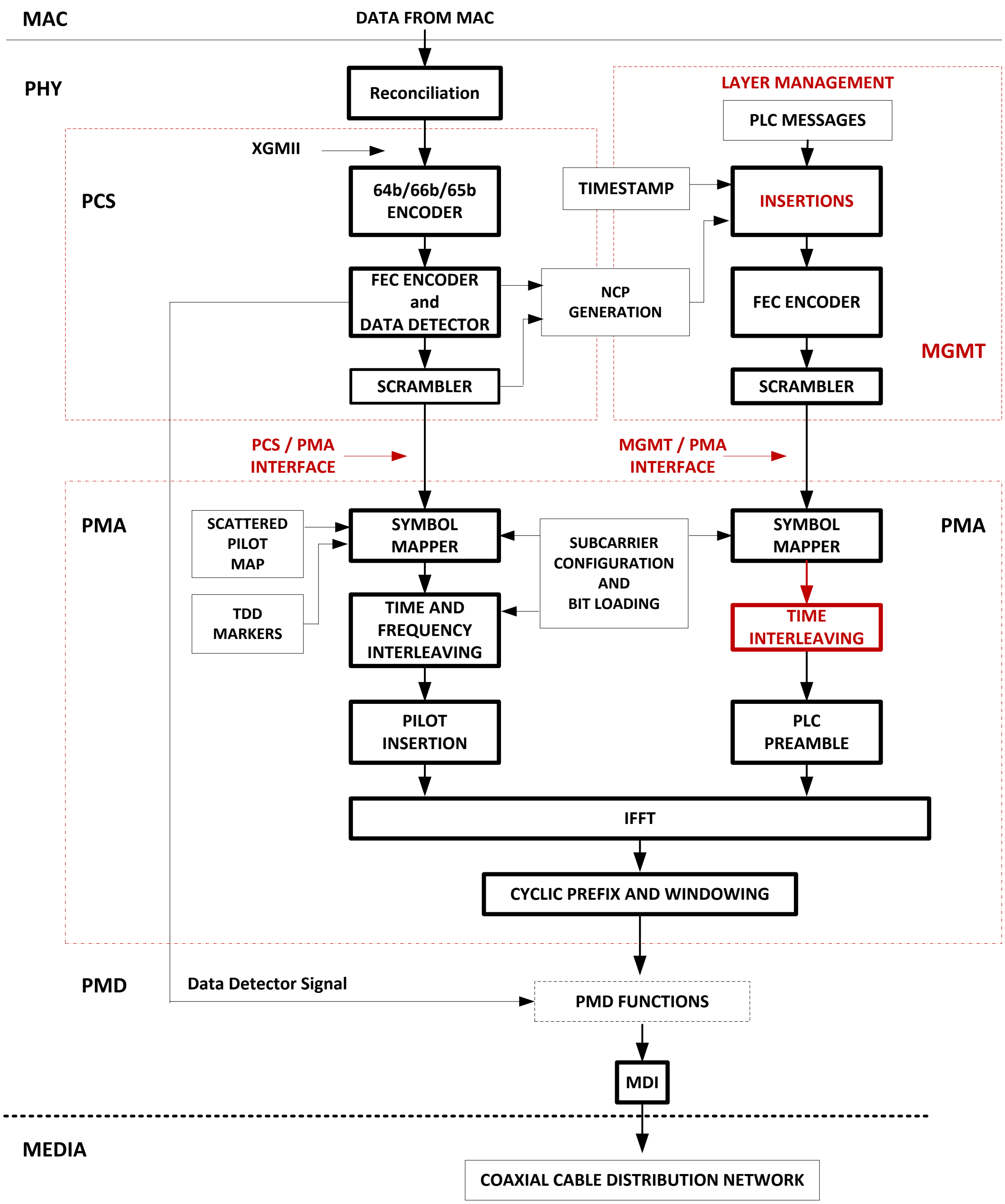
[Downstream Baseline Proposal Text – to be included in P802.3bn draft.]

[NOTE: ~~Crossed out / strikethrough~~ text should not be included in the draft. With the exception that this document presumes the 8K FFT will be removed based on Task Force preference. If not removed, the relevant stricken text needs to be un-stricken and included in the document.]

Downstream PHY Processing



Downstream Exclusion Band Rules

- There has to be at least one contiguous modulated OFDM bandwidth of 22 MHz or greater, which will enable an OFDM channel bandwidth of 24 MHz including guardbands.
- Exclusion bands separate contiguous modulation bands.
- The minimum contiguous modulation band has to be 2 MHz.
- Exclusion bands are a minimum of 1 MHz but increment above 1 MHz by granularity of individual subcarrier of 50 kHz.
- Exclusion bands plus individually excluded subcarriers are limited to 20% or less of spanned modulation spectrum, where the spanned modulation spectrum is defined as: frequency of maximum active subcarrier – frequency of minimum active subcarrier.
- The number of individually excluded subcarriers is limited by the following:
    - The total spectrum of individually excluded subcarriers cannot exceed 5% of any contiguous modulation spectrum.
    - The total spectrum of individually excluded subcarriers cannot exceed 5% of a 6 MHz moving window across the contiguous modulation spectrum.
    - The total spectrum of individually excluded subcarriers cannot exceed 20% of a 1 MHz moving window across the contiguous modulation spectrum.
- The 6 MHz of contiguous spectrum reserved for the PLC cannot have any exclusion bands or excluded subcarrier.

Time and Frequency Synchronization

The CLT MUST lock the 204.8 MHz Downstream OFDM Clock to the 10.24 MHz CLT Master Clock (see Table 1-1).

The CLT MUST lock the Downstream OFDM RF transmissions to the 10.24 MHz CLT Master Clock (see Table 1-1).

[NOTE for Editors: Table 1-1 or the values contained may already be present in the draft in another location or form. Ensure that values are consistent.]

Table 1-1 - Downstream OFDM parameters

Parameter	4K mode	~~8K mode~~
Downstream master clock frequency	10.24 MHz	
Downstream Sampling Rate (fs)	204.8 MHz	
Downstream Elementary Period (Tsd)	1/(204.8 MHz)	
Channel bandwidths	24 MHz … 192 MHz	
Minimum contiguous modulation band (see Section 7.2.5.1)	2 MHz	
IDFT size	4096	~~8192~~
Subcarrier spacing	50 kHz	~~25 kHz~~
FFT duration (Useful symbol duration) (Tu)	20 µs	~~40 µs~~
Number of active subcarriers in signal (192 MHz channel) Values refer to 190 MHz of used subcarriers.	3800	~~7601~~

Parameter	4K mode	~~8K mode~~
Spacing between first and last active subcarrier	190 MHz	
Cyclic Prefix	~~0.9375 µs (192 * T_{sd})~~ 1.25 µs (256 * T_{sd}) 2.5 µs (512 * T_{sd}) 3.75 µs (768 * T_{sd}) ~~5 µs (1024 * T_{sd})~~	
Windowing	Tukey raised cosine window, embedded into cyclic prefix 0 µs (0 * T_{sd}) 0.3125 µs (64 * T_{sd}) 0.625 µs (128 * T_{sd}) 0.9375 µs (192 * T_{sd}) 1.25 µs (256 * T_{sd})	

Subcarrier Clocking

The "locking" of subcarrier "clock and carrier" are defined and characterized by the following rules:

Each OFDM symbol is defined with a Subcarrier Clock frequency of nominally 20 usec. For each OFDM symbol, the Subcarrier Clock period (us) may vary from nominal with limits defined in this section [Time and Frequency Synchronization].

- The number of cycles of each subcarrier generated by the CLT during one period of the Subcarrier Clock (for each OFDM symbol) MUST be an integer number.
- The CLT Subcarrier Clock MUST be synchronous with the 10.24 MHz Master Clock defined by:
  Subcarrier Clock frequency = (M/N)*Master Clock frequency where M = 20, and N = 8192
- The limitation on the variation from nominal of the Subcarrier Clock frequency at the output connector is defined in this section [Time and Frequency Synchronization].
- Each OFDM symbol has a cyclic prefix which is an integer multiple of 1/64th, of the Subcarrier Clock period.
- Each OFDM symbol duration is the sum of one Subcarrier Clock period and the cyclic prefix duration.
- The number of cycles of each subcarrier generated by the CLT during the OFDM symbol duration (of each symbol) MUST be K+K*L/64, where K is an integer related to the subcarrier index and frequency upconversion of the OFDM channel, and L is an integer related to the cyclic prefix. (K is an integer related to the subcarrier index and increases by 1 for each subcarrier).
- The phase of each subcarrier within one OFDM symbol is the same, when each is assigned the same constellation point (I + jQ), relative to the Reference Time of the OFDM symbol. There is nominally no change in phase on each subcarrier for every cycle of 64 OFDM symbols, when both are assigned the same I + jQ, and referenced to the Reference Time of their respective OFDM symbol.

Downstream OFDM Symbol Clock Jitter

The CLT MUST adhere to the following double sideband phase noise requirements for the downstream OFDM symbol clock over the specified frequency ranges:

• < [-21 + 20*log (f_{DS} /204.8)] dBc (i.e., < 0.07 nSec RMS) 10 Hz to 100 Hz

• < [-21 + 20*log (f_{DS} /204.8)] dBc (i.e., < 0.07 nSec RMS) 100 Hz to 1 kHz

• < [-21 + 20*log (f_{DS} /204.8)] dBc (i.e., < 0.07 nSec RMS) 1 kHz to 10 kHz

• < [-4 + 20*log (f_{DS} /204.8)] dBc (i.e., < 0.5 nSec RMS) 10 kHz to 100 kHz

• < [2 + 20*log (f_{DS} /204.8)] dBc (i.e., < 1 nSec RMS) 100 kHz to (f_{DS} /2),

where f_{DS} is the frequency of the measured clock in MHz.

The CLT MUST use a value of f_{DS} that is an integral multiple or divisor of the downstream symbol clock. For example, an f_{DS} = 409.6 MHz clock may be measured if there is no explicit 204.8 MHz clock available.

Downstream Timing Acquisition Accuracy

The downstream clock timing is defined with respect to downstream OFDM frame.

The CNU MUST be able to adjust its clock to synchronize its own clock timing with OFDM downstream frame for proper operation.

The CNU MUST be able to acquire downstream clock timing from downstream traffic (pilots, preambles, or mixed pilots, preambles, and data).

The CNU MUST have a timing acquisition resolution better than 1 sample (4.8828125 ns).

Downstream Carrier Frequency Acquisition Accuracy

The CNU MUST be able to acquire the carrier frequency from downstream (pilots, preambles, or mixed pilots, preambles and data).

Downstream Acquisition Time

The CNU MUST achieve downstream signal acquisition (frequency and time lock) in less than 60s for a device with no previous network frequency plan knowledge.

In other cases it is expected that the CNU would be able to achieve downstream acquisition in less than 30s.

Symbol Mapping to QAM Constellations

Mapping Bits to QAM Constellations

The mapping of bits to QAM constellations is carried out in the Symbol Mapper.

[Note to Editors: QAM constellation mapping as per prodan_3bn_02_1113.pdf as per TD#103. More text is likely needed.]

Once FEC encoded codewords have been created, the codewords are placed into OFDM symbols. Because each subcarrier in an OFDM symbol can have a different QAM modulation, the codewords must first be demultiplexed into parallel cell words; these cell words are then mapped into constellations based on the corresponding bit loading pattern of the subcarrier's QAM constellation.

Transmitter Bit Loading for Symbol Mapping

~~All subcarriers of an OFDM symbol may not have the same constellation; t~~The constellation for each subcarrier is given in a table that details the bit loading pattern. This bit-loading pattern may change and is signaled via the PLC.

Excluded subcarriers are subcarriers that are forced to zero-valued modulation at the transmitter. Non-excluded subcarriers are referred to as active subcarriers. Active subcarriers are never zero-valued. The notation $S^{(E)}$ is used here to define the set of excluded subcarriers. This set will never be empty because there are always excluded subcarriers at the edges of the OFDM channel.

Continuous pilots are pilots that occur at the same frequency location in every OFDM symbol. The notation $S^{(C)}$ is used here to define the set of continuous pilots.

The PLC resides in a contiguous set of subcarriers in the OFDM channel. The CLT adds the PLC to the OFDM channel after time and frequency interleaving; the CNU extracts the PLC subcarriers before frequency and time de-interleaving. These subcarriers occupy the same spectral locations in every symbol. The notation $S^{(P)}$ is used here to define the set of PLC subcarriers.

For bit loading, continuous pilots and the PLC are treated in the same manner as excluded subcarriers; hence, the set of subcarriers that includes the PLC, continuous pilots and excluded subcarriers is defined as:

$$S^{(PCE)} = S^{(P)} \cup S^{(C)} \cup S^{(E)}$$

The subcarriers in the set $S^{(PCE)}$ do not carry data. The other subcarriers that do not carry data are the scattered pilots. However, scattered pilots are not included in the set $S^{(PCE)}$ because they do not occupy the same spectral locations in every OFDM symbol.

The modulation order of the data subcarriers is defined using a bit-loading profile. This profile includes the option for zero bit-loading. Such subcarriers are referred to as zero-bit-loaded subcarriers and are BPSK modulated using the randomizer LSB, as described in Section ***Randomization***.

All active subcarriers with the exception of pilots are transmitted with the same average power. Pilots are transmitted boosted by a factor of 2 in amplitude (approximately 6 dB).

Scattered pilots do not occur at the same frequency in every symbol; in some cases scattered pilots will overlap with continuous pilots. If a scattered pilot overlaps with a continuous pilot, then that pilot is no longer considered to be a scattered pilot. It is treated as a continuous pilot.

The following notation is used here and applies to a single OFDM channel:

N: The total number of subcarriers in the OFDM symbol, equaling either 4096 or 8192

N_C: The number of continuous pilots in an OFDM symbol

N_S: The number of scattered pilots in an OFDM symbol

N_E: The number of excluded subcarriers in an OFDM symbol

N_P: The number of PLC subcarriers in an OFDM symbol

N_D: The number of data subcarriers in an OFDM symbol

The values of N, N_C, N_E and N_P do not change from symbol to symbol for a given OFDM template; the values of N_S and N_D change from symbol to symbol.

The following equation holds for all symbols:

$$N = N_C + N_S + N_E + N_P + N_D$$

The value of N is 4096 for 50 kHz subcarrier spacing ~~and 8192 for 25 kHz subcarrier spacing~~. From this equation it is clear that $(N_S + N_D)$ is a constant for a given OFDM template. Therefore, although the number of data subcarriers (N_D) and the number of scattered pilots (N_S) in an OFDM symbol changes from symbol to symbol, the sum of these two numbers is invariant over all symbols. Interleaving and de-interleaving are applied to the set of data subcarriers and scattered pilots of size $N_I = N_D + N_S$.

1.2.2.4.1 Bit Loading

The bit loading pattern defines the QAM constellations assigned to each of the 4096 ~~or 8192~~ subcarriers of the OFDM transmission. This bit loading pattern can change from profile to profile. Continuous pilot locations, PLC locations and exclusion bands are defined separately, and override the values defined in the bit-loading profile. Let the bit loading pattern for profile i be defined as $A_i(k)$, where:

k is the subcarrier index that goes from 0 to (N-1)

N is either 4096 ~~or 8192~~

$A_i(k) \in \{0, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14\}$. A value of 0 indicates that the subcarrier k is zero-bit-loaded. Other values indicate that the modulation of subcarrier k is QAM with order $2^{A_i(k)}$.

Let the sequence $\{A_i(k),\ k = 0, 1, \dots\ ,\ (N-1),\ k \not\in S^{PCE}\}$ be arranged as N_I consecutive values of another sequence:

$$B_i(k),\ k = 0, 1, \dots\ ,\qquad (N_I - 1)$$

Given the locations of the excluded subcarriers, continuous pilots and the PLC in the OFDM template, it is possible to obtain the bit-loading pattern $B_i(k)$ that is applicable only to spectral locations excluding excluded subcarriers, continuous pilots, and PLC subcarriers. However, note that $B_i(k)$ does contain the spectral locations occupied by scattered pilots; these locations change from symbol to symbol.

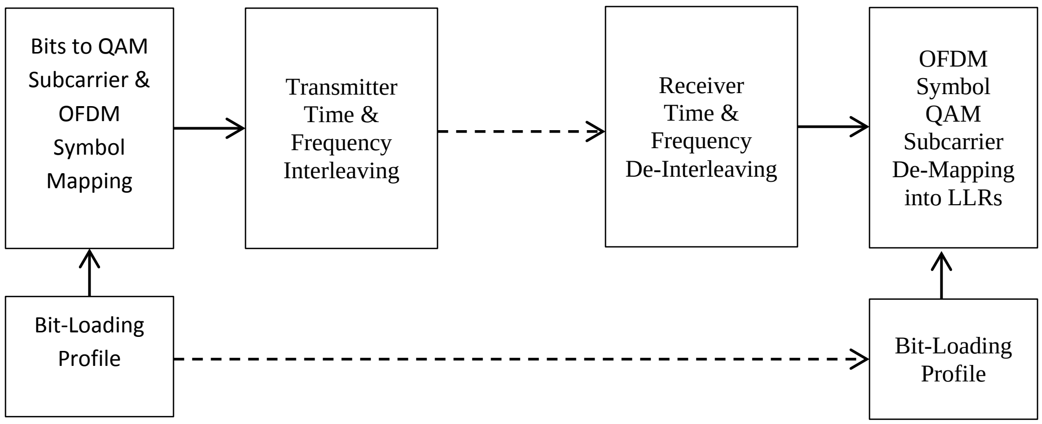


Figure 1–2 - Bit Loading, Symbol Mapping, and Interleaving

The excluded subcarriers, PLC subcarriers, and continuous pilots are excluded from the processes of interleaving and de-interleaving; scattered pilots and data subcarriers are subject to interleaving and de-interleaving. Hence, the total number of subcarriers that pass through the interleaver and de-interleaver is $N_I = (N_D + N_S)$ and this number does not change from symbol to symbol.

The interleaver introduces a 1-1 permutation mapping P on the N_I subcarriers. Although interleaving consists of a cascade of two components, namely time and frequency interleaving, it is only frequency interleaving that defines the mapping P. This is because time interleaving does not disturb the frequency locations of subcarriers.

The corresponding permutation mapping applied at the receiver de-interleaver is P^{-1}.

In order to perform bit-loading, it is necessary to work out the bit loading pattern at the node at which it is applied, i.e., at the input to the interleavers. This is given by:

$$C_i(k) = P^{-1}(B_i(k))$$

Since the time interleaver does not change the frequency locations of subcarriers, the sequence $C_i(k)$ is obtained by sending $\{B_i(k), k = 1, 2, \dots, N_I - 1\}$ through the frequency de-interleaver.

Note that $C_i(k)$ gives the bit-loading pattern for N_I subcarriers. Yet, some of these subcarriers are scattered pilots that have to be avoided in the bit-loading process. Hence, a two-dimensional binary pattern $D(k, j)$ is used to identify subcarriers to be avoided during the process of bit-loading. Because the scattered pilot pattern has a periodicity of 128 in the time dimension, this binary pattern also has periodicity 128 in the column dimension j.

$D(k, j)$ is defined for $k = 0, 1, \dots, (N_I - 1)$ and for $j = 0, 1, \dots, 127$

The process to create the binary pattern $D(k,j)$ begins with the transmitted scattered pilot pattern defined in **Interleaving and De-interleaving**. The pattern is defined in reference to the preamble of PLC and the periodicity of the PLC cycle time.

The CLT executes the following steps to obtain the pattern $D(k,j)$:

1. Define a two-dimensional binary array $P(k,j)$ in the subcarrier transmitted domain that contains a one for each scattered pilot location and zero otherwise:

$P(k,j)$, for $k = 0, 1, \dots\ , N-1$ and for $j = 0, 1, \dots\ , 127$

Here, the value of *N* is either 4096 ~~or 8192~~. The first column of this binary sequence corresponds to the first OFDM symbol following the preamble of the PLC.

2. Exclude the rows corresponding to excluded subcarriers, continuous pilots, and PLC from the two-dimensional array $P(k,j)$ to give an array $Q(k,j)$. The number of rows of the resulting array is N_I and the number of columns is 128.

3. Pass this two-dimensional binary array $Q(k,j)$ through the frequency de-interleaver and then the time de-interleaver, with each column treated as an OFDM symbol. After the 128 columns of the pattern have been input into the interleaver, re-insert the first *M* columns, where *M* is the depth of the time interleaver. This is equivalent to periodically extending $Q(k,j)$ along the dimension j and passing (128+*M*) columns of this extended sequence through the frequency de-interleaver and the time de-interleaver.

4. Discard the first *M* symbols coming out of the time de-interleaver and collect the remaining 128 columns into an array to give the binary two-dimensional array $D(k,j)$ of size ($N_I \times 128$).

For bit loading the CLT accesses the appropriate column j of the binary pattern bit $D(k,j)$ together with the appropriate bit loading profile $C_i(k)$. If the value of the bit $D(k,j)$ is 1, the CLT MUST skip this subcarrier k and move to the next subcarrier. This subcarrier is included as a placeholder for a scattered pilot that will be inserted in this subcarrier location after interleaving. After each symbol the column index j has to be incremented modulo 128.

The CLT uses this binary two-dimensional array $D(k,j)$ of size ($N_I \times 128$) in order to do bit-loading of OFDM subcarriers, as described earlier in this section.

The corresponding operation in the CNU is de-mapping the QAM subcarriers to get Log-Likelihood-Ratios (LLRs) corresponding to the transmitted bits. This operation, described below, is much simpler than the mapping operation in the transmitter.

The scattered pilots and data subcarriers of every received symbol are subjected to frequency and time de-interleaving. The scattered pilots have to be tagged so that these can be discarded at the output of the time and frequency de-interleavers. This gives N_I subcarriers for every OFDM symbol. The CNU accesses these N_I de-interleaved subcarriers together with the bit-loading pattern $C_i(k)$ to implement the de-mapping of the QAM subcarriers into LLRs. If the subcarrier k happens to be a scattered pilot, then this subcarrier, as well as the corresponding value $C_i(k)$, is skipped and the CNU moves to the next subcarrier $(k+1)$.

Interleaving and De-interleaving

To minimize the impacts of burst noise and ingress on the EPoC signals, time and frequency interleaving are applied to OFDM symbols in the following order: time interleaving, then frequency interleaving. These interleaving methods are discussed in this section.

The time interleaver is a convolutional interleaver that operates in the time dimension on individual subcarriers of a sequence of OFDM symbols. The time interleaver does not change the frequency location of any OFDM subcarrier. A burst event can reduce the SNR of all the subcarriers of one or two consecutive OFDM symbols; the purpose of the time interleaver is to disperse these burst-affected OFDM subcarriers between M successive OFDM symbols, where M is the interleaver depth. This dispersion distributes the burst-affected subcarriers uniformly over a number of LDPC codewords.

The frequency interleaver works along the frequency dimension. The frequency interleaver changes the frequency locations of individual OFDM subcarriers; latency is not introduced, except for the data store and read latency. The aim of frequency interleaving is to disperse ingress, e.g., LTE that affects a number of consecutive subcarriers over the entire OFDM symbol. Frequency interleaving distributes the burst-affected subcarriers over a number of LDPC codewords.

The CLT first applies a time interleaver to an OFDM symbol worth of N_I subcarriers to get a new set of N_I subcarriers. These N_I subcarriers are made up of N_D data subcarriers and N_S scattered pilots.

$$N_I = N_D + N_S$$

It must be noted that although N_D and N_S are not the same for every OFDM symbol, the value of N_I is a constant for all OFDM symbols in a given system configuration. The value of N_I is a function of the channel bandwidth, number of excluded subcarriers, number of PLC subcarriers and the number of continuous pilots. The CLT then subjects these N_I subcarriers to frequency interleaving. The value of N_I does not exceed ~~7537 for 8K FFT mode and~~ 3745 for the 4K FFT mode.

Note that both time and frequency interleaving are applied only to data subcarriers and scattered pilots. Continuous pilot, subcarriers that have been excluded (used to support legacy channels in spectral regions, for example) and the subcarriers of the physical layer link channel (PLC) are not interleaved. The CLT MUST NOT interleave continuous pilots, excluded subcarriers or the subcarriers of the PLC.

Time Interleaving

~~The CLT MUST time interleave as described in this section.~~ The CLT MUST time interleave after OFDM symbols have been mapped to QAM constellations and before they are frequency interleaved.

The time interleaver is a convolutional interleaver that operates at the OFDM subcarrier level. If the depth of the interleaver is M, then there are M branches, as shown in Figure 1-3.

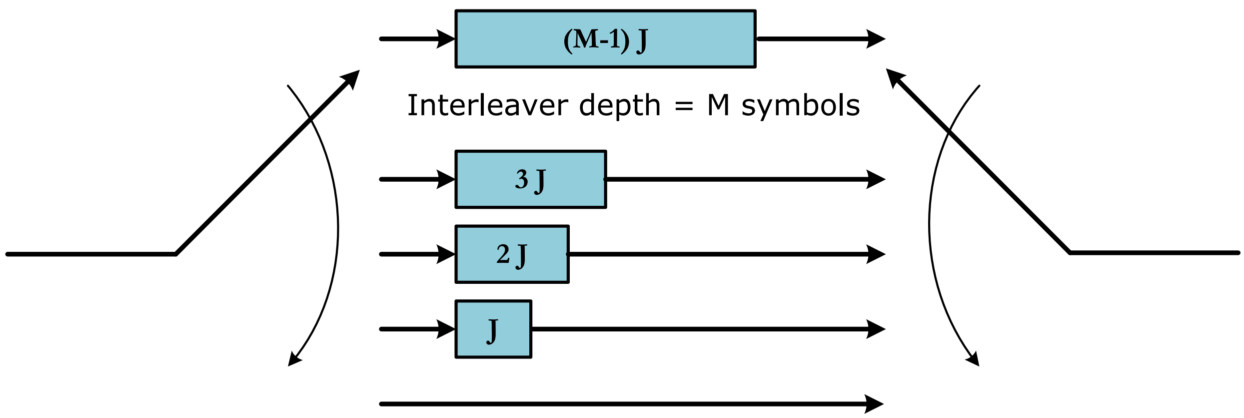


Figure 1-3 - Time Interleaver Structure

The CLT MUST support a maximum value of M equal to 32 for 20 µs symbol duration (50 kHz subcarrier spacing~~) and 16 for 40 µs symbol duration (25 kHz subcarrier spacing)~~.

The CLT MUST support all values of M from 1 to the maximum value of M ~~(inclusive of both limits)~~.

Each branch is a delay line; the input and output will always be connected to the same delay line. This delay line will be clocked to insert a new subcarrier into the delay line and to extract a subcarrier from the delay line. Next, the commutator switches at the input, and the output will move to the next delay line in the direction shown by the arrows in Figure 1-3. After the delay line with the largest delay, the switch will move to the delay line with zero delay.

The lowest frequency subcarrier of an OFDM symbol always goes through the branch with zero delay. Then the commutator switch at input and the corresponding commutator switch at output are rotated by one position for every new subcarrier.

The value of J is given by the following equation:

$$J = ceil(\frac{N_I}{M})$$

Here, N_I is the number of data subcarriers and scattered pilots in an OFDM symbol. See Section ~~1.1.6.3 for details on interleaving scattered pilots~~. **Interleaving Impact on Continuous Pilots, Scattered Pilots, PLC and Excluded Spectral Regions**.

If N_I were not divisible by M, all of the branches would not be filled. Therefore, "dummy subcarriers" are added to the symbol to make the number of subcarriers equal to a multiple of M. The number of dummy subcarriers is given by:

$$J * M - N_I$$

The dummy subcarriers are added for definition purposes only; at the output of the interleaver these dummy subcarriers are discarded. An implementation will use a single linear address space for all the delay lines in Figure 1-3. Writing and reading dummy subcarriers will not be needed.

1.2.2.5 Frequency Interleaving

[Note: This section is T.B.D.]

1.2.2.6 Interleaving Impact on Continuous Pilots, Scattered Pilots, PLC and Excluded Spectral Regions

~~EPoC transmissions contain continuous pilots for receiver synchronization and scattered pilots for channel estimation. In addition, there could be nulled regions to accommodate legacy channels. There will also be a physical layer link channel (PLC).~~

The CLT interleaves scattered pilots and data subcarriers, but does not interleave continuous pilots, the PLC, and subcarriers belonging to nulled regions. With respect to scattered pilots, it must be noted here that CLT actually interleaves the subcarriers that are tagged to act as placeholders for scattered pilots, since at the time of interleaving the scattered pilots have not yet been inserted. The actual BPSK modulation to these placeholder subcarriers is applied after interleaving as described in Section ***Downstream Pilot Patterns.***

The CLT inserts scattered pilot placeholders prior to time and frequency interleaving such that when these placeholders get time and frequency interleaved, the resulting placeholders conform to the required scattered pilot pattern described in in Section **Downstream Pilot Patterns**.

To accomplish this, the CLT has to retain a reference pattern for inserting scattered pilot placeholders prior to interleaving. Since the scattered pilot pattern repeats every 128 symbols, this pattern is a (N_I x 128) two-dimensional bit pattern. A value of one in this bit-pattern indicates the location of a scattered pilot. The CLT inserts data subcarriers where this reference pattern has a zero and scattered pilot placeholders where this pattern has a one.

This reference pattern may be derived from the following procedure:

1. In the time-frequency plane, create a two-dimensional bit-pattern of zeros and ones from the transmitted "diagonal" scattered pilot patterns described in in Section **Downstream Pilot Patterns**. This pattern has a periodicity of 128 symbols and has a value of one for a scattered pilot location and zero otherwise. Let the time axis be horizontal and the frequency axis vertical.

2. Delete all horizontal lines containing continuous pilots, excluded subcarriers, and PLC from the above mentioned two-dimensional bit pattern; note the some scattered pilots could coincide with continuous pilots. These locations are treated as continuous pilot locations.

3. Send the resulting bit-pattern through the frequency de-interleaver and the time de-interleaver in succession. This will give another two-dimensional bit pattern that has a periodicity of 128 symbols. The appropriate 128-symbol segment of this bit-pattern is chosen as the reference bit pattern referred to above.

Note that the CLT has to synchronize the scattered pilot pattern to the PLC preamble, as described in Section **Downstream Pilot Patterns**. This uniquely defines the 128-symbol segment that has to be used as the reference pattern.

Scattered pilots are not in the same subcarrier location in every symbol; hence some scattered pilots can coincide with continuous pilots in some OFDM symbols. The size of the overlap between the set of scattered pilots and the set of continuous pilots will change from symbol to symbol. As a result, the number of data subcarriers in a symbol will not be the same for all OFDM symbols. Note that in the nomenclature used below, when a scattered pilot coincides with a continuous pilot, then that pilot is referred to as a continuous pilot.

Although the number of data subcarriers can change from symbol to symbol, the number of data subcarriers and scattered pilots are the same for every symbol. This is referred to as N_I in this section. Let N_D denote the number of data subcarriers in a symbol and N_S denote the number of scattered pilots in a symbol. These two parameters, i.e., N_D and N_S, will change from symbol to symbol. However, the sum of these two, i.e., N_I is a constant for a given system configuration.

$$N_I = N_S + N_D$$

Hence the number of OFDM subcarriers that are interleaved does not change from symbol to symbol. This is important, because if not for this, the output of the convolutional time interleaver may have dummy or unused subcarriers in the middle of interleaved OFDM symbols.

The insertion of continuous pilots, PLC and excluded regions happens after both time and frequency interleaving.

~~Interleaving data and scattered pilots together has another important advantage. This is to do with bit loading. A transmitted profile is said to have non-uniform bit loading if the QAM constellation that is applied to subcarriers is not constant over the entire frequency band. If the data subcarriers are interleaved and scattered pilots are added later, then the data subcarriers will have to be shifted to accommodate the scattered pilots. This shift will be different from symbol to symbol, and this complicates non-uniform bit-loading. Hence, having the scattered pilots in-place during the bit-loading process greatly simplifies the bit loading operation. The insertion of continuous pilots, PLC and nulled regions also results in shift of data subcarriers, but this shift is the same for every symbol, and can easily be accounted for in the bit loading process.~~

The CLT only interleaves data subcarriers and scattered pilots, and therefore only needs information about the number of data subcarriers and scattered pilots per symbol. In addition, the interleaver does not need to know what modulation has been applied to an individual data subcarrier. Regardless of modulation scheme, all OFDM symbols will have the same number of data subcarriers and scattered pilots, and the modulation pattern of these data subcarriers may change from symbol to symbol.

IDFT

Downstream Transmitter Inverse Discrete Fourier Transform

The CLT transmitter MUST use the IDFT definition and subcarrier referencing method described in this section.

This section defines the inverse discrete Fourier transform (IDFT) used in the CLT transmitter for EPoC. OFDM subcarrier referencing for other definitions such as PLC location, continuous pilots, exclusion bands and bit loading is also described.

The OFDM signal assembled in the frequency domain consists of 4096 subcarriers for the 4K FFT ~~and 8192 subcarriers for the 8K FFT~~. The OFDM signal is composed of:

- Data subcarriers
- Scattered pilots
- Continuous pilots
- PLC subcarriers
- Excluded subcarriers that are zero valued

This signal is described according to the following IDFT equation:

$$x(i) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \exp\left(j \frac{2\pi i\left(k-\frac{N}{2}\right)}{N}\right), \quad for \;\; i = 0, 1, \ldots, (N-1)$$

The resulting time domain discrete signal, $x(i)$, is a baseband complex-valued signal, sampled at 204.8 Msamples per second.

In this definition of the IDFT:

$X(0)$ is the lowest frequency component;

$X(N/2)$ is the DC component or the mean value of the sequence $x(i)$;

$X(N\text{-}1)$ is the highest frequency component.

The IDFT is illustrated in Figure 1–6.

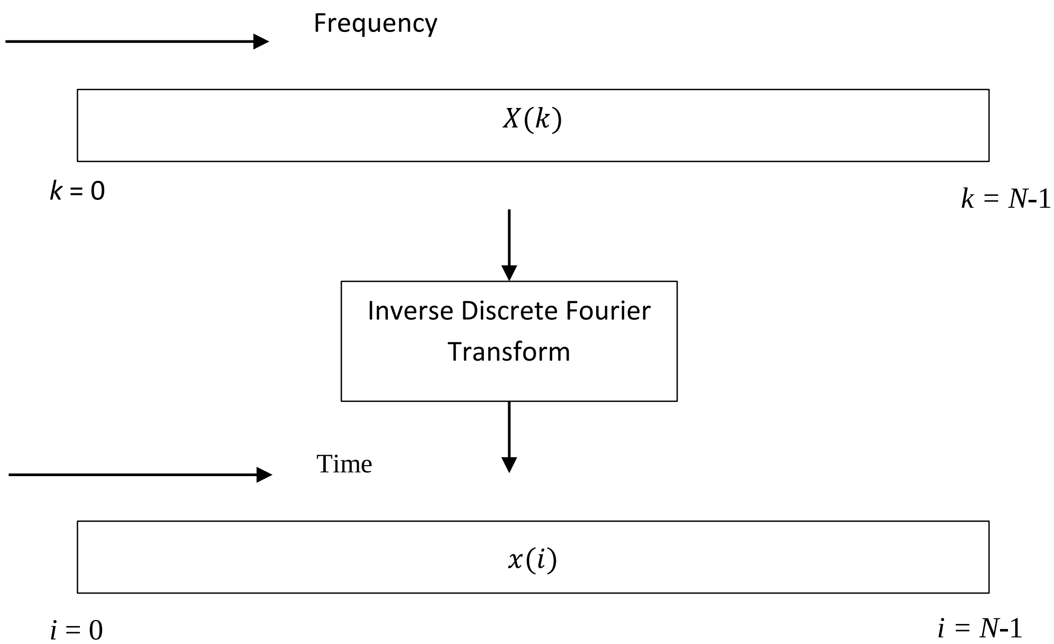


Figure 1–1 - Inverse Discrete Fourier Transform

The sample rate in the time domain is 204.8 Msamples/s. Hence, the N samples of the discrete Fourier transform cover a frequency range of 204.8 MHz. This gives the subcarrier spacing shown in Table 1–2.

Table 1–2 - Subcarrier Spacing

IDFT Size *N*	**Carrier Spacing**
4096	50 kHz
~~8192~~	~~25 kHz~~

The maximum channel bandwidth is 192 MHz; this corresponds to 3841 subcarriers in 4K mode ~~and 7681 subcarriers in 8K mode~~. The active bandwidth of the channel is expected to be 190 MHz; this corresponds to 3800 subcarriers in 4K ~~mode and 7601 subcarriers in 8K mode~~.

The following table describes what the different values of k mean for 4K FFTs ~~and 8K FFT~~s.

Table - k Definitions for 4K ~~and 8K~~ FFT

Value of k		**Description**
4K FFT	**~~8K FFT~~**	
0	~~0~~	Lowest frequency subcarrier of the DFT
128	~~256~~	Lower-end subcarrier of the 192 MHz channel
148	~~296~~	Lower-end subcarrier of the 190 MHz band
2048	~~4096~~	DC component
3948	~~7896~~	Upper-end subcarrier of the 190 MHz band
3968	~~7936~~	Upper-end subcarrier of the 192 MHz channel
4095	~~8191~~	Highest frequency subcarrier of the DFT

The OFDM channel bandwidth can be any value from 24 MHz to 192 MHz; smaller bandwidths than 192 MHz are achieved by nulling subcarriers $X(k)$ prior to the IDFT. Note that the channel need not be centered at the subcarrier $k = N/2$, although this would be the most logical approach when transmitting a channel with bandwidth less than 192 MHz.

~~For example, consider transmitting an OFDM signal with a subcarrier spacing of 25 kHz over a 24 MHz channel with an active bandwidth of 22 MHz. The channel would have 881 active subcarriers, including all edge subcarriers. The most logical thing to do would be to assign these active subcarriers to:~~

$\cancel{\{X(k), k = 3656, 3657, \ldots, 4095, 4096, 4097, \ldots, 4535, 4536\}}$

~~All other subcarriers are nulled for exclusion. This results in a channel that is symmetrically placed around the DC component of the time domain sequence~~ $\cancel{\{x(i), i = 0, 1, \ldots, 8191\}}$~~. However, the 881 active subcarriers may occupy any other contiguous region of the frequency domain sequence~~ $\cancel{\{x(k),\ k = 0, 1,\ \ldots\ , 8191\}}$~~.~~

Subcarrier Referencing

It is necessary to refer to specific OFDM subcarriers for several definitions:

a) Defining continuous pilot locations

b) Defining exclusion bands and excluded individual subcarriers

c) Defining bit loading profiles

Each of these definitions uses the index *k* of the equation defined in the preceding section to refer to a specific subcarrier.

The subcarrier index goes from 0 to 4095 for the 4K FFT ~~and from 0 to 8191 for the 8K FFT; each of these definitions is limited to these subcarrier indices.~~

The PLC is also defined with reference to $k = 0$. The OFDM template carried by the PLC defines the subcarrier index of the lowest frequency subcarrier of the PLC. Hence, once the CNU detects the PLC, the CNU knows the location of $k = 0$. Since the FFT size is also known, it is possible to precisely compute the FFT of the data channel containing the PLC.

Note that scattered pilot placement is not referenced to $k = 0$; instead, it is referenced directly to the PLC preamble.

~~Cyclic Prefix and Windowing~~

~~This section describes how cyclic prefixes are inserted and how a window is applied to the output of the IDFT at the CLT and how they are handled by the CNU.~~

~~The addition of a cyclic prefix enables the receiver to overcome the effects of inter-symbol-interference and inter-carrier-interference caused by micro-reflections in the channel. Windowing maximizes channel capacity by sharpening the edges of the spectrum of the OFDM signal. Spectral edges occur at the two ends of the spectrum of the OFDM symbol, as well as at the ends of internal exclusion bands.~~

~~The number of active OFDM subcarriers can be increased by sharpening these spectral edges. However, sharper spectral edges in the frequency domain imply longer tapered regions in the time domain, resulting in increased symbol duration and reduction in throughput. Therefore, there is an optimum amount of tapering that maximizes channel capacity. This optimum is a function of channel bandwidth as well as the number of exclusion bands.~~

Cyclic Prefix Insertion and Windowing

The CLT MUST follow the procedure described in Section **Cyclic Prefix and Windowing Algorithm** for cyclic prefix insertion and windowing, using CLT specific cyclic prefix and roll-off period values.

The CLT MUST support cyclic prefix extension and windowing as described in Section **Cyclic Prefix and Windowing Algorithm**.

The CLT MUST support the cyclic prefix values defined in Table 1–4 for ~~both~~ 4K ~~and 8K~~ FFTs.

The CNU MUST support the cyclic prefix values listed defined Table 1–4 for ~~both~~ 4K ~~and 8K~~ FFTs.

[NOTE: confirm which values are to be retained in Tables 1-4 and 1-5 for EPoC.]

Table 1–3 - Cyclic Prefix (CP) Values

Cyclic Prefix (µs)	Cyclic Prefix Samples (N_{cp})
~~0.9375~~	~~192~~
1.25	256
2.5	512
3.75	768
~~5.0~~	~~1024~~

The cyclic prefix (in µs) are converted into samples using the sample rate of 204.8 Msamples/s and is an integer multiple of: 1/64 * 20 µs.

The CLT MUST support the five parameter values specified for this roll-off listed in Table 1–5.

Table 1–4 - Roll-Off Prefix (RP) Values

Roll-Off Period (µs)	Roll-Off Period Samples (N_{cp})
0	0
~~0.15625~~	~~32~~
0.3125	64
0.625	128
0.9375	192
1.25	256

The CLT MUST NOT allow a configuration in which the RP value is ≥ the CP value.

Cyclic Prefix and Windowing Algorithm

The algorithm for cyclic prefix extension and windowing is described here with reference to Figure 1-7.

~~The CNU MUST support cyclic prefix extension and windowing as described in this section.~~

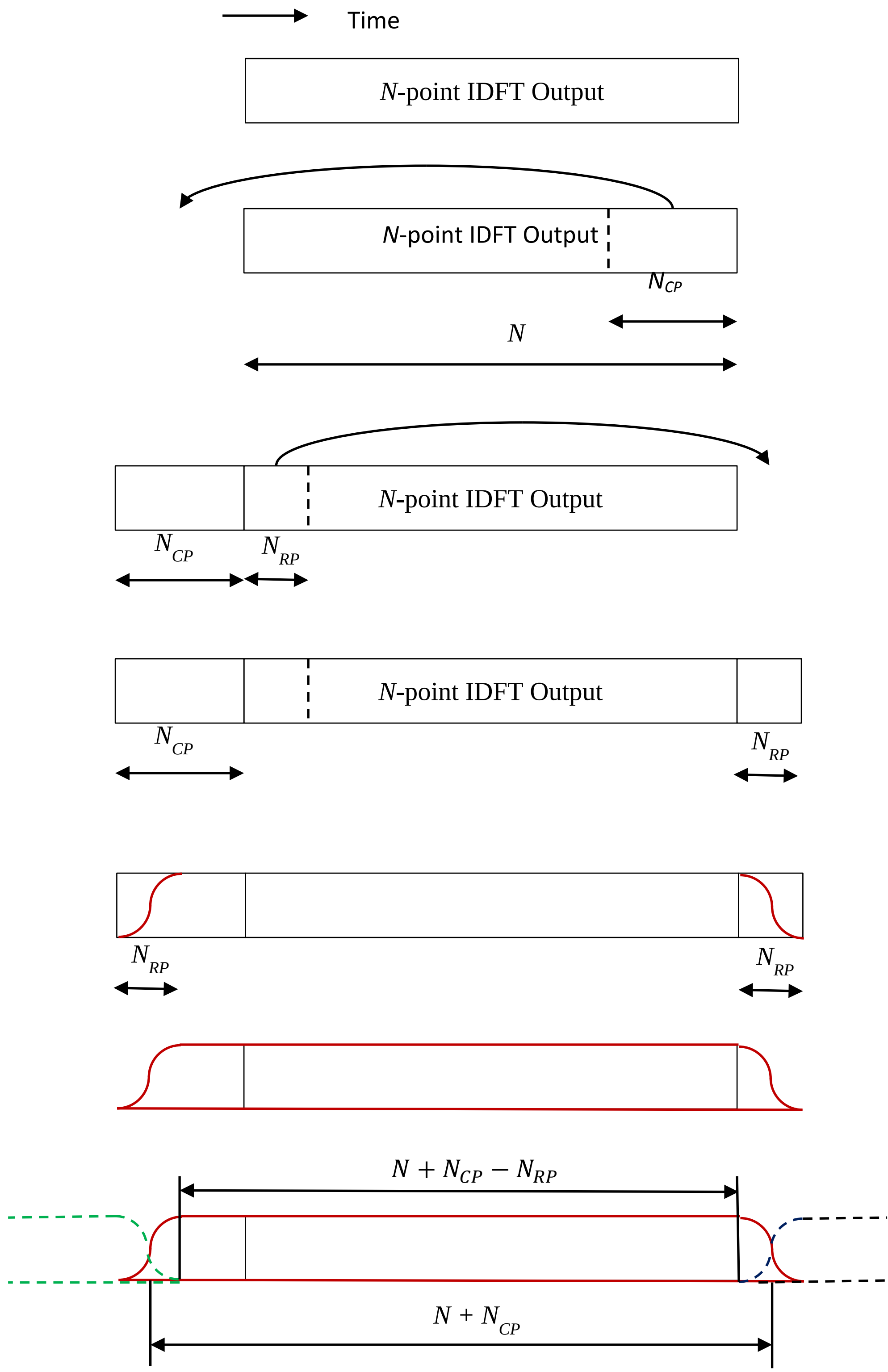


Figure 1-7 – Cyclic Prefix and Windowing Algorithm

Processing begins with the *N*-point output of the IDFT. Let this be:

$$\{\, x(0),\ x(1), \dots\ , x(N-1)\}$$

The N_{CP} samples at the end of this *N*-point IDFT are copied and prepended to the beginning of the IDFT output to give a sequence of length (N+N_{CP}):

$$\{x(N-N_{CP}),\ x(N-N_{CP}+1), \dots ,\ x(N-1),\ x(0),\ x(1), \dots\ , x(N-1)\}$$

The N_{RP} samples at the start of this *N*-point IDFT are copied and appended to the end of the IDFT output to give a sequence of length (N+N_{CP}+N_{RP}):

$$\{x(N-N_{CP}),\ x(N-N_{CP}+1), \dots ,\ x(N-1),\ x(0),\ x(1), \dots\ , x(N-1), x(0), x(1),\ \dots\ , x(N_{RP}-1)\}$$

Let this extended sequence of length (N+N_{CP}+N_{RP}) be defined as:

$$\{y(i),\ \ i=0,\ 1, \dots\ , (N+N_{CP}+N_{RP}-1)\}$$

N_{RP} samples at both ends of this extended sequence are subject to tapering. This tapering is achieved using a raised-cosine window function; a window is defined to be applied to this entire extended sequence. This window has a flat top and raised-cosine tapering at the edges, as shown in Figure 1-8.

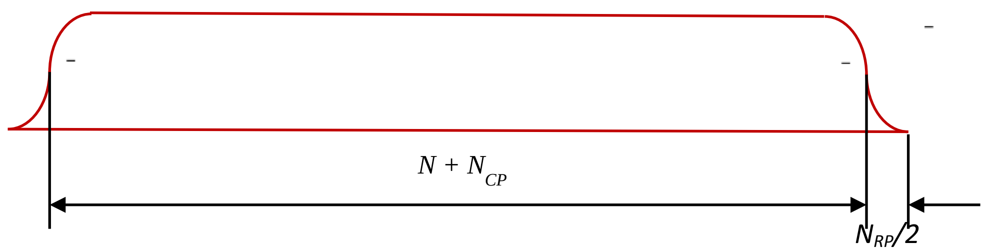


Figure 1-2 – Tapering Window

The window function $w(i)$ is symmetric at the center; therefore, only the right half of the window is defined in the following equation:

$$w\left(\frac{N+N_{CP}+N_{RP}}{2}+i\right)=1.0\,,\ \ for\ \ i=0,1,\dots\ , \left(\frac{N+N_{CP}-N_{RP}}{2}-1\right)$$

$$w\left(i+\frac{N+N_{CP}+N_{RP}}{2}\right)\ =\ \frac{1}{2}\left(1-\sin\left(\frac{\pi}{\alpha(N+N_{CP})}\left(i-\frac{N+N_{CP}}{2}+1/2\right)\right)\right),$$

for $i=\left(\frac{N+N_{CP}-N_{RP}}{2}\right), \dots\ , \left(\frac{N+N_{CP}+N_{RP}}{2}-1\right)$

Here,

$$\alpha\ =\ \frac{N_{RP}}{N+N_{CP}}$$

defines the window function for $(N+N_{CP}+N_{RP})/2$ samples. The complete window function of length (N + N_{CP} + N_{RP}) is defined using the symmetry property as:

$$w\left(\frac{N+N_{CP}+N_{RP}}{2}-i-1\right)\ =w\left(\frac{N+N_{CP}+N_{RP}}{2}+i\right),$$

for $i=0,1,\dots,\dfrac{N+N_{CP}+N_{RP}}{2}-1$

This yields a window function (or sequence): $\{w(i),\ i = 0, 1, \ldots\ , (N + N_{CP} + N_{RP} - 1)\}$. The length of this sequence is an even-valued integer.

The above window function is applied to the sequence $\{y(i)\}$:

$$z(i) = \ y(i)\, w(i), \quad for\ i = 0, \qquad 1, \ldots\ , (N + N_{CP} + N_{RP} - 1)$$

Each successive set of N samples at the output of the IDFT yields a sequence $z(i)$ of length $(N + N_{CP} + N_{RP})$. Each of these sequences is overlapped at each edge by N_{RP} samples with the preceding and following sequences, as shown in the last stage of Figure Error**! No text of specified style in document.**-7. Overlapping regions are added together.

To define this "overlap and add" function mathematically, consider two successive sequences $z_1(i)$ and $z_2(i)$. The overlap and addition operations of these sequences are defined using the following equation:

$$z_1(N + N_{CP} + i) + z_2(i), \ \ \text{for } i = 0, 1, \ldots, N_{RP} - 1$$

That is, the last N_{RP} samples of sequence $z_1(i)$ are overlapped and added to the first N_{RP} samples of sequence $z_2(i)$.

[Authors NOTE: The following text is additional to what was in laubach_3bn_04c_1113.pdf]

Downstream Pilot Patterns

Downstream pilots are subcarriers modulated by the CLT with a defined modulation pattern that is known to all the CNUs in the system to allow interoperability.

There are two types of pilots: continuous and scattered. Continuous pilots occur at fixed frequencies in every symbol. Scattered pilots occur at different frequency locations in different symbols~~. Each of these pilot types for DOCSIS 3.1 is defined in the following sections.~~

Scattered Pilots

The scattered pilot pattern repeats after every 128 OFDM symbols (PLC Cycle time) in time.

The main purpose of scattered pilots is the estimation of the channel frequency response for the purpose of equalization. ~~There are two scattered pilot patterns, one for 4K FFT and one for 8K FFT~~. Although these pilots occur at different frequency locations in different OFDM symbols, the patterns repeat after every 128 OFDM symbols; in other words, the scattered pilot pattern has a periodicity of 128 OFDM symbols along the time dimension.

Scattered Pilot Pattern for 4K FFT

The CLT MUST create scattered pilots for 4K FFTs in the manner described in this section.

Figure 7–69 shows the 4K FFT scattered pilot pattern for OFDM transmissions.

The scattered pilot pattern is synchronized to the PLC as shown in Figure 7–69. The first OFDM symbol after the PLC preamble has a scattered pilot in the subcarrier just after the highest frequency subcarrier of the PLC. Two such scattered pilots that are synchronized to the PLC preamble are marked as red circles~~ in Figure 7–72~~.

The remainder of the scattered pilot pattern is linked to the scattered pilot synchronized to the PLC preamble, using the following rules:

In each symbol scattered pilots are placed every 128 subcarriers.

From symbol to symbol, scattered pilots are shifted by one subcarrier position in the increasing direction of the frequency axis. This will result in scattered pilots placed in the exclusion band and in the PLC band.

Scattered pilots are nulled in the exclusion bands; all the subcarriers in the exclusion bands are zero-valued subcarriers.

Scattered pilots are nulled when these coincide with nulled subcarriers; all nulled subcarriers are zero-valued subcarriers.

In the PLC, normal PLC signals (i.e., PLC data or the PLC preamble) are transmitted instead of scattered pilots. The CLT MUST NOT transmit scattered pilots in the PLC band.

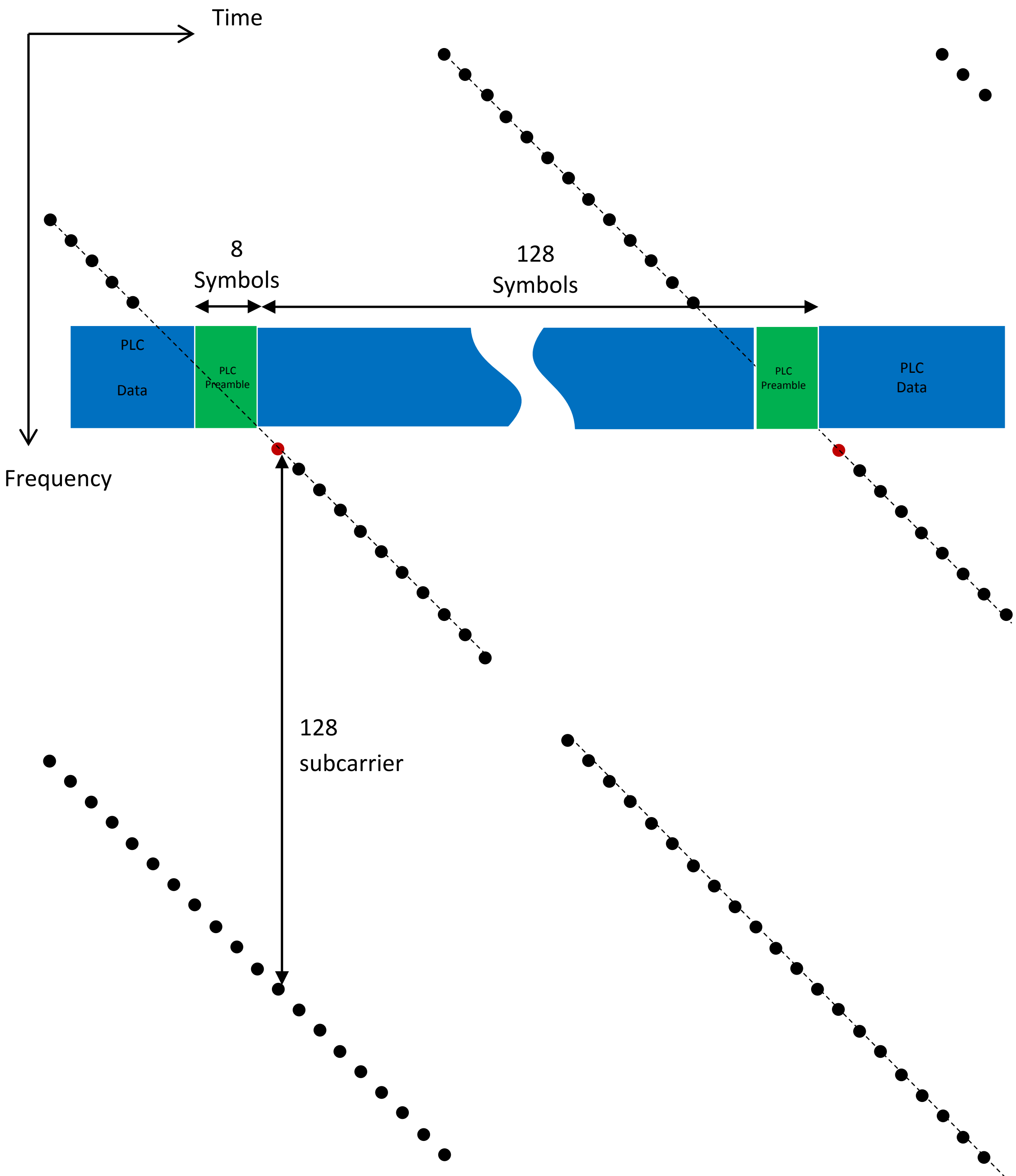


Figure 7–3 - 4K FFT Downstream Pilot Pattern ***<u>(Informational)</u>***

There are 8 preamble symbols in the PLC; for 4K FFT, there are 8 PLC subcarriers in each symbol.

Mathematically, the scattered pilot pattern for a 4K FFT is defined as follows. Let a subcarrier (depicted in red in the above figure just after the PLC preamble) be referred to as $x(m,n)$, where:

m is the frequency index

n is the time index (i.e., the OFDM symbol number)

The scattered pilots in the 128 symbols following (and including symbol n) are given by:

Symbol n: x(n, m±128i), for all non-negative integers i

Symbol (n+1): x(n+1, m±128i + 1) , for all non-negative integers i

Symbol (n+2): x(n+2, m±128i + 2) , for all non-negative integers i

⋮

Symbol (n+127): x(n+127, m±128i + 127) , for all non-negative integers i

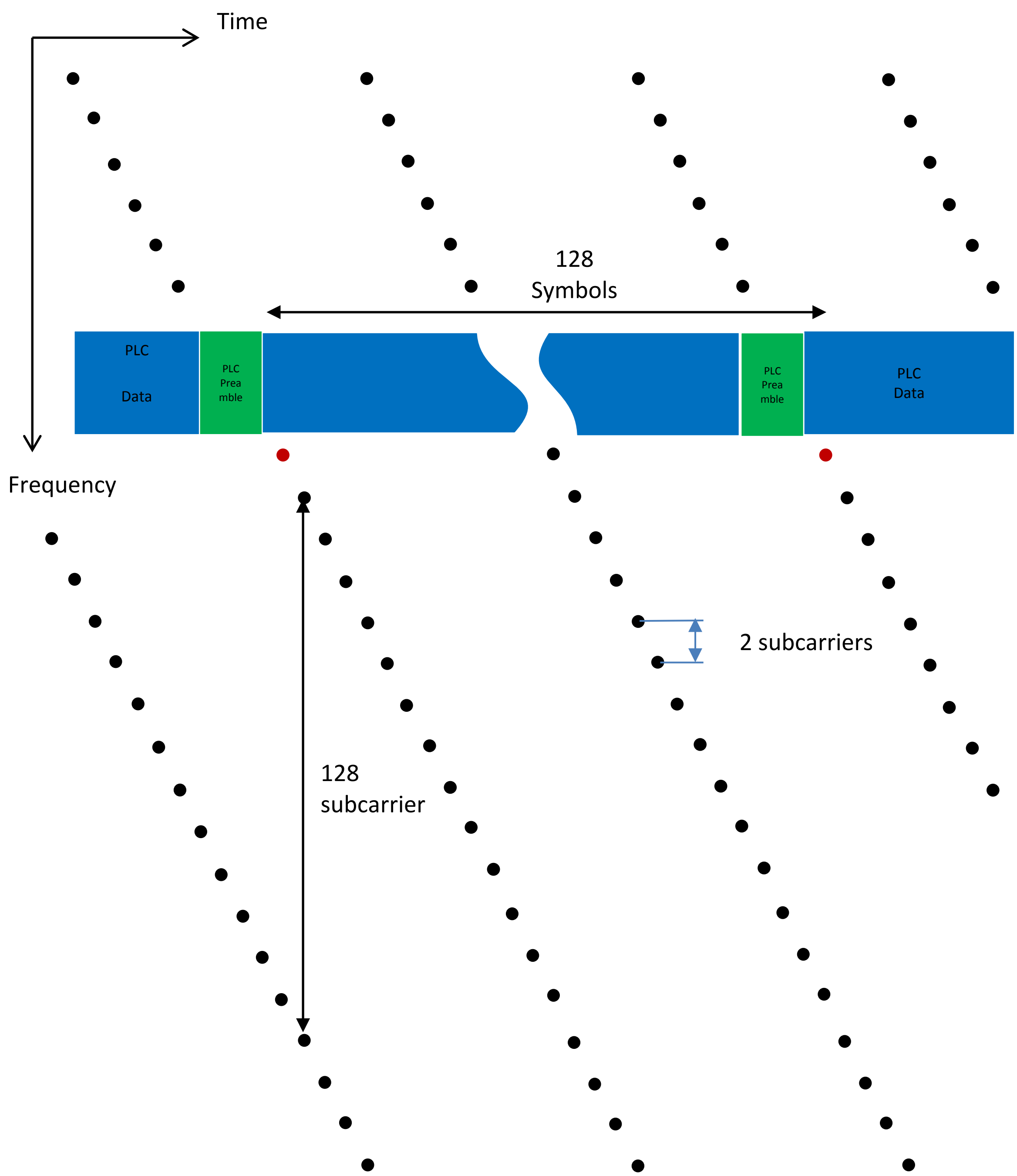
Each of the above locations is a scattered pilot, provided that it does not fall on a continuous pilot, on the PLC, on an exclusion zone or on a excluded subcarrier. If the scattered pilot coincides with a continuous pilot it is treated as a continuous pilot and not as a scattered pilot.

This pattern repeats every 128 symbols. That is, symbol (128+n) has the same scattered pilot pattern as symbol n.

~~*1.1.1.1.1 Scattered Pilot Pattern for 8K FFT*~~

~~The CLT MUST create scattered pilots for 8K FFTs in the manner described in this section.~~

~~Figure 7–70 shows a scattered pilot pattern that may be used for OFDM transmissions employing 8K FFT. This is used here for explanation purposes only and to help with the derivation of the scattered pilot pattern actually used in 8K FFT OFDM transmissions depicted in Figure 7–71.~~



~~*Figure 7–4 - A Downstream Scattered Pilot Pattern for 8K FFT (for Explanation Purposes Only)*~~

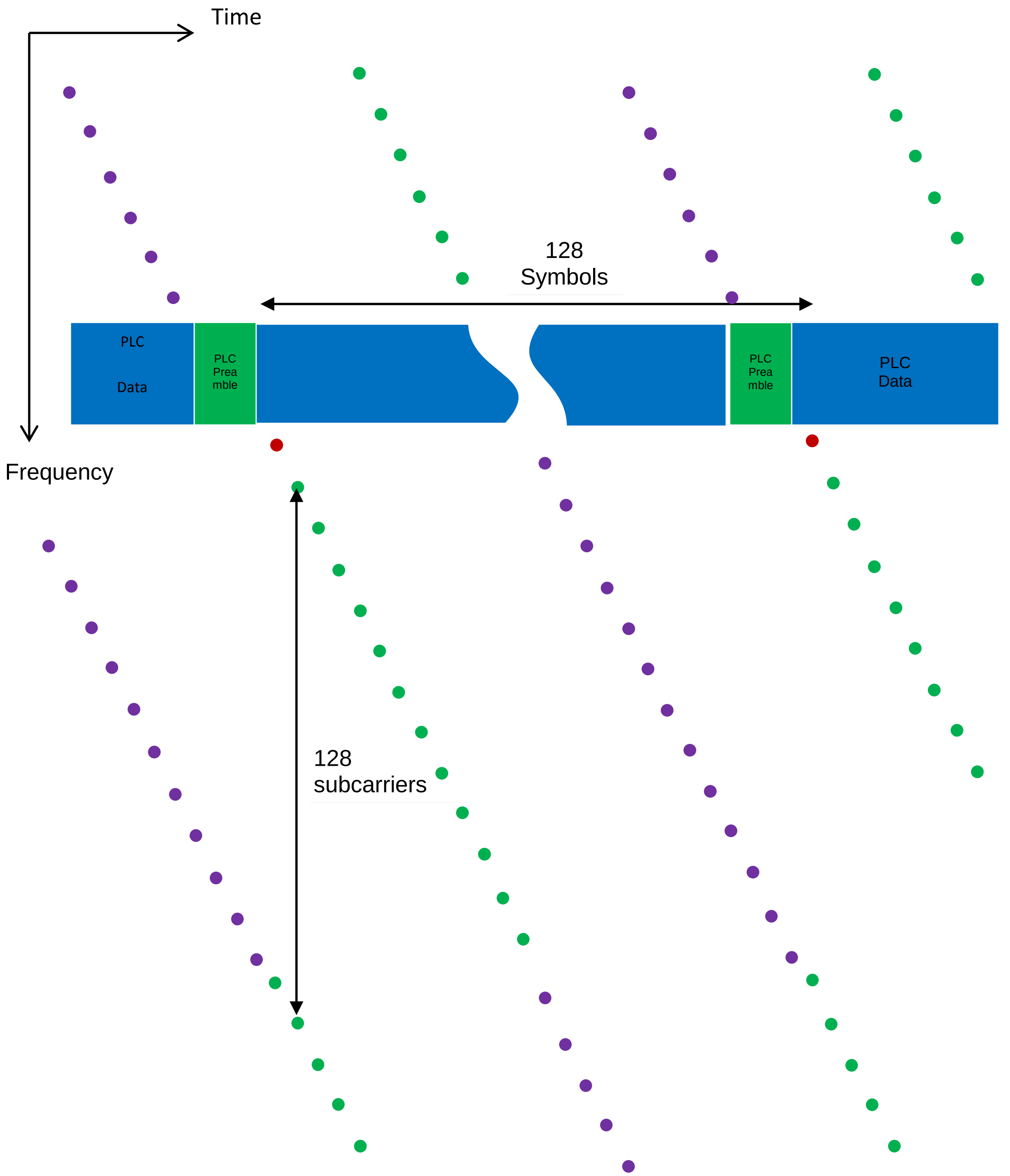
~~The scattered pilot pattern is synchronized to the PLC as shown in Figure 7–69. The first OFDM symbol after the PLC preamble has a scattered pilot in the subcarrier just after the highest frequency subcarrier of the PLC. Two such scattered pilots that are synchronized to the PLC preamble are marked as red circles in Figure 7–70.~~

~~In the case of an 8K FFT, pilots are stepped by two subcarriers from one OFDM symbol to the next. Since the pilot spacing along the frequency axis is 128, this results in a pilot periodicity of 64 in the time dimension. When Figure~~

~~7–69 and Figure 7–70 are compared, it is clear that the periodicity is half for the 8K scattered pilot pattern. However, because an 8K symbol is twice as long as a 4K symbol, the scattered pilot periodicity in terms of actual time is approximately the same for both the 4K and 8K FFTs. This allows channel estimates for 8K FFTs to be obtained in approximately the same amount of time as for the 4K FFT. However, scattered pilots for 8K FFTs do not cover all subcarrier locations and hence intermediate channel estimates have to be obtained through interpolation.~~

~~Noise can also be estimated using scattered pilots, and again, the noise at subcarrier locations not covered by scattered pilots in the 8K FFT can be obtained through interpolation. Note that this interpolation operation could fail in the presence of narrowband ingress; interpolation could also be problematic when there are excluded subcarriers.~~

~~To overcome these interpolation problems, the entire 8K scattered pilot location can be shifted by one subcarrier location after 64 subcarriers, as illustrated in Figure 7–71. This may be treated as the interlacing of two identical scattered pilot patterns. The set of purple scattered pilots are shifted one subcarrier space in relation to the set of green scattered pilots. As a result the scattered pilots cover all subcarrier locations; noise at every subcarrier location can be estimated without interpolation. Note that periodicity of the 8K FFT scattered pilot pattern is now 128, not 64.~~



~~***Figure 7–5 – 8K FFT Downstream Scattered Pilot Pattern***~~

~~Mathematically, the scattered pilot pattern for an 8K FFT is defined as follows. Let the subcarrier (depicted in red in Figure 7–71 just after the PLC preamble) be referred to as $x(m,n)$ where:~~

~~*m* is the frequency index~~

~~*n* is the time index (i.e., the OFDM symbol number)~~

~~The scattered pilots in the first 64 symbols following and including symbol *n* are given by:~~

~~Symbol n:~~ ~~x(n, m ± 128i), for all non-negative integers i~~

~~Symbol (n+1):~~ ~~x(n + 1, m ± 128i + 2), for all non-negative integers i~~

~~Symbol (n+2):~~ ~~x(n + 2, m ± 128i + 4), for all non-negative integers i~~

~~⋮~~

~~Symbol (n+63):~~ ~~x(n + 63, m ± 128i + 126), for all non-negative integers i~~

~~The scattered pilot sequence of the next 64 symbols is the same as above, but with a single subcarrier shift in the frequency dimension.~~

~~Symbol (n+64):~~ ~~x(n + 64, m ± 128i + 1), for all non-negative integers i~~

~~Symbol (n+65):~~ ~~x(n + 65, m ± 128i + 3), for all non-negative integers i~~

~~Symbol (n+66):~~ ~~x(n + 66, m ± 128i + 5), for all non-negative integers i~~

~~⋮~~

~~Symbol (n+127):~~ ~~x(n + 127, m ± 128i + 127), for all non-negative integers i~~

~~⋮~~

~~Each of the above locations is a scattered pilot, provided that it does not fall on a continuous pilot, on the PLC, on an exclusion zone or on a nulled subcarrier. If the scattered pilot coincides with a continuous pilot it is treated as a continuous pilot and not as a scattered pilot.~~

~~This pattern repeats every 128 symbols. That is, symbol (128+n) has the same scattered pilot pattern as symbol n.~~

~~Continuous Pilots~~

~~Continuous pilots occur at the same frequency location in all symbols and are used for receiver synchronization. Placement of continuous pilots is determined in two ways:~~

~~a) Predefined continuous pilot placement around the PLC~~

~~b) Continuous pilot placement defined via PLC messages~~

~~Note that continuous and scattered pilots can overlap; the amount of overlap, in terms of number of carriers, changes from symbol to symbol. Overlapping pilots are treated as continuous pilots.~~

Predefined Continuous Pilots around the PLC

As discussed in Section ***PLC Placement*** the PLC is placed at the center of a 6 MHz spectral region. Four pairs of predefined continuous pilots are placed symmetrically around the PLC as shown in Figure 7–72. The spacing between each pilot pair and the PLC are different to prevent all pilots from being impacted at the same time by echo or interference.

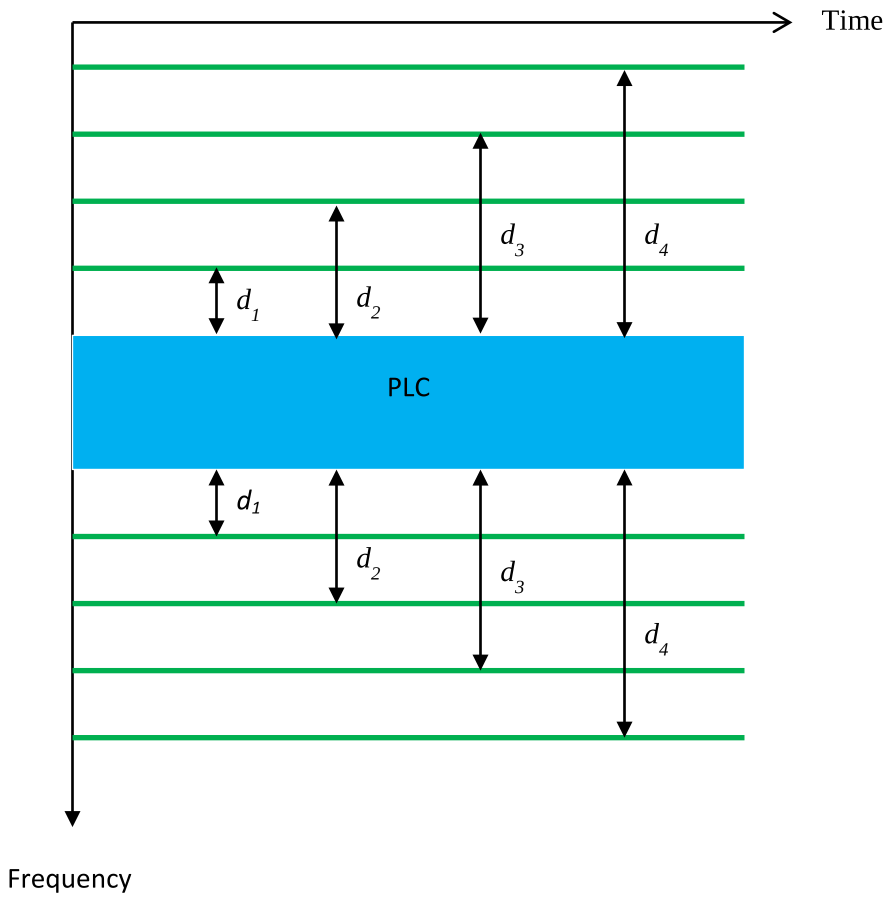


Figure 7–6 - Placement of Predefined Continuous Pilots Around the PLC

The locations of the continuous pilots are defined with reference to the edges of the PLC band. Hence, once the PLC has been detected, these continuous pilots also become known to the receiver.

Table 7–45 provides the values of d_1, d_2, d_3, and d_4, measured in number of subcarriers from the PLC edge. That is, d_x is absolute value of the difference between the index of the continuous pilot and the index of the PLC subcarrier at the PLC edge nearest to the continuous pilot. The index of a subcarrier is the integer k of the IDFT definition given in Section ***IDFT***. For example, let the lowest frequency subcarrier of the PLC have the IDFT index k equal to 972. Then according to Table 7–36 **RF Output Electrical Requirements** for the 4K FFT mode the continuous pilot nearest to this lowest frequency PLC subcarrier will have the IDFT index k of (972-15)=957. The index k of the highest frequency PLC subcarrier of this OFDM channel is 979. Hence continuous pilot that is nearest upper frequency edge of the PL has an index k of 994.

The table provides the number of subcarriers from the edge of the PLC to the placement of the pilot for the two FFT sizes. For each distance (d_x) defined in Table 7–45, the CLT MUST place two pilots: one d_x subcarriers above and one d_x subcarriers below the edge of the PLC band.

Table 7–5 - Subcarrier Distances for Placement of Predefined Pilots

		d_1	d_2	d_3	d_4
4K FFT	**PLC 8 subcarriers**	15	24	35	47
~~**8K FFT**~~	~~**PLC 16 subcarriers**~~	~~30~~	~~48~~	~~70~~	~~94~~

Continuous Pilot Placement Defined by PLC Message

The CLT MUST define a set of continuous pilots distributed as uniformly as possible over the entire OFDM spectrum in addition to the predefined continuous pilots described in the preceding section.

The CLT MUST ensure that there are no isolated active OFDM spectral regions that are not covered by continuous pilots.

It is not practical to predefine the locations of this set of continuous pilots because of exclusion bands and excluded subcarriers.

The CLT MUST provide the continuous pilot placement definition via the PLC in accordance with messaging formats contained in the MULPI specification.

The CLT MUST adhere to the rules given below for the definition of this set of continuous pilot locations conveyed to the CNU via PLC messaging. It is noted that these rules do not apply to the eight predefined pilots.

The CLT MUST place the continuous pilots generated using these rules in every OFDM symbol, in addition to the eight predefined continuous pilots.

The CLT MUST obtain the value of N_{CP} using the following formula:

$$N_{CP} = \min\left(\max\left(8, ceil\left(M * \left(\frac{F_{max} - F_{min}}{190e6}\right)\right)\right), 120\right) \quad (1)$$

In this equation F_{max} refers to frequency in Hz of the highest frequency active subcarrier and F_{min} refers to frequency in Hz of the lowest frequency active subcarrier of the OFDM channel. It is observed that the number of continuous pilots is linearly proportional to the frequency range of the OFDM channel. It may also be observed that the minimum number of continuous pilots defined using the PLC cannot be less than 8, and the maximum number of continuous pilots defined using the PLC cannot exceed 120. Therefore, the total number of continuous pilots, including the predefined ones, will be in the range 16 to 128, both inclusive.

The value of M in equation (1) is kept as a parameter that can be adjusted by the CLT. Nevertheless, the CLT MUST ensure that M is in the range given by the following equation:

$$120 \geq M \geq 48 \quad (2)$$

The typical value proposed for M is 48.

The CLT MUST use the algorithm given below for defining the frequencies for the location of these continuous pilots.

Step 1:

Merge all the subcarriers between F_{min} and F_{max} eliminating the following:

Exclusion bands

6 MHz band containing the PLC

Known regions of interference, e.g., LTE

Known poor subcarrier locations, e.g., CTB/CSO

Let the merged frequency band be defined as the frequency range $[0, F_{merged\_max}]$.

Step 2:

Define a set of N_{CP} frequencies using the following equation:

$$F_i = \frac{F_{merged\_max}}{2N_{CP}} + \frac{i * F_{merged\_max}}{N_{CP}}; \text{ for } i = 0, 1, \ldots, N_{CP} - 1 \quad (3)$$

This yields a set of uniformly spaced N_{CP} frequencies:

$$\{\frac{F_{merged\_max}}{2N_{CP}}, \frac{3F_{merged\_max}}{2N_{CP}}, \ldots, F_{merged\_max} - \frac{F_{merged\_max}}{2N_{CP}}\} \quad (4)$$

Step 3:

Map the set of frequencies given above to the nearest subcarrier locations in the merged spectrum. This will give a set of N_{CP} approximately uniformly spaced subcarriers in the merged domain.

Step 4:

De-merge the merged spectrum through the inverse of the operations through which the merged spectrum was obtained in step 1.

Step 5:

If any continuous pilot is within 1 MHz of a spectral edge, move this inwards (but avoiding subcarrier locations impacted by interferences like CSO/CTB) so that every continuous pilot is at least 1 MHz away from a spectral edge. This is to prevent continuous pilots from being impacted by external interferences. If the width of the spectral region does not allow the continuous pilot to be moved 1 MHz from the edge then the continuous pilot has to be placed at the center of the spectral band.

Step 6:

Identify any spectral regions containing active subcarriers (separated from other parts of the spectrum by exclusion bands on each side) that do not have any continuous pilots. Introduce an additional continuous pilot at the center of every such isolated active spectral region.

In the unlikely event that the inclusion of these extra pilots results in the total number of continuous pilots defined by PLC exceeding 120, return to step 1 and re-do the calculations after decrementing the value of N_{CP} by one.

Step 7:

Test for periodicity in the continuous pilot pattern and disturb periodicity, if any, through the perturbation of continuous pilot locations using a suitable algorithm. A simple procedure would be to introduce a random perturbation of up to ±5 subcarrier locations around each continuous pilot location, but avoiding subcarrier locations impacted by interferences like CSO/CTB.

The CLT MUST transmit this continuous pilot pattern to the CNUs in the system using the PLC.

Pilot Modulation

For both continuous and scattered pilots, the CLT MUST modulate these subcarriers as described in the following section.

Continuous and scattered pilots are BPSK modulated using a pseudo-random sequence. This pseudo-random sequence is generated using a 13-bit linear feedback shift register, shown in Figure 7–73 with polynomial (x^13+x^12+x^11+x^8+1).

This linear feedback shift register is initialized to all ones at the *k*=0 index of the 4K or 8K discrete Fourier transform defining the OFDM signal (refer to Section **IDFT**). It is then clocked after every subcarrier of the FFT. If the subcarrier is a pilot (scattered or continuous), then the BPSK modulation for that subcarrier is taken from the linear feedback shift register output.

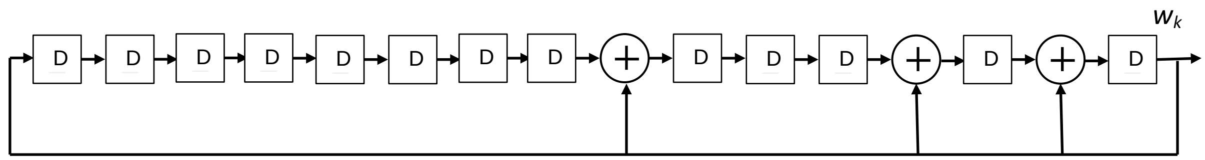


Figure 7–7 - 13-Bit Linear Feedback Shift Register for the Pilot Modulation Pseudo-Random Sequence

For example, let the output of the linear feedback shift register be w_k. The BPSK modulation used for the pilot would be:

$$w_k = 0:\ BPSK\ Constellation\ Point = 1 + j0$$

$$w_k = 1:\ BPSK\ Constellation\ Point = -1 + j0$$

Pilot Boosting

The CLT MUST multiply the real and imaginary components of continuous and scattered pilots by a real-valued number such that the amplitude of the continuous and scattered pilots is twice the root-mean-square value of the amplitude of other subcarriers of the OFDM symbol; That is, continuous and scattered pilots are boosted by approximately 6 dB with reference to other subcarriers.

Randomization

The CLT MUST randomize cell words of data subcarriers~~, NCP subcarriers and PLC subcarriers,~~ just before mapping these onto QAM constellations, as described in this section.

The CLT MUST also introduce BPSK-modulated subcarriers for the following subcarriers during the randomization process, as described in this section.

a) Zero-bit-loaded subcarriers of the codewords of individual profiles

~~b) Zero-bit-loaded subcarriers in the NCP segment~~

c) Zero-bit-loaded subcarriers that may be ~~are~~ introduced to complete the symbol

~~NCP and zero bit-loading are described in Section 7.5.5.5.~~

The wordlength (η_{MOD}) of a cell word ranges from 4 bits for 16-QAM to 14 bits for 16384-QAM.

For 16-QAM to 4096-QAM the CLT MUST randomize each cell word through a bit-wise exclusive-OR operation with the η_{MOD} least significant bits (LSBs) of the 12-bit register D0 of the linear feedback shift register (LFSR) shown in Figure 7–45.

$$\left(z_0 \ldots z_{\eta_{MOD}-1}\right) = \left(y_0 \ldots y_{\eta_{MOD}-1}\right)\ bitwiseXOR\ \ (D_0[0] \ldots D_0[\eta_{MOD} - 1])$$

For 8192-QAM the CLT MUST randomize the 13 bits of the cell word through a bit-wise exclusive-OR operation with the 12 bits of register D0 and the LSB of register D1 of Figure 7–45, as given below:

$$(z_0 \ldots z_{12}) = (y_0 \ldots y_{12})\ bitwiseXOR\ \ (D_0[0] \ldots D_0[\eta_{MOD} - 1]\ D_1[0])$$

For 16384-QAM the CLT MUST randomize the 14 bits of the cell word through a bit-wise exclusive-OR operation with the 12 bits of register D0 and the 2 LSBs of register D1 of Figure 7–45, as given below:

$$(z_0 \ldots z_{13}) = (y_0 \ldots y_{13})\ bitwiseXOR\ \ (D_0[0] \ldots D_0[\eta_{MOD} - 1]\ D_1[0]\ D_1[1])$$

~~NCP subcarrier cell words are 2-bit for QPSK, 4-bit for 16-QAM or 6-bit for 64-QAM. The CLT MUST randomize these through bit-wise exclusive-OR operation with the 2, 4 or 6 LSBs of the 12-bit register D0.~~

The CLT MUST set the zero-bit-loaded subcarriers in the data segment ~~and NCP segment~~ to the BPSK modulation given by LSB of register D0.

$$z_0 = D_0[0]$$

The CLT MUST clock the LFSR once, after each of the previous operations.

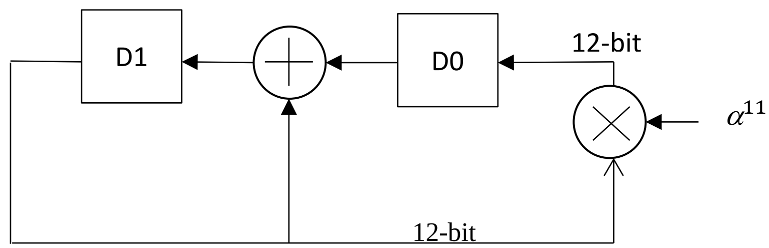


Figure 7–8 - Linear Feedback Shift Register for Randomization Sequence

The LFSR is defined by the following polynomial in $GF[2^{12}]$.

$$x^2 + x + \alpha^{11}$$

The $GF[2^{12}]$ is defined through polynomial algebra modulo the polynomial:

$$\alpha^{12} + \alpha^6 + \alpha^4 + \alpha + 1$$

Each 12-bit $GF[2^{12}]$ element is a polynomial of α with a maximum degree of 11. The coefficient of α^0 is referred to as the LSB and the coefficient of α^{11} is referred to as the MSB.

This LFSR is initialized to the hexadecimal numbers given below:

D0 = "555"

D1 = "AAA"

This initialization is carried out at the beginning of an OFDM symbol, synchronized to the preamble of the PLC. Since the PLC subcarriers are inserted after time and frequency interleaving and data subcarriers are randomized before time and frequency interleaving, the following explanation is provided about how randomization is synchronized to the PLC.

[NOTE: the following two paragraphs need to be updated as per the commutator change to the Time Interleaver.]

Note that the first subcarrier of an OFDM symbol passes through the time interleaver arm with zero delay. Therefore the LFSR is initialized when this subcarrier is part of the OFDM symbol following the last OFDM symbol carrying the PLC preamble. Hence LFSR is initialized once for every 128 OFDM symbols.

The first subcarrier referred to previously can be a data subcarrier or a scattered pilot placeholder because both of these are time interleaved. If it is a data subcarrier then the cell word of that data subcarrier is randomized with the initialized values of D0 and D1, namely hexadecimal "555" and "AAA". After that the LFSR is clocked once. If the first subcarrier mentioned previously is a scattered pilot placeholder the LFSR is initialized but it is not clocked. This is because the LFSR is clocked only after each data or NCP subcarrier (including zero-bit-loaded subcarriers).

Cell Word Mapping into I/Q Constellations

The CLT MUST modulate each randomized cell word from the randomizer described in Section ***Randomization*** using a BPSK, QPSK, 16-QAM, 64-QAM, 128-QAM, 256-QAM, 512-QAM, 1024-QAM, 2048-QAM, or 4096-QAM constellation.