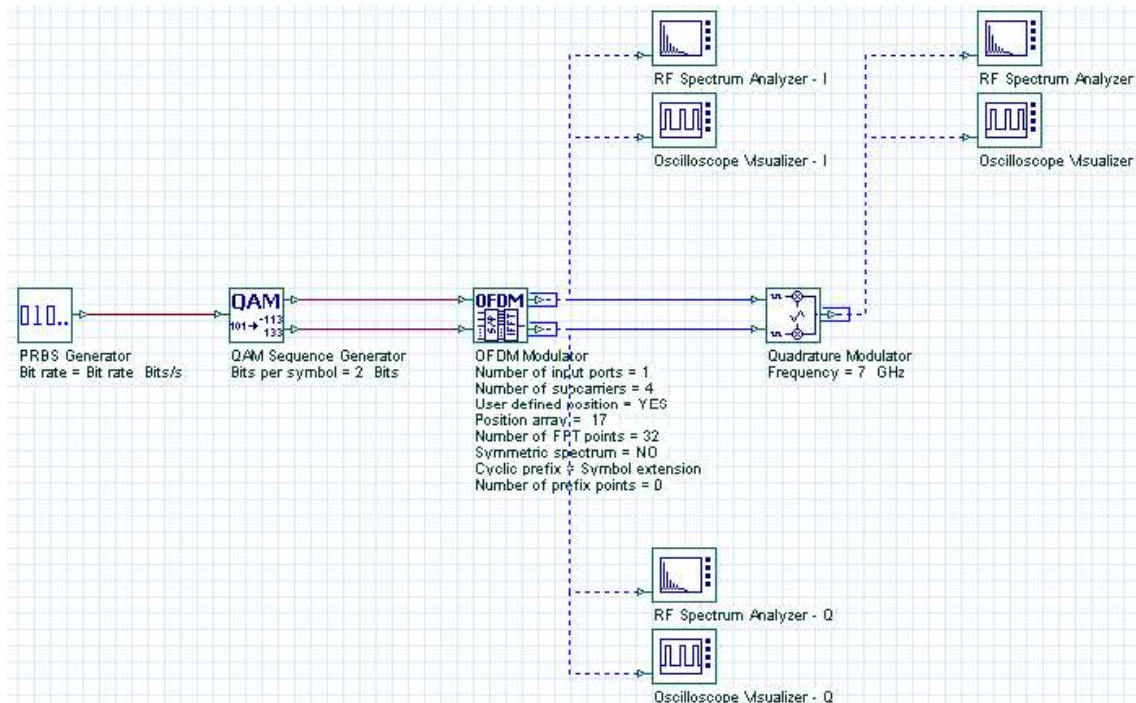**Figure 2   OFDM transmitter - System configuration**

Figure 2 shows the coding of 10 Gbps data to 4-QAM symbols. The 4-QAM symbols are then mapped to 4 subcarriers defined in the OFDM modulator. Finally, I and Q generated analog waveforms are converted to real-valued waveforms by mixing with a RF carrier. In this example, the OFDM modulator presents the following parameters:

Number of users = 1;

Number of subcarriers = 4;

Initial Position of the subcarriers in the spectrum = 17;

Number of IFFT points = 32;

Number of prefix points = 0;

The subcarrier frequencies are integer multiples of $1/T_{symbol}$, where T_{symbol} is the duration of an OFDM symbol, and in this case the frequency is 1.25 GHz. Since the initial position defined by the OFDM modulator is 17 (position "Number of IFFT points / 2 = 16" stands for a subcarrier frequency of 0), the initial subcarrier will be allocated at 1.25 GHz, and the subsequent subcarriers will be at 2.5 GHz, 3.75 GHz, and 5 GHz, respectively. The allocation of subcarriers, as shown in Figure 3, can also be visualized from the "Graphs" property of OFDM Modulator in project browser. Figure 4 shows the spectrum of the In-phase signal at the OFDM output as well as the up-converted OFDM signal spectrum.
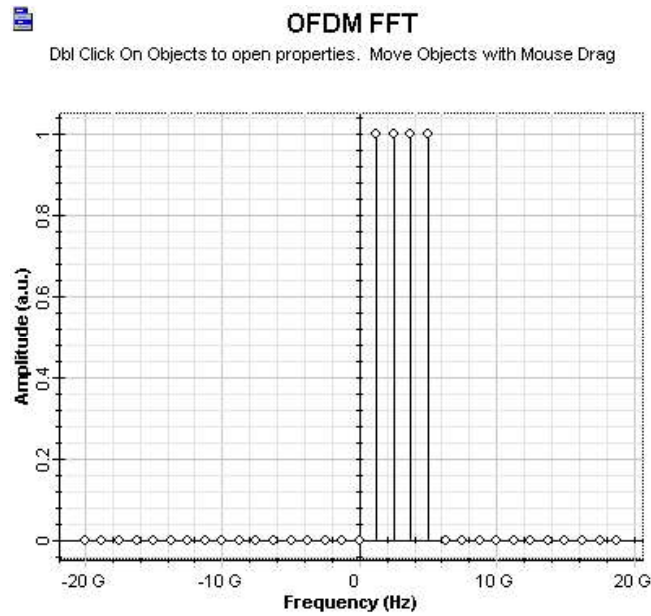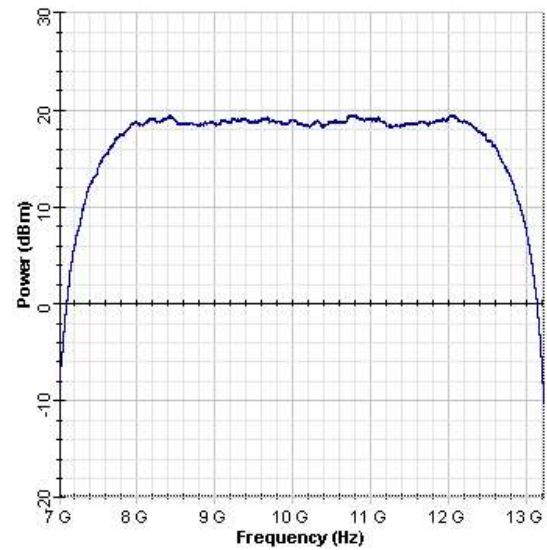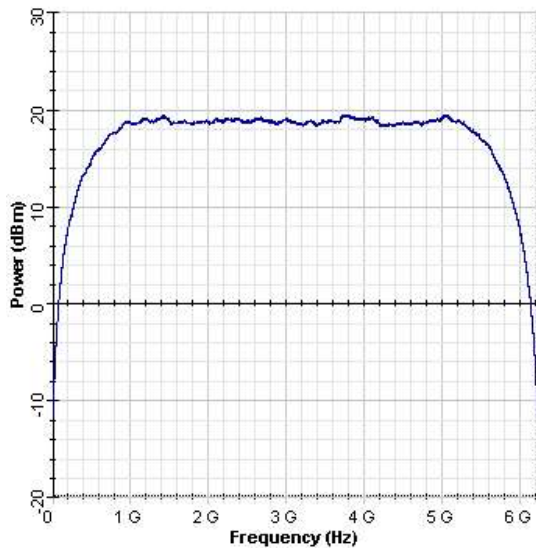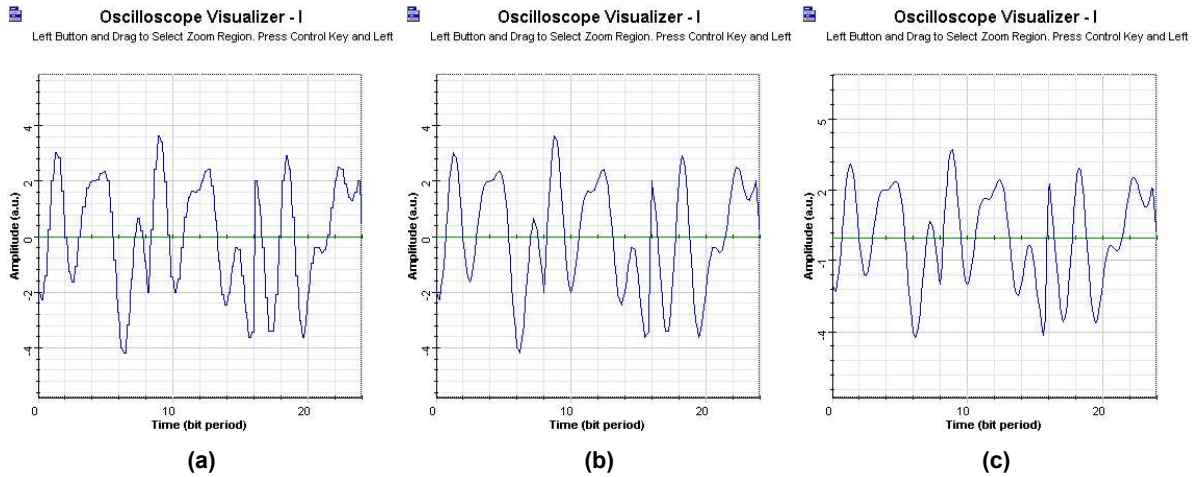
Figure 3   Allocation of OFDM subcarriers

Figure 4   (a) OFDM output (In-phase) (b) Up-converted OFDM output

(a)	(b)

The time-domain In-phase signal at the OFDM output is shown in Figure 5, with "Interpolation" set to Step, Linear, and Cubic, respectively.

Figure 5 OFDM time-domain output (In-phase) with "Interpolation" set to (a) Step, (b) Linear, and (c) Cubic, respectively.

(a)   (b)   (c)

In the simulation results presented above, no guard period was added to the simulation.

In the next simulation, the OFDM transmitter used was the same as presented above, however, different guard periods (no guard period, symbol extension with 16 points, and zero transmission guard time with 16 points) were added to the OFDM symbol. The time-domain In-phase signal at the OFDM output is presented in Figure 6.

BER Analysis

When performing the BER analysis of OFDM systems it is important to consider that when prefixes are added by the OFDM modulator, the time window (or sequence length) of the simulation is temporarily extended beyond that defined by the global parameter settings. When the same prefixes are then removed at the OFDM demodualtion stage, the original sequence length is re-established, however a portion of the information from the original data stream is lost. To avoid including this portion of the bit stream within the BER calculation it is required to ignore a certain portion of the trailing bits from the orginal bit sequence.

Within the BER Analyzer this can be set within the parameter *Ignore end bits* using the following formula:

$$Bits_{ignore} = S - int \left[\frac{n_{FFT} \times S}{n_{Sub} \times Bits_{Sym} \times (n_{FFT} + n_{Prefix})} \right] \times n_{Sub} \times Bits_{Sym}$$
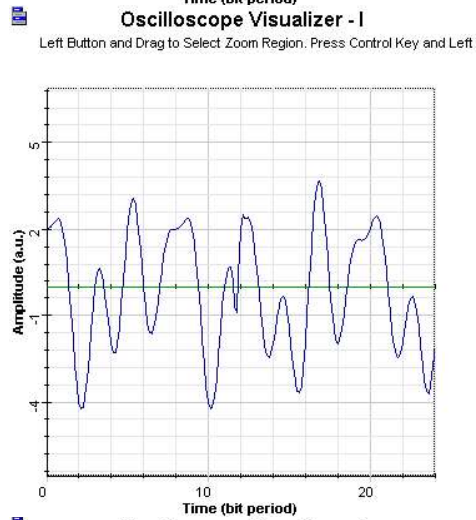
where S is the Sequence length, n_{FFT} is the number of FFT points, n_{Sub} is the number of subcarriers, and n_{Prefix} is the number of prefix points

Figure 6   Time-domain In-phase signal at the OFDM output with different type of guard periods
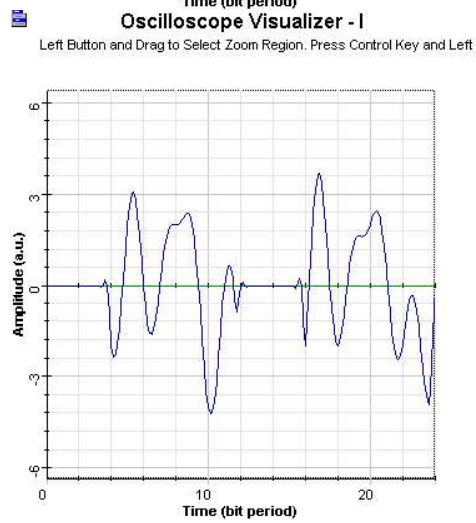
No
guard period
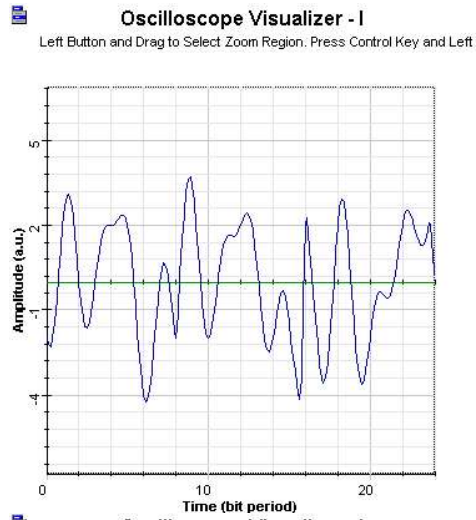
Symbol extension
guard period

Zero transmission
guard period

References

[1]   Armstrong, J. , "OFDM for Optical Communications", J. Lightwave Technology, vol. 27, pp. 189-204, Feb 2009.

OFDM Modulator Measured

This is an OFDM Modulator Measured component which modulates a digital signal into multiple orthogonal sub-carriers.

Ports

Name and description	Port type	Signal type	Supported Modes
Input - I 1	Input	M-Ary	-
Input - Q 1	Input	M-Ary	-
Output - I	Output	Electrical	-
Output - Q	Output	Electrical	-

Parameters

Main

Name and description	Default value	Default unit	Units	Value range
Maximum possible sub-carriers Table with the subcarrier index data	64	-	-	-
Symmetric spectrum Defines if the input vector to the IFFT is constrained to have hermetian symmetry	False	-	-	[True, False]
Cyclic prefix Defines which guard period will be used	Symbol extension	-	-	Symbol extension, Zero values
Number of prefix points Defines the number of points used in the guard period	0	-	-	[0, 1e+008]

DAC

Name and description	Default value	Default unit	Units	Value range
Interpolation Defines the type of interpolation that will be used	Cubic	-	-	Linear, Cubic, Step
Smoothing filter Determines whether or not the smoothing filter is enabled	False	-	-	[True, False]

Simulation

| Name and description	Default value	Default unit	Units	Value range
Sample rate Frequency simulation window	Sample rate	Hz	Hz, GHz, THz	[1, 1e+100]
Enabled Determines whether or not the component is enabled	True	-	-	[True, False]

Graphs

Name and description	X Title	Y Title
OFDM FFT	Frequency (Hz)	Amplitude (a.u.)

Technical Background

Orthogonal Frequency Division Multiplexing [1] is a multi-carrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. The following diagram describes the different parts of the OFDM Modulator Measured component.

Figure 1 OFDM modulator diagram
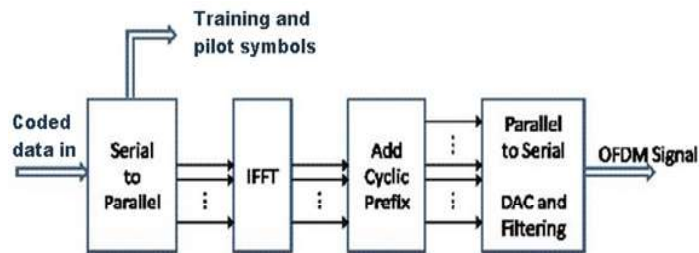
The input data can be in different modulations formats, for example: BPSK, QPSK, QAM, etc. This input serial symbol stream is shifted into a parallel format. Then the data is transmitted in parallel by assigning each symbol to one carrier in the transmission.

After mapping the spectrum, an inverse Fourier transform is used to find the corresponding time waveform. The cyclic prefix (guard period) can then be added to start each symbol.

The component allows the introduction of a cyclic extension of the symbol transmitted or a guard time with zero transmission. The parameter Number of prefix points defines how many points will be used in the guard period.

Different interpolation techniques (Step, Linear, and Cubic) can be used to function as the digital-to-analog converter. After the DAC, the parallel data is shifted back into the serial symbol stream. An internal smoothing filer is applied depending on whether the parameter "Smoothing filter" is enabled or not.

The figure below presents an example of OFDM transmitter using the OFDM Modulator Measured.

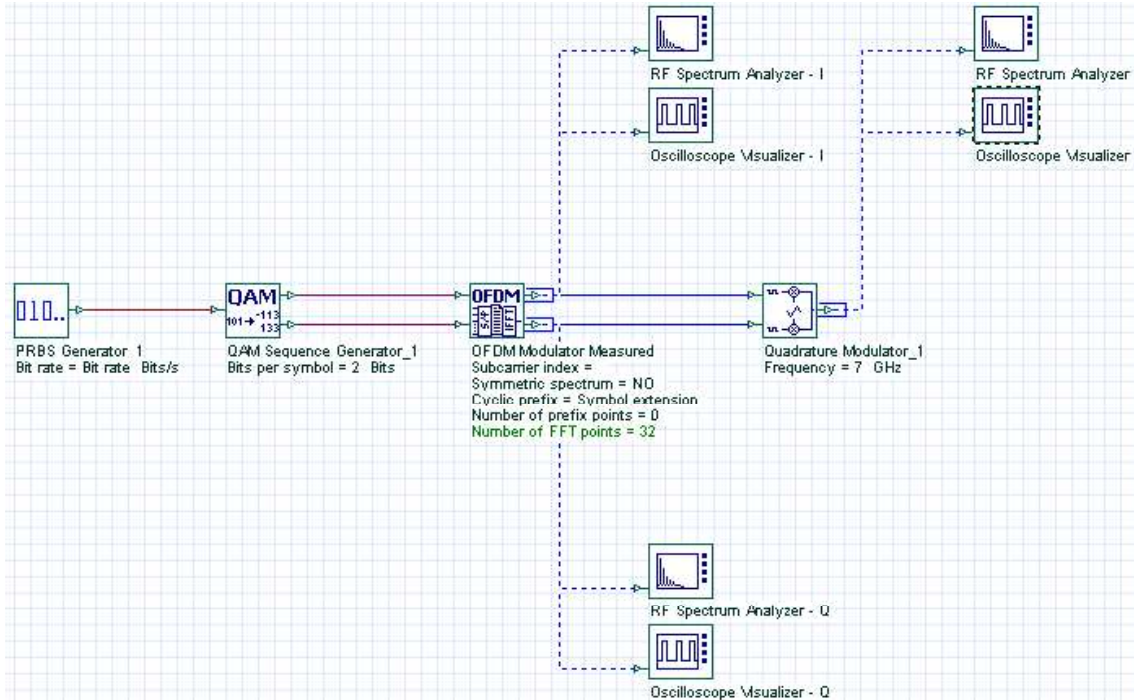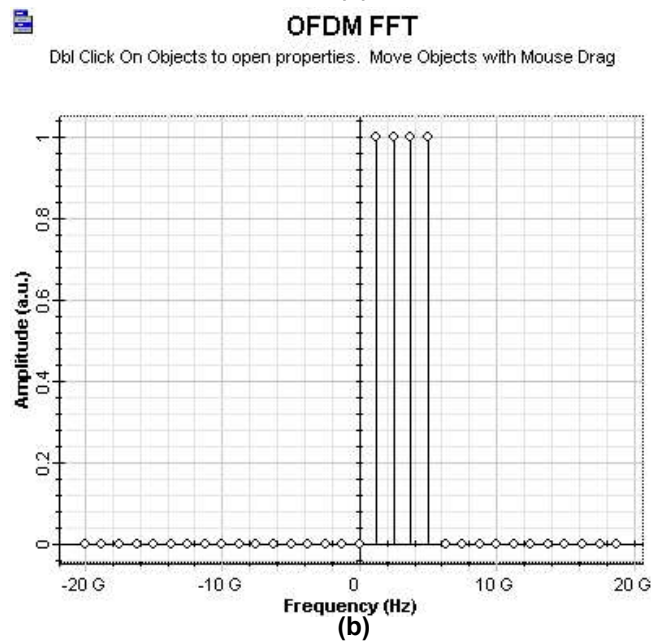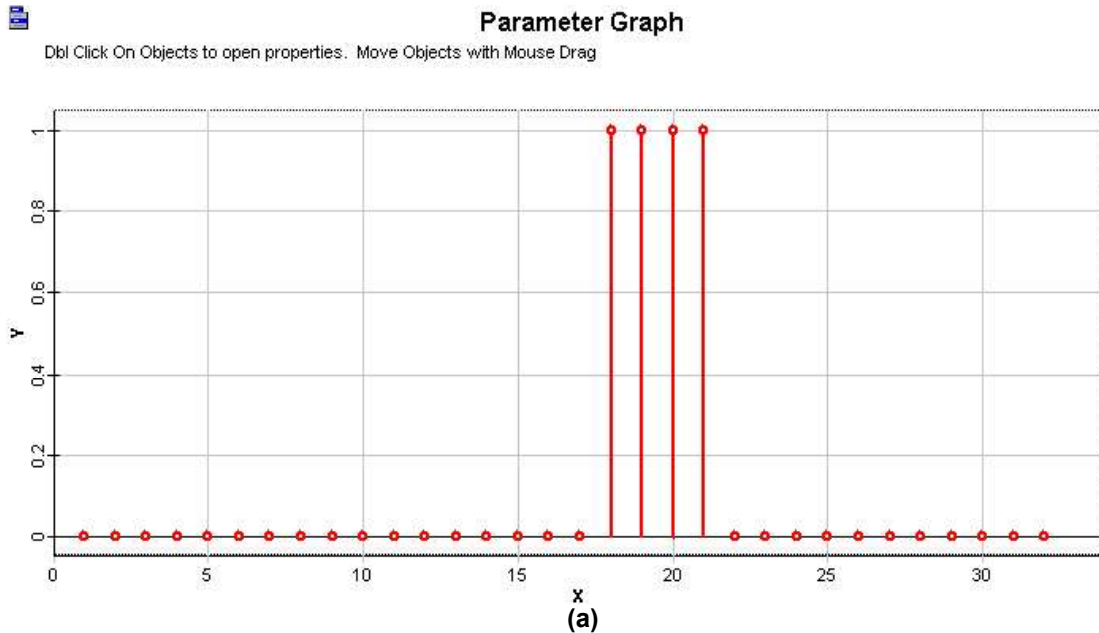**Figure 2   OFDM transmitter - System configuration**

Figure 2 shows the coding of 10 Gbps data to 4-QAM symbols. The 4-QAM symbols are then mapped to 4 subcarriers defined in the OFDM Modulator Measured. Finally, I and Q generated analog waveforms are converted to real-valued waveforms by mixing with a RF carrier.

In this example, the Number of prefix points = 0, and the subcarrier information are defined by the parameter "Subcarrier index", which uses a N x 1 table. The data in the tabel is visualized in Figure 3(a), with x-axis representing the row number of the table, and y-axis representing the values in the corresponding table cells. The table has 32 rows, which means "Number of IFFT points = 32". For the table cell values, there are four "1"s (all other are "0"s), which means "Number of subcarriers = 4".

Once we know the number of subcarriers, we can calculate the subcarrier frequencies. The subcarrier frequencies are integer multiples of $1/T_{symbol}$, where T_{symbol} is the duration of an OFDM symbol, and in this case the frequency is 1.25 GHz.

For the position of subcarriers, the definition here is slightly different from the component "OFDM Modulator". Since the numbering of rows starts from 1, not 0, here row number "**Number of IFFT points / 2 + 1 = 17**" stands for a subcarrier frequency of 0. In the table, the value of the cells located at row 18, 19, 20, and 21 is "1", so the subcarriers are located at 1.25 GHz, 2.5 GHz, 3.75 GHz, and 5 GHz, respectively.

Figure 3   (a) Loaded table data (b) Allocation of OFDM subcarriers

Parameter Graph

Dbl Click On Objects to open properties. Move Objects with Mouse Drag

(a)

OFDM FFT

Dbl Click On Objects to open properties. Move Objects with Mouse Drag

(b)

The allocation of subcarriers, as shown in Figure 3(b), can be visualized from the "Graphs" property of OFDM Modulator Measured in project browser. Figure 4 shows the spectrum of the In-phase signal at the OFDM output as well as the up-converted OFDM signal spectrum.

The time-domain In-phase signal at the OFDM output is shown in Figure 5, with "Interpolation" set to Step, Linear, and Cubic, respectively.

Figure 4   (a) OFDM output (In-phase) (b) Up-converted OFDM output

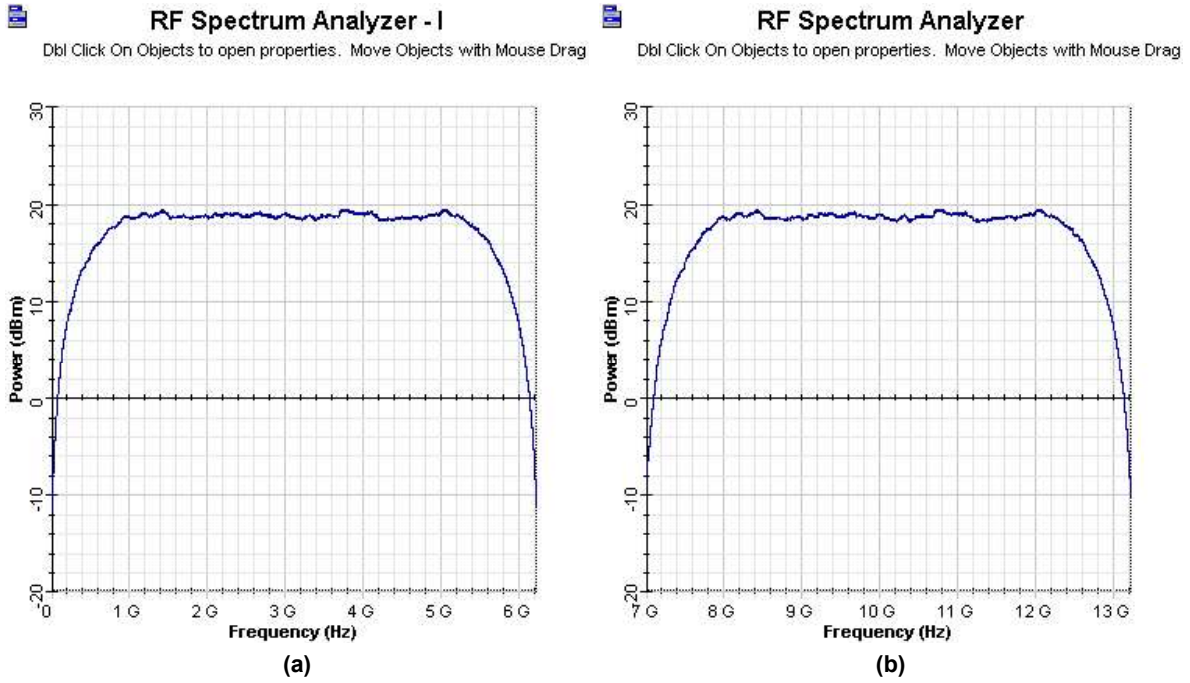(a)   (b)
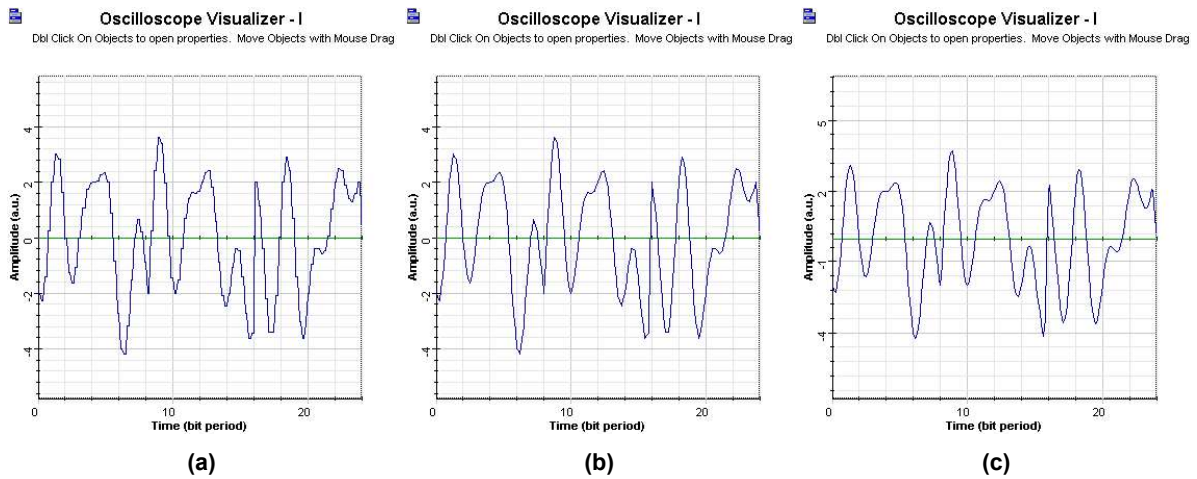
Figure 5   OFDM time-domain output (In-phase) with "Interpolation" set to (a) Step, (b) Linear, and (c) Cubic, respectively.

(a)   (b)   (c)

In the next simulation, the OFDM transmitter used was the same as presented before, however, different guard periods (no guard period, symbol extension with 16 points, and zero transmission guard time with 16 points) were added to the OFDM symbol. The time-domain In-phase signal at the OFDM output is presented in Figure 6.

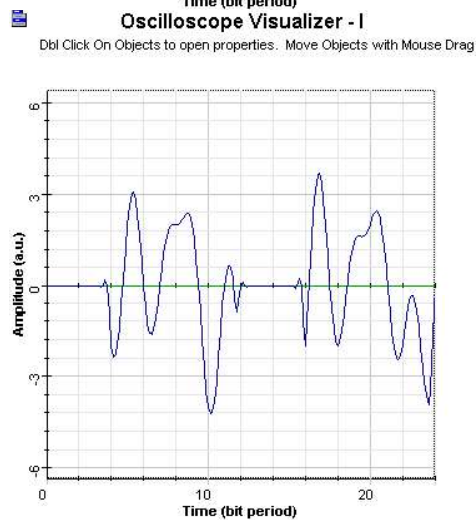**Figure 6   Time-domain In-phase signal at the OFDM output with different type of guard periods**

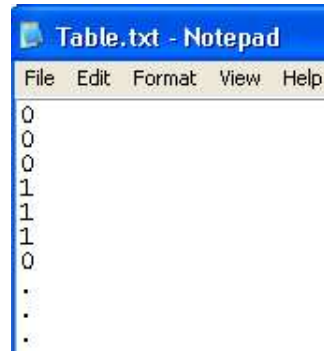**No
guard period**
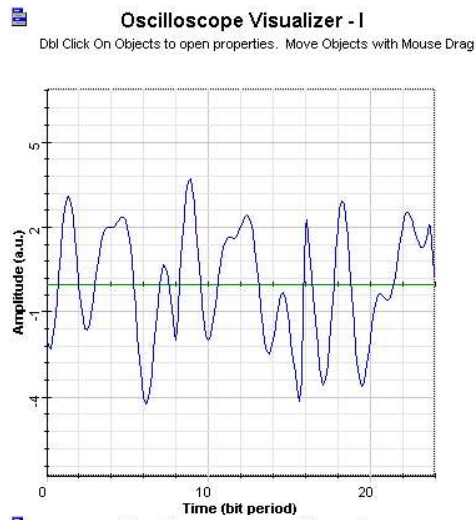
**Symbol extension
guard period**
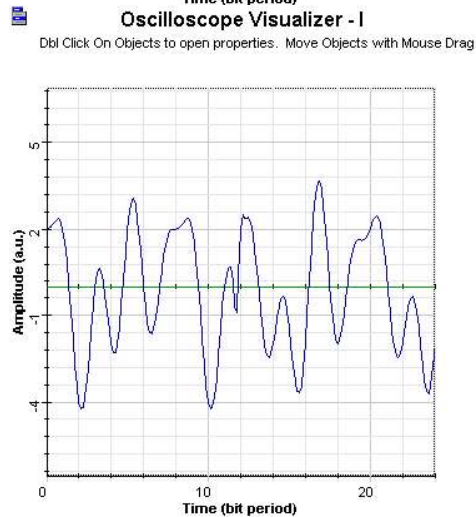
**Zero transmission
guard period**

The format of the file for the loaded sub-carrier index data can be seen as follows:

Figure 7   Example of the file for the loaded sub-carrier index data

References

[1]   Armstrong, J. , "OFDM for Optical Communications", J. Lightwave Technology, vol. 27, pp. 189-204, Feb 2009.

OFDM Modulation

This component modulates a digital signal into multiple orthogonal sub-carriers.

Ports

Name and description	Port type	Signal type
Input - I 1	Input	M-ary
Input - Q 1	Input	M-ary
Output - I	Output	Electrical
Output - Q	Output	Electrical
Output - Training	Output	Electrical

Parameters

Main

Name and description	Default value	Default unit	Value range
Maximum possible sub-carriers Table with the sub-carrier index data	64	-	-
Symmetric spectrum Defines if the input vector to the IFFT is constrained to have hermitian symmetry	False	-	-
Cyclic prefix Defines which guard period will be used	Symbol extension		Symbol extension, Zero values
Number of prefix points Defines the number of points used in the guard period	0	-	-
Average OFDM power	0	dBm	W, mW, dBm
Input port parameters			
Number of input ports (users)	1	-	-

Name and description	Default value	Default unit	Value range
Number of sub-carriers per port	1		
Sub-carrier locations	1		
Equalize port powers	TRUE		TRUE, FALSE
Parameters for dual polarization system			
Dual polarization	FALSE		TRUE, FALSE
Polarization	X		X, Y
Number of training symbols	0		

DAC

Name and description	Default value	Default units	Unit	Value range
Interpolation Defines the type of interpolation that will be used	Cubic	-	-	Linear, Cubic, Step
Smoothing filter Determines whether or not the smoothing filter is enabled	False	-	-	True, False

Simulation

Name and description	Default value	Default units	Unit	Value range
Sample rate Frequency simulation window	Sample rate	Hz	Hz, GHz, THz	[0,+INF[
Enabled Determines whether or not the component is enabled	True	-	-	True, False

Graphs

| Name and description	X Title	Y Title
OFDM FFT	Frequency (Hz)	Amplitude (a.u.)

Technical background

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier transmission technique[1], which divides the available spectrum into many orthogonal subcarriers, each one being modulated by a low rate data stream. The purpose of this format is to

significantly reduce inter-carrier and inter-symbol interference (ICI and ISI). **Figure 1** shows a schematic of the OptiSystem *OFDM Modulation* component

Figure 1   OFDM modulator diagram
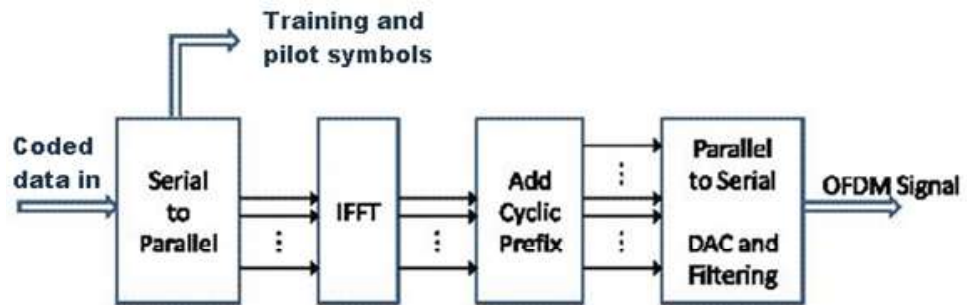
Coded data in

The input data is a serial stream of coded symbols. The available formats for the OFDM demodulation component are: BPSK, QPSK, 8PSK, 16PSK, 4QAM, 16QAM, 64QAM. It is possible to use multiple users/ports at different modulation formats. However, care must be taken to ensure each user sends their data at the same symbol rate (see **Example #2**).

Serial to Parallel

The purpose of this block is two-fold:

- It copies the input data onto an output channel that can be directly read in by the demodulation component. Since these are the known initial symbols, the demodulator can use these for training (preamble) and pilot symbols. If you are going to perform dual polarization analysis, then some of the initial training symbols will have to be modified for the demodulator (see Example #3 for details).
- It converts the input serial data stream into a parallel stream of OFDM symbols as pictorially represented in **Figure 2**.

**Figure 2   Serial to parallel block**
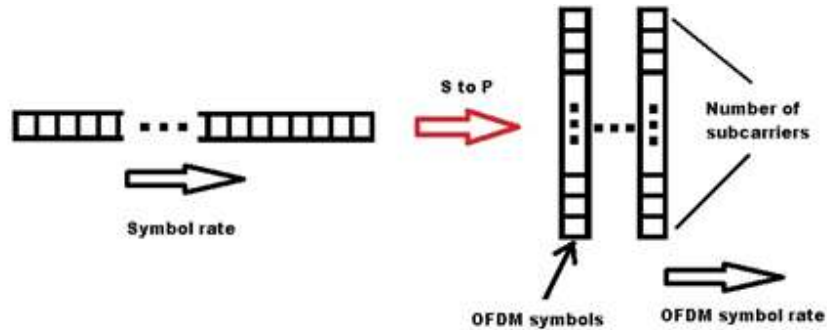
IFFT

After the data has been placed into a number of OFDM symbols, OFDM symbols are allocated to subcarriers which correspond to orthogonal frequencies (0 ISI) for the system. To transmit this data along an optical carrier, each OFDM symbol must be converted from the frequency domain to the time domain. This is accomplished by applying an inverse Fourier transform on each OFDM symbol.

Add Cyclic Prefix

We now have all OFDM symbols in the frequency domain. Due to the dispersive nature of the optical channels (such as a fiber), it is desirable to add a guard extension or, preferably, a cyclic prefix to each OFDM time-domain symbol to reduce the ISI and ICI [1]. This is represented in **Figure 3**.

Figure 3   Cyclic prefix
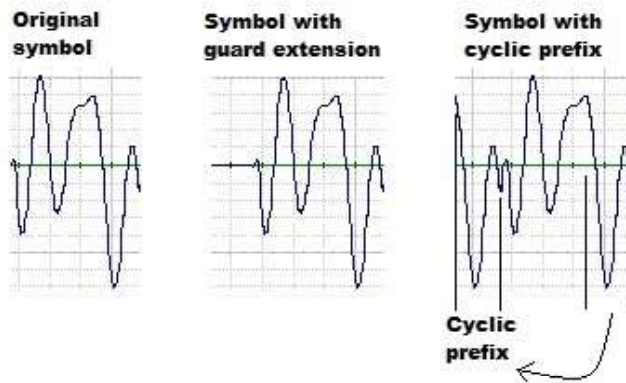
Parallel to Serial, DAC and Filtering

Each time-domain OFDM symbol is now placed into a serial stream. Different interpolation techniques (Step, Linear and Cubic) can be used to function as the digital-to-analog converter. An internal smoothing filter is applied if the parameter *Smoothing filter* is selected.

Important considerations

Symbol and bit rates

It is crucial to correctly set the symbol and bit rates. This applies not only to the global values but to the settings within the bit stream generators associated with the OFDM system.

Within one OFDM symbol period, all the individual symbols required for that OFDM symbol must be sent with:

*OFDM symbol period = Individual symbol period * Total number of sub-carriers possible*

Two examples follow for an QPSK system. In these examples the global bit rate is 40Gbit/s. Since this is an QPSK modulation (2 bits per symbol), the symbol rate will be 20Gsym/s. In both cases there are a total of 128 sub-carriers available such that:

*OFDM symbol period = Symbol period * 128 = 128/(Symbol rate) = 2 * 128 /Global bit rate.*

In the first case (see **Figure 4**) we are using all 128 subcarriers. Thus to fill up an entire OFDM symbol in the OFDM symbol period, the generating PRBS bit rate is set to the Global bit rate (*Bit rate *128 / 128 = Bit rate*). In the second case, we only need to fill up 80 of the sub-carriers (the others will be set to zero automatically) in one OFDM symbol period. Therefore the PRBS will generate bits at a slower rate than the global bit rate (*Bit rate * 80 /128*)

Figure 4   QPSK Example

Global bit rate: 40Gbit/s, Global symbol rate: 20Gsym/s
Symbol rate = 1/2 bit rate since QPSK
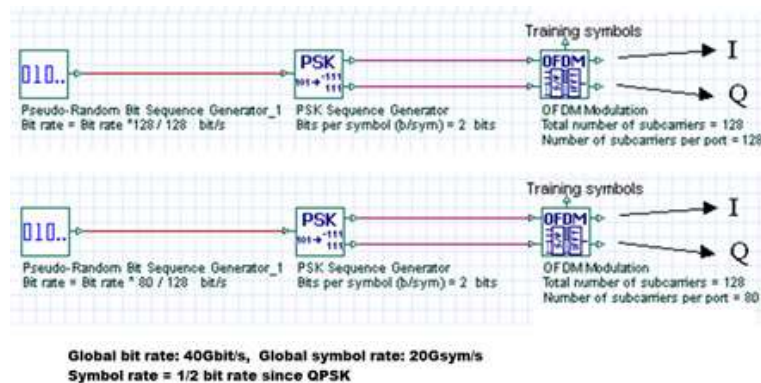
In the next example (see **Figure 5**), we have a similar situation except that the symbol rate is now ¼ of the bit rate due to the 16QAM modulation. For these two examples, the bit rate of the PRBS generator does not depend on the modulation format, but rather on the total number of subcarriers available and the amount actually used.

Figure 5   QAM Example
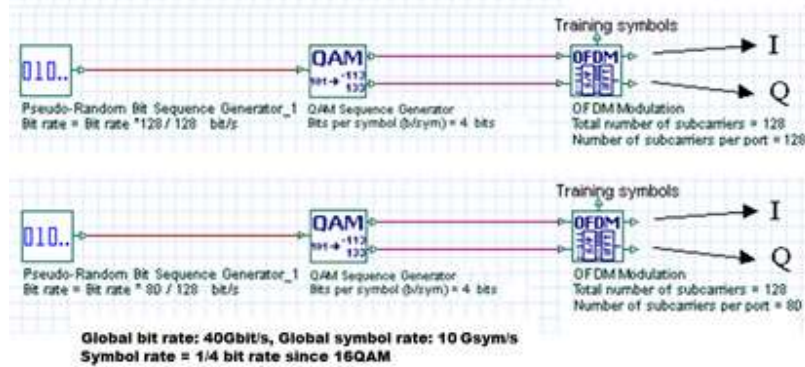
When using multiple ports and mixed modulations, the situation becomes more complicated. However, the principle that all relevant symbols must be filled into their respective sub-carriers still holds. See **Example #2** for the case of two ports and mixed modulations.

Sub-carrier locations

The **OFDM Modulation** component provides you with a number of options to specify the locations of the subcarriers being used. Examples of the notation used include:

Notation	Sub-carrier allocation
1, 5, 10	Sub-carriers placed at positions 1, 5, and 10
1,5,10,21-30	Sub-carriers placed at positions 1, 5, 10 and 21 to 30
1,5,10,21-30x2	Sub-carriers placed at positions 1, 5, 10, 21, 23, 25, 27, 29 *"x2" means that positions are skipped by two locations*
1#4x3	Sub-carriers placed at positions 1, 4, 7, and 10 *"#" represents the number of sub-carriers to be positioned*
1,5,10;31,35,40	Port 1 has positions 1, 5, and 10 Port 2 has positions 31, 35 and 40 *Semi-colons are used to separate the sub-carriers by port number*

Example #1: Single polarization one port.

In this example, an QPSK sequence is sent to the **OFDM modulation** component. There are 128 possible subcarriers available. Of these, 80 are used and placed at locations 25 to 104. (Note: setting the subcarrier locations as *25#80* will give the same results).

Figure 6   Example of single polarization QPSK system and a representation of the sub-carrier locations
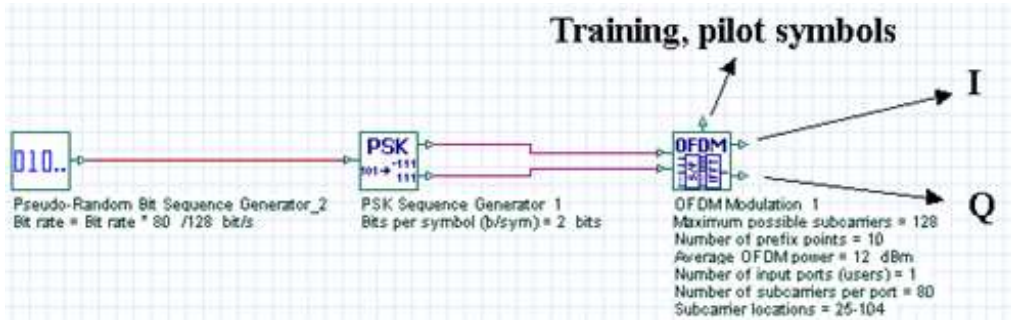
Of particular importance are the settings for the various Symbol rates and Bit rates. Note these properties in the global layout

The global Bit rate is 40 Gbit/s. Since this is QPSK modulation, the time-domain OFDM symbols will be transmitted at the Symbol rate of 20 Gsym/s. The serial to parallel OFDM symbol generator works by first collecting enough serial symbols to fill an OFDM symbol. These then undergo an IFFT and are prefixed. The serialization is repeated again until all input serial symbols are processed. If we wish to fill all 128 of the sub-carriers, then the PRBS generator must be set to produce bits at a rate of the global Bit rate. However, in this case we only need to produce 80 symbols in the time it takes to create one OFDM symbol. Thus, the PRBS is set at a rate of *Bit rate*80/128*.

Example #2: Single polarization, two ports.

In this example the total number of subcarriers available is again 128. The subcarriers for the first port are located at 25 to 64 (we can use 25-64 or 25#40). The subcarriers for the second port are located at 65 to 104 (we can use 65-104 or 65#40). This creates a total of 80 subcarriers.

Figure 7   An example of a mixed modulation single polarization OFDM modulation system and a representation of the sub-carrier locations
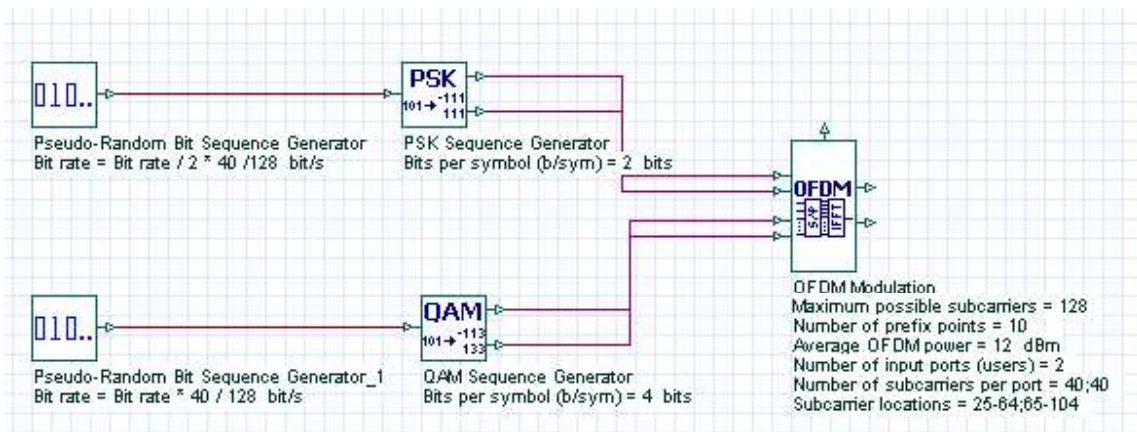
The port parameters are separated by a semicolon. The parameter *Equalize port powers* is checked which means that each port will be normalized to the same average power over their subcarriers.

Disp	Name	Value	Units
✓	Maximum possible subcar	128	
☐	Symmetric spectrum	☐	
☐	Cyclic prefix	Symbol extension	
✓	Number of prefix points	10	
✓	Average OFDM power	12	dBm
	Input port parameters		
✓	Number of input ports (us	2	
✓	Number of subcarriers per	40;40	
✓	Subcarrier locations	25-64;65-104	
☐	Equalize port powers	✓	
	Parameters for dual polarization system		
☐	Dual polarization	☐	
☐	Polarization	X	
☐	Number of training symbol	0	

Again, particular attention must be paid to the Bit rates of the PRBS, especially when using mixed modulation to make sure the symbols are transmitted to the modulator at the correct rate. In this case the output time domain signal will be transmitted at the *16QAM Symbol rate = Bit rate / 4*.

During the time that the OFDM symbol will be filled only 40 QPSK symbols and 40 16QAM symbols need to be sent to the modulator. In addition, QPSK has a symbol rate twice that of the 16QAM thus the bit rate of the PRBS into the QPSK coder is *Bit rate / 2*40/128* and that of the PRBS into the 16QAM coder is *Bit rate*40 /128*.

Example #3: Dual polarization, two ports.

This example is similar to **Example #2**, except that we must have a modulator for the X and the Y polarization (only the X polarization component is shown in **Figure 8**). Please refer to the sample files in "OptiSystem 13 Samples/Advanced modulation systems/OFDM systems" for full dual polarization examples.

Figure 8   An example of a mixed modulation single polarization OFDM modulation system and a representation of the sub-carrier locations
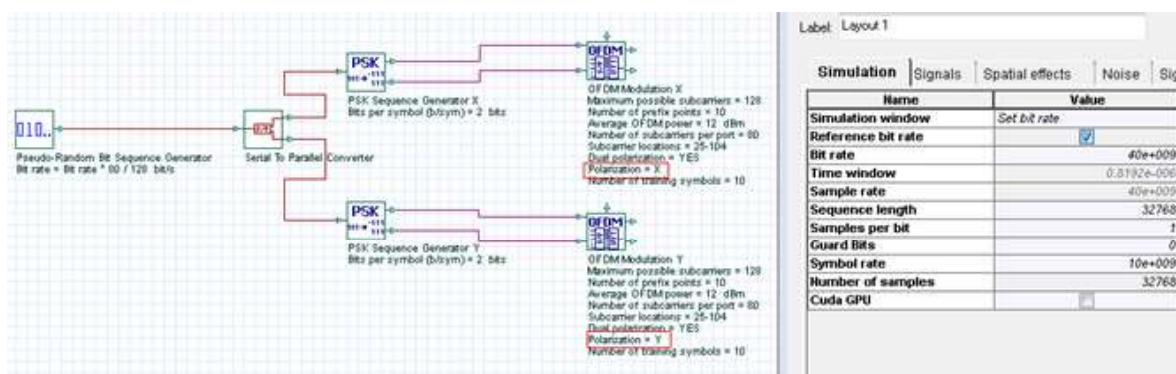
In the case of the modulator being used in a single polarization system, it is unnecessary to specify the polarization or number of training symbols. However if we are using the **OFDM Demodulation Dual Polarization** component it is necessary to set the correct training symbols to account for any polarization mixing.

In the **OFDM Demodulation Dual Polarization** component, the training symbols must follow the format:

$$t_k(i) = \begin{bmatrix} t_{X,k}(i) \\ t_{Y,k}(i) \end{bmatrix}, \; t_k\left(i + \frac{N_T}{2}\right) = \begin{bmatrix} t_{X,k}(i) \\ -t_{Y,k}(i) \end{bmatrix}, \; i = 1 \ldots \frac{N_T}{2}$$

where k is the sub-carrier index, i is the training symbol index and N_T is the number of training symbols. Choosing Dual polarization "X" or "Y" ensures that the X and Y polarization symbols are respectively set correctly.

References

[1] X. Liu, F. Buchali, and R. W. Tkach, "Improving the nonlinear tolerance of polarization-Division-Multiplexed CO-OFDM in long-haul fiber transmission," J. Lightw. Tech., vol. 27, no. 16, pp. 3622-3640, 2009.

[2] X. Liu and F. Buchali, "A novel channel estimation method for PDM-OFDM enabling improved tolerance to WDM nonlinearity," presented at the OFC'09, paper OWW5