Chapter 3

Orthogonal Frequency Division Multiplexing OFDM

3.1 Introduction

In this chapter we will try to give a detailed description of the OFDM system regarding its structure and spectrum issues, we will also discuss the topics related to it like the cyclic prefix and the different pilots arrangement. In each topic we will state how these are defined and related to the standard we follow [1]. Finally we will list some applications that are based on OFDM technique rather than the DVB-H system.

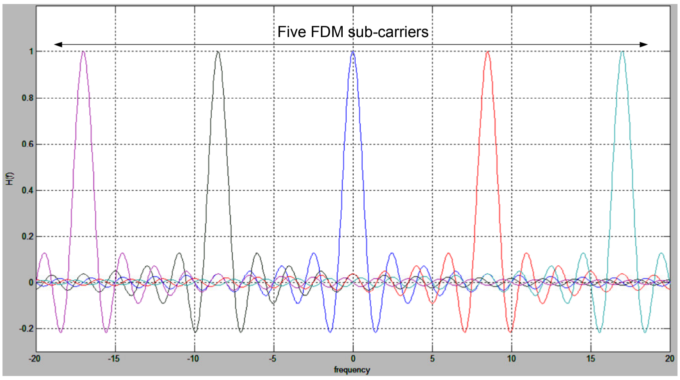
3.2 OFDM System Overview

Orthogonal Frequency Division Multiplexing technique was initially derived from the FDM (Frequency Division Multiplexing) one that was employed for telephone lines systems since 1920. It is based on dividing the available spectrum into equal narrow sub-bands and multiplexing them between different low-rate sources by assigning single or more sub-bands per source, such that every source can utilize part of the system spectrum for the whole time (opposite to the TDM (Time Division Multiplexing) system).

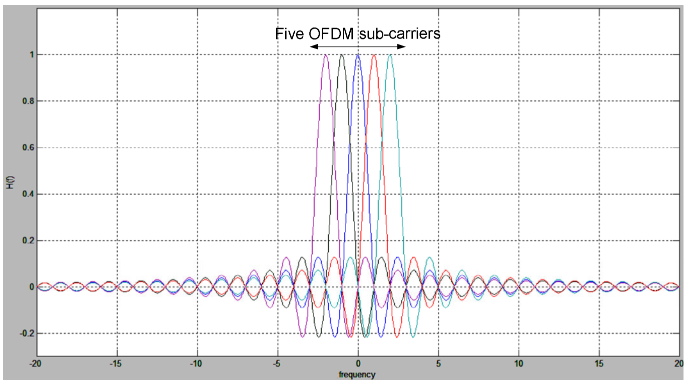
At the FDM receiver, to be able to receive the assigned sub-band without interference effect from the neighboring sub-bands, sufficient gaps have to be inserted between the sub-bands to ensure an accepted level of interference which will result in a degradation in the spectrum efficiency as these gaps will not be used for data transmission, i.e. waste of the system resources.

Introducing the OFDM technique, we were able to overcome the FDM drawbacks mentioned above beside other drawbacks like ISI (Inter Symbol Interference) and channel fading problems as will be shown later.

OFDM technique allows us to concatenate the previously mentioned sub-bands together in a smaller spectrum without needing to insert in-between gaps or worrying about the interference problem as the orthogonality principle – from which the name of the technique comes – guarantees the ability of easily separating the individual sub-channels at the receiver as will be explained in sub-section (3.3.3.1). Based on that, we will be able to transmit more and more channels on the allocated spectrum compared with the FDM system as shown in figure (3.1).



(a) FDM



(b) OFDM

Figure 3.1: Comparison of spectrum utilization for (a) FDM and (b) OFDM

The overlapped sub-bands of the OFDM system may be considered as different carriers each with small modulation bandwidth around it. That is why OFDM is also referred to as MCM (Multi Carrier Modulation) and DMT (Discrete Multi Tone) system but the MCM definition does not always guarantee that the orthogonality is fulfilled. In OFDM system it is not conditioned to have single source per carrier, the whole OFDM spectrum may be assigned to a single high data rate source, such that the symbols of the system are carried in parallel on the different carriers of the OFDM spectrum, in this way the symbol duration will be increased for times the number of symbols sent in parallel as shown in figure (3.2), where in the serial case the four QPSK symbols take about 25 seconds to be transmitted (symbol period = 6.25 seconds) while in the parallel case the four symbols are sent over 25 seconds but each symbol has symbol period of 25 seconds as they are sent over different carriers simultaneously. So, we may conclude that in comparison to single carrier system, the data can be sent over both systems with the same bit rate but the OFDM system will have longer symbol period. This effective increase in symbol period - beside the guard interval insertion that will be discussed in sub-section (3.3.4) - makes the OFDM able to overcome the ISI problem as it makes the symbol duration -in most applications- longer than channel impulse response (or the channel length as sometimes referred to), consequently it will be robust against long echoes of multi-path radio channels.

Regarding the fading problem, specially the frequency selective fading, this problem was greatly solved by the OFDM technique because selective fading that affects the wide-band of single carrier system is transformed into flat fading that affects single narrow-band sub-carriers and consequently rather than affecting the composite time domain signal in the single carrier case, only one or two symbols – depending on the number of sub-carriers that will be affected by the fading – will be distorted in the OFDM case.

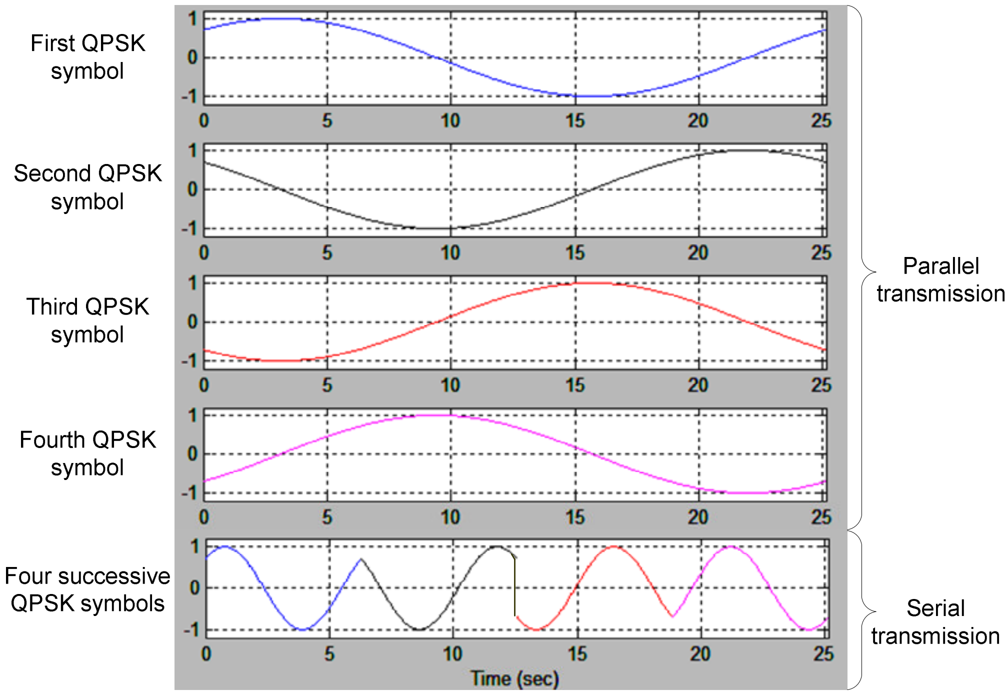


Figure 3.2: Effective Increase in symbol duration due to parallel transmission

As we see till now, the OFDM implementation needs generation of set of carriers with different frequencies. At the start of the system emersion, this was complicated as we need a bank of oscillators at both transmitter and receiver sides plus the sophisticated Fourier and inverse Fourier transforms computations. But nowadays, the great progress in the field of VLSI (Very Large Scale Integration) chips design and fabrication and the field of DSP (Digital Signal Processing) makes both generation of the different carrier frequencies and the Fourier transform computation based on the fast technique FFT (Fast Fourier Transform) easily feasible.

3.3 System Architecture

Based on the DVB-H system description we discussed in chapter two which demonstrates the randomization, coding, interleaving and mapping applied to the input data stream, the last format we reached was the vector representation $Y = (y_0, y_1, y_2, ..., y_{1511})$ as depicted by equation (2.13) in sub-section (2.2.5.2), where '1511' represents maximum data carrier index in case of DVB-H system 2K mode.

In order to carry out the OFDM modulation, the outcome of the symbol-wise interleaver and the signal constellation mapper will be applied to the set of blocks shown in figure (3.3) which represents the basic block diagram of the OFDM system added to it the specifications of the DVB-H standard. The detailed explanation of each of these blocks will be given in the following sub-sections with an illustration of the orthogonality concept.

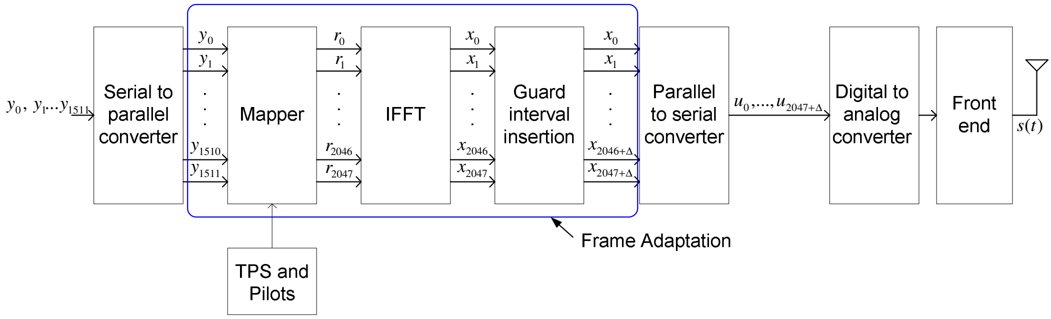


Figure 3.3: OFDM system block diagram with DVB-H specifications

3.3.1 Serial to Parallel Conversion

As we stated previously, the OFDM systems are working based on carrying many low data-rate narrow-band modulated signals on the allocated spectrum instead of one high data-rate signal with wide-band. This can be achieved through transforming the serial output represented by vector 'Y' into parallel signals as shown in figure (3.2). The number of bits carried over each single parallel line depends on the modulation scheme we follow, i.e. bits per line in QPSK case will be two, while it will be four and six in case of 16-QAM and 64-QAM respectively. Consequently the number of data bits per an OFDM symbol will be equal to the number of data bits per parallel line multiplied by the number of the output parallel lines.

3.3.2 TPS and Pilots Mapping

The outcome of the serial to parallel converter will not be directly applied to the IFFT (Inverse Fast Fourier Transform) block as there is other information that must be added to the OFDM symbol in order to be able to receive and read the data correctly at the receiver side. This information includes the pilots and the TPS (Transmission Parameter Signaling), where pilots help the receiver in estimating the RF channel, thus being able to enhance the SNR (Signal to Noise Ratio), while TPS signals define the structure of the system as will be shown in sub-section (3.3.2.2).

3.3.2.1 Pilots

As the radio signal propagates through the RF channel, it suffers many impairments such as amplitude attenuations and phase variations. These undesirable effects result in erroneous reception of the data bits. Alongside the interleaving and error correction codes, a set of sub-carriers - named as *pilots* – are inserted within the sub-carriers that carry the data such that the amplitudes and phases of these pilots are previously known by the receiver. Transmitting the composite radio signal on the RF channel, both data and pilots sub carriers will have roughly the same amplitude and phase variations with minor differences. However, receiving these pilots while having a complete previous knowledge about its values prior to the incidence of the channel effect, makes it possible to estimate the channel characteristics in frequency domain $H(\omega)$ at these pilots frequencies. This knowledge of some points of the channel transfer function facilitates the estimation of the rest of the transfer function at the desired data sub carriers frequencies and consequently the equalization of the channel effect to a large extent and obtaining better reception quality.

The pilots are also used for frequency synchronization, following the phase noise and identification of the transmission mode but in this thesis we are mainly concerned about the utilization of the pilots in channel estimation purpose.

3.3.2.1.a Comb Type Pilots

Generally, pilots may be arranged in many forms within the OFDM symbols. The comb type pilot arrangement is one of the most two known types of these arrangements (the second one will be discussed in the next sub-section). Comb type pilots are arranged such that on every OFDM symbol, individual sub-carriers will be always sent as pilots as shown in figure (3.4). This type of arrangement is used for fast varying channels as the channel characteristics may change within the duration of single OFDM symbol.

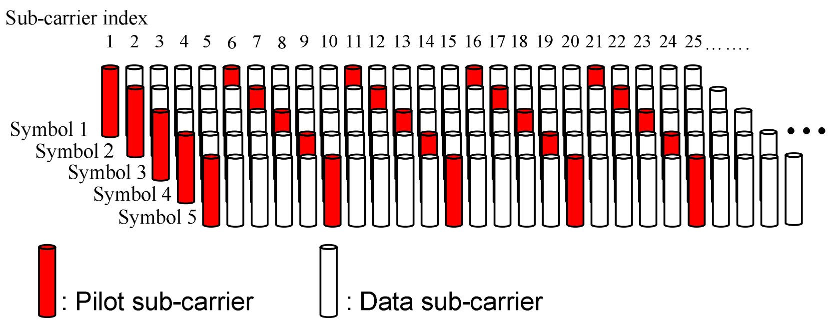


Figure 3.4: Comb type pilot arrangement

3.3.2.1.b Block Type Pilots

It is the other major type of pilots arrangement in which all sub-carriers in some periodically chosen OFDM symbols will be transmitted as pilots as shown in figure (3.5). Block type pilots are usually applied for the systems with slowly changing channels as the channel will not change a lot for several OFDM symbols and if the channel stay the same between two successive pilots OFDM symbols, we can find exact channel estimation for the in-between data symbols.

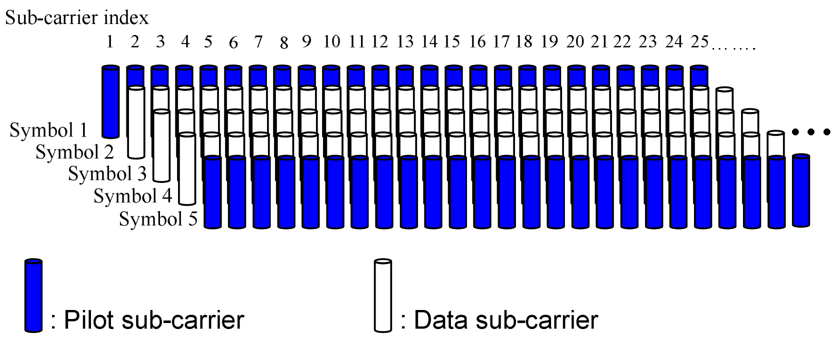


Figure 3.5: Block type pilot arrangement

Mapping and positions of pilots employed in the DVB-H system are precisely defined in the DVB-H standard [1] as will be illustrated here in the following sub-section. For the easiness of dealing with the sub carriers, an index will be defined for it following the index used in the standard, such that the index numbering of the sub carriers will range from $K_{\min}$ to $K_{\max}$, where $K_{\min}$ = 0 for any mode while $K_{\max}$ =1704, 3408 and 6816 for the 2K, 4K and 8K modes respectively. This index range includes data, pilots and TPS sub carriers. While data symbols are transmitted with normalized energy levels of one, the pilots are sent at a boosted energy level of $E[c \times c^{*}] = \frac{16}{9}$, where this value come from the modulation scheme applied to the pilots that is defined by equations (3.1 and 3.2)

$$\mathrm{Re}\{c_{m,l,k}\} = \frac{4}{3} * 2(\frac{1}{2} - w_k) \tag{3.1}$$

$$\mathrm{Im}\{c_{m,l,k}\} = 0 \tag{3.2}$$

where,

m : OFDM frame index

l : OFDM symbol time index (range from 0 to 67)

k : OFDM sub carrier index

$c_{m,l,k}$: Complex symbol carried on sub carrier k of OFDM symbol l in frame m

w_k : PRBS output (either 0 or 1)

w_k mentioned in equation (3.1) and denoted as the PRBS output represents a key element in the modulation of the pilots. As the pilots sub carriers will carry no data, a symbol value must be assigned to it in order to apply modulation, but it can not be assigned a value of one for all pilots neither a value of zero as this will lead to the appearance of single spectral lines in the OFDM spectrum that may cause problems in carrier synchronization and clock recovery. So, we have to assign a random pattern of zeros and ones to be carried on the pilots but as we stated before, the values of the pilots must be previously known at the receiver, thus we have to generate it in a random way at the transmitter side such that the receiver can generate it in exactly the same random way. That is why a PRBS generator was used as illustrated in figure (3.6); it consists of eleven shift registers initialized with a sequence of eleven ones at every OFDM symbol start. The PRBS - also known as the reference sequence - will continue generating zeros and ones whether the sub carrier is a data or pilot one, but the PRBS output value w_k will be assigned to the sub-carrier according to its index k, i.e. when the sub-carrier index coincides with one of the predefined pilot indices, the sub-carrier will take its value from the PRBS output.

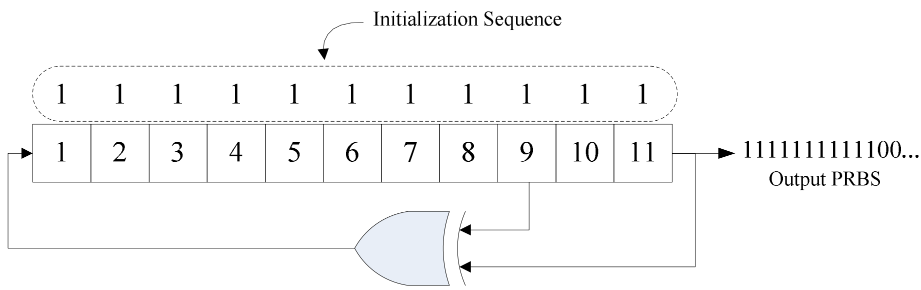


Figure 3.6: Reference Sequence PRBS generator

Invoking equations (3.1 and 3.2), we note that the modulation of the pilots sub carriers is effectively a BPSK (Binary Phase Shift Keying) one as we see from the following illustration:

$$\text{If } w_k = 0\text{ , } \operatorname{Re}\{c_{m,l,k}\} = \frac{4}{3} \text{ and } \operatorname{Im}\{c_{m,l,k}\} = 0 \tag{3.3}$$

$$\text{If } w_k = 1\text{ , } \operatorname{Re}\{c_{m,l,k}\} = \frac{-4}{3} \text{ and } \operatorname{Im}\{c_{m,l,k}\} = 0 \tag{3.4}$$

That is to say we have only two symbol values with phase difference = 180°.

Regarding the DVB-H system, pilots are mainly categorized into two categories, the scattered pilots and the continual pilots as will be discussed in the next two sub-sections.

3.3.2.1.c Scattered Pilots

Scattered pilots are sent in a periodic manner either in the time domain or in the frequency domain. For the frequency domain we have a scattered pilot pattern with periodicity of twelve (e.g. 1, 13, 25, …) but the start of each pilots pattern will not always be at sub-carrier index '1' as the first OFDM symbol in the frame, it will differ from symbol to another which leads us to the time domain periodicity where the frequency pilots pattern will be repeated every four OFDM symbols, i.e. pilots of the fifth OFDM symbol will also start at sub-carrier index '1'. This theoretical illustration may be also summarized through equation (3.5) that gives the complete definition of scattered pilots indices:

$$k_{scatterd\ pilot} = K_{\min} + 3 * (l(\text{mod})4) + 12 * p \qquad (3.5)$$

where,

$k_{scattered\ pilot}$: scattered pilot index

p : an integer that takes values ≥ 0, such that $k_{scattered\ pilot} \in [K_{\min}, K_{\max}]$

For raveling out what equation (3.5) represents, we will substitute in it by some numerical values to clarify the time domain and frequency domain periodicities we stated before, as introduced below in table (3-1):

Table 3-1: Scattered pilots indices

l \ *p*	***0***	***1***	***2***	***3***	**…….**	***139***	***140***	***141***	***142***
0	0	12	24	36	…….	1668	1680	1692	1704
1	3	15	27	39	…….	1671	1683	1695	1707
2	6	18	30	42	…….	1674	1686	1698	1710
3	9	21	33	45	…….	1677	1689	1701	1713
4	0	12	24	36	…….	1680	1680	1692	1704

Considering the entries of table (3-1), we may note the following. As we increase the value of p by one, the pilot index increases by twelve which is the frequency domain periodicity we stated before. Also, the pilots pattern of the fifth symbol ($l = 4$) is a repetition of that of the first symbol ($l = 0$) which demonstrates the period of four in the time domain as we previously mentioned. Finally the shading of the last column is to mark out where the scattered pilots indices stop as we have to fulfill the limits inequality, $K_{\min} \le k_{scattered\,pilot} \le K_{\max}$, where $K_{\max}$ = 1704 as we take the 2K mode as our example.

Scattered pilots format may be further illustrated through figure (3.7) in which we illustrate the scattered pilots positions within the data sub-carriers and how their levels are relatively higher than the data ones.

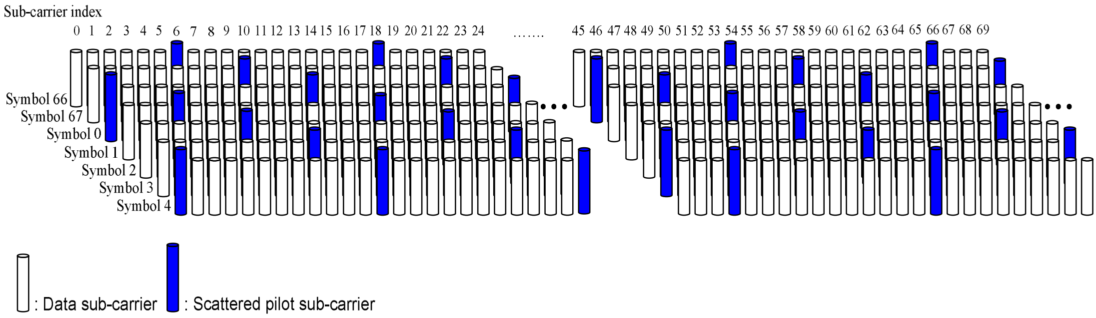


Figure 3.7: Scattered pilots pattern

3.3.2.1.d Continual Pilots

By analogy to what we explained before, we may say that the continual pilots have no periodicity in the frequency domain while it has periodicity of one in the time domain, i.e. the continual pilots do not follow a uniform pattern in the frequency domain while it is repeated for every OFDM symbol – comb type – with the same positions whatever the index of this symbol as shown below in figure (3.8).

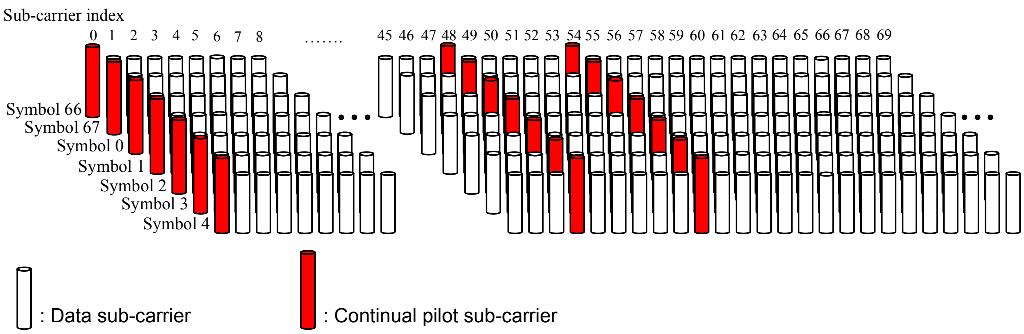


Figure 3.8: Continual pilots pattern

Defining the continual pilots as not having a uniform pattern, its indices have to be defined one by one as will be stated in the appendix where tables (A-1, A-2 and A-3) define their positions for the 2K (45 continual pilots), 4K (89 continual pilots) and 8K (177 continual pilots) modes respectively.

Adding the continual pilots to the pattern of pilots shown in figure (3.7), we will have the following complete DVB-H pilots representation displayed in figure (3.9).

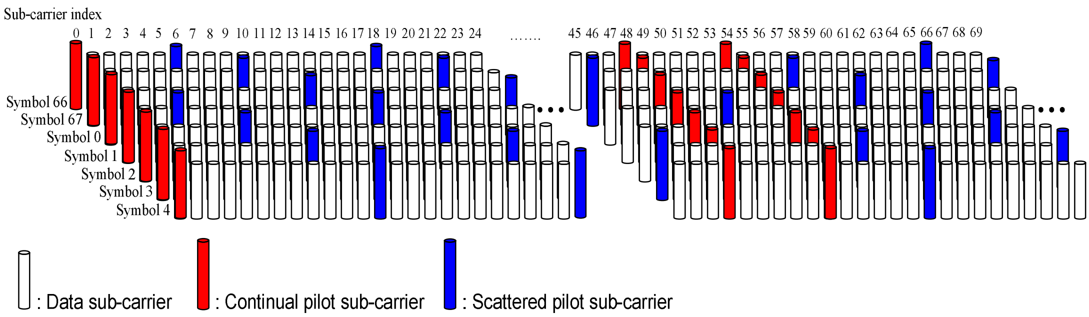


Figure 3.9: Complete DVB-H pilots pattern (Scattered and continual)

3.3.2.2 TPS (Transmission Parameter Signaling)

Considering what we illustrated since the start of chapter two till now, we note that there are so many specifications regarding the structure of an OFDM symbol in the DVB-H system, such as the code rate to be used in the punctured convolutional encoder, hierarchical/non-hierarchical mode, uniform/non-uniform constellation diagrams,… . All these information are transmitted on a pre-defined set of sub-carriers called the TPS sub-carriers. These sub-carriers are transmitted in the same format of continual pilots, i.e. no uniform pattern (no periodicity) in the frequency domain and repeated for every single OFDM symbol in the same positions in the time domain (periodicity of one) [10]. Similar to the continual pilots case, the TPS sub-carriers indices for the 2K (17 TPS sub-carrier), 4K (34 TPS sub-carrier) and 8K (68 TPS sub-carrier) modes will be listed in the appendix in tables (A-4, A-5 and A-6).

These TPS sub-carriers will carry the specifications related to the parameters listed below in table (3-2):

Table 3-2: Parameters specified by the TPS sub-carriers

Parameter	Specifications carried on the TPS sub carriers
Modulation scheme	QPSK, 16-QAM or 64-QAM and the value of α
Hierarchy	Hierarchical or non-Hierarchical transmission
Guard Interval	Length of guard interval (to be explained in sub-section (3.3.4))
Code rates	Inner punctured convolutional encoder rate (1/2, 2/3, 3/4, 5/6, 7/8)
Transmission mode	2K, 4K or 8K
Frame number	Frame position in the super-frame format
Cell identification	Cell-ID of the transmitting station

For full definition of these parameters, we need only 68 bits defined as the 'TPS block' and are categorized as depicted in table (3-3):

Table 3-3: TPS bits categorization

Function	Number of bits
Initialization	1
Synchronization	16
Information	37
Redundancy for error correction	14

These bits can be further itemized as illustrated here in table (3-4), while its format will be explained in the following sub-sections:

Table 3-4: TPS bits groups functions

Bit index	Function
s_0	Initialization
s_1 to s_{16}	Synchronization word
s_{17} to s_{22}	TPS length indicator
s_{23} , s_{24}	Frame number
s_{25} , s_{26}	Constellation diagram
s_{27}	Interleaving
s_{28} , s_{29}	Hierarchy
s_{30} , s_{31} , s_{32}	HP stream code rate
s_{33} , s_{34} , s_{35}	LP stream code rate
s_{36} , s_{37}	Guard interval
s_{38} , s_{39}	Transmission mode
s_{40} to s_{47}	Cell identification
s_{48} , s_{49}	DVB-H signaling
s_{50} to s_{53}	Set to zero
s_{54} to s_{67}	Error protection

As we see from table (3-4), the information carried by the TPS sub-carriers are of great importance, in order to protect it against deep fades and other channel effects, BCH coding is applied for error correction beside some sort of diversity as only one TPS bit will be transmitted per OFDM symbol (68 TPS bits over 68 OFDM symbols that constitute one

OFDM frame), such that every single TPS bit per OFDM symbol will be repeated over all TPS sub-carriers assigned for that symbol, i.e. in 2K mode every TPS bit will be repeated 17 times per OFDM symbol at the sub-carriers indices listed in table (A-4).

3.3.2.2.a Initialization

The TPS sub-carriers are DBPSK (Differential Binary Phase Shift Keying) modulated, i.e. we have to define an initialization bit which will be xor-ed with first TPS bit to be transmitted, this is the function carried through the first bit of the TPS block, s_0. The value of this bit is derived from the PRBS or reference sequence (w_k) defined in sub section (3.3.2.1) as follows:

$$\mathrm{Re}\{c_{m,l,k}\} = 2(\frac{1}{2} - w_k) \quad (3.6)$$

$$\mathrm{Im}\{c_{m,l,k}\} = 0 \quad (3.7)$$

This means that the TPS carriers are transmitted at normal - not boosted - power level as their energy = $E[c \times c^*] = 1$ like the data OFDM sub-carriers. Defining the value of s_0 we can carry on the DBPSK modulation defined below in equations (3.8 and 3.9) for carrier k of symbol l ($l \succ 0$) in frame m:

If $s_l = 0$, $\mathrm{Re}\{c_{m,l,k}\} = \mathrm{Re}\{c_{m,l-1,k}\}$ and $\mathrm{Im}\{c_{m,l,k}\} = 0$ (3.8)

If $s_l = 1$, $\mathrm{Re}\{c_{m,l,k}\} = -\mathrm{Re}\{c_{m,l-1,k}\}$ and $\mathrm{Im}\{c_{m,l,k}\} = 0$ (3.9)

3.3.2.2.b Synchronization

As the OFDM super-frame consists of four OFDM frames, these frames are identified within the super-frame by defining the bits of s_1 to s_{16} as ‘0011010111101110’ for the first and third TPS blocks (first and third OFDM frames) in each OFDM super-frame. While for the second and fourth TPS blocks in the same OFDM super-frame s_1 to s_{16} are defined as ‘1100101000010001’which is the inversion of the last one.

3.3.2.2.c TPS Length Indicator

TPS length indicator bits will be the first information bits to be transmitted of the 37 bits defined in table (3-3), where the six bits (s_{17} to s_{22}) will represent a count of the number of the TPS information bits used according to the following three different situations listed in table (3-5):

Table 3-5: Different situations of TPS length indicator bits and its format

Situation	Bits s_{17} to s_{22}
Cell identification information NOT transmitted	010111 (23 TPS bits)
Cell identification information transmitted	011111 (31 TPS bits)
DVB-H signaling used	100001 (33 TPS bits)

3.3.2.2.d Frame Number

Defining the super-frame as consisting of four OFDM frames, we have to determine which OFDM frame is sent at this instance. This is accomplished through the s_{23} and s_{24} bits that are defined as follows in table (3-6):

Table 3-6: Format of TPS bits allocated for frame number definition

OFDM Frame number in the OFDM super-frame	Bits s_{23} and s_{24}
1	00
2	01
3	10
4	11

3.3.2.2.e Constellation

Referring to the modulation schemes defined in sub-section (2.2.6), the s_{25} and s_{26} bits are allocated for marking out which scheme is used as illustrated below in table (3-7):

Table 3-7: Format of TPS bits allocated for modulation scheme specification

Modulation scheme	Bits s_{25} and s_{26}
QPSK	00
16-QAM	01
64-QAM	10
Reserved	11

3.3.2.2.f Interleaving

Reviewing the inner interleaver explained in sub-section (2.2.5), it has to be determined if we carry out the native interleaving (2K, 4K and 8K modes) or the in-depth interleaving (2K and 4K), this is defined through bit s_{27} as clarified below in table (3-8):

Table 3-8: Format of TPS bit allocated for inner interleaver specification

Inner interleaver	**Bit s_{27}**
Native interleaver	0
In-depth interleaver	1

3.3.2.2.g Hierarchy

Completing the definition of the modulation schemes, we have to indicate if this scheme is uniform or non-uniform depending on the value of α, which is directly related to the hierarchy issue as non-hierarchical transmission applies uniform constellation with $\alpha = 1$, while for hierarchical transmission α may take any of the pre-defined values in sub-section (2.2.6). Designation of such hierarchy information will be carried on s_{28} and s_{29} bits as defined below in table (3-9):

Table 3-9: Format of TPS bits allocated for Hierarchy information specification

α	**Bits s_{28} and s_{29}**
Non-hierarchical	00
1	01
2	10
4	11

3.3.2.2.h Code Rates

Classifying transmission as hierarchical and non-hierarchical was mainly for the sake of protecting set of data bits (HP bits) with higher degree of redundancy than the rest of bits (LP bits). So, for non-hierarchical mode in which all bits are equally protected, we need to define single coding rate labeled by the s_{30}, s_{31}, s_{32} bits according to the values listed in table (3-10), while s_{33}, s_{34}, s_{35} bits are set to zero. Regarding the hierarchical mode, two coding rates have to be defined, one for the HP stream and the other for the LP stream where the first one will be carried over the s_{30}, s_{31}, s_{32} bits and the second on the s_{33}, s_{34}, s_{35} bits as follows:

Table 3-10: Format of TPS bits allocated for coding rate specification

Coding rate	**Bits s_{30}, s_{31} and s_{32} (Non-hierarchical or HP)** **Bits s_{33}, s_{34} and s_{35} (set to zero or LP)**
1/2	000
2/3	001
3/4	010
5/6	011
7/8	100
Reserved	101
Reserved	110
Reserved	111

3.3.2.2.i Guard Interval

As will be further explained in sub-section (3.3.4), we add a guard interval between the OFDM symbols in the time domain to combat the effect of echoes, where its length varies according to the severity of the radio channel through which the signal propagates. These different values (normalized to the useful duration of the OFDM symbol T_U) alongside its bit allocation on the s_{36} and s_{37} bits are listed below in table (3-11):

Table 3-11: Format of TPS bits allocated for guard interval specification

Normalized guard interval length	**Bits s_{36} and s_{37}**
1/32	00
1/16	01
1/8	10
1/4	11

3.3.2.2.j Transmission Mode

DVB-H is working with different modes and different number of sub-carriers for each mode and according to the FFT size that is most appropriate for this number of sub-carriers (first number that is power of two and higher than the number of sub-carriers) the mode takes its name. Consequently we have 2K, 4K and 8K modes defined through s_{38} and s_{39} bits as listed in table (3-12):

Table 3-12: Format of TPS bits allocated for transmission mode identification

Transmission mode	Bits s_{38} and s_{39}
2K	00
8K	01
4K	10
Reserved	11

Note that, although 4K mode is smaller than 8K mode in terms of number of sub-carriers, but it is order as a binary count is higher than that of 8K mode as the 4K mode is recently added to the specification of the standard as a specialized one for the mobile terminals reception.

3.3.2.2.k Cell Identification

A cell is defined as the geographical area covered with the DVB-H signals, where the cell is uniquely identified to the system through a cell identification called ‘cell_ID’ [2]. This cell_ID supports the frequency handover and quicker signal scan. It is represented into sixteen bit field (b_{15} to b_0) that is optionally transmitted on the previously allocated bits s_{40} to s_{47} such that, the most significant byte (b_{15} to b_8) will be transmitted over the s_{40} to s_{47} bits in the odd frames of the super-frame, while the least significant byte (b_7 to b_0) will be transmitted over the s_{40} to s_{47} bits in the even frames of the same super-frame as depicted in table (3-13):

Table 3-13: Format of TPS bits allocated for cell identification

Odd frames (frame 1 or 3)	Even frames (frame 2 or 4)	Bits s_{40} to s_{47}
Cell_ID b_{15}	Cell_ID b_7	s_{40}
Cell_ID b_{14}	Cell_ID b_6	s_{41}
Cell_ID b_{13}	Cell_ID b_5	s_{42}
Cell_ID b_{12}	Cell_ID b_4	s_{43}
Cell_ID b_{11}	Cell_ID b_3	s_{44}
Cell_ID b_{10}	Cell_ID b_2	s_{45}
Cell_ID b_9	Cell_ID b_1	s_{46}
Cell_ID b_8	Cell_ID b_0	s_{47}

If the cell_ID was not planned to be provided by the system, bits s_{40} to s_{47} will be set to zero.

3.3.2.2.l DVB-H Signaling

It is especially added for the DVB-H system over the DVB-T (Digital Video Broadcasting -Terrestrial) in order to enhance and speed up the DVB-H service discovery to the receivers through providing an easy signaling access. This was possible to be done by using the s_{48} to s_{53} bits that were previously reserved in the DVB-T standard and were initially set to zero. So, the s_{48} and s_{49} bits are allocated for the DVB-H signaling to inform the receivers about the availability of a DVB-H transmission through marking out two parameters that are essential in any DVB-H transmission which are the time slicing and the MPE-FEC (Multi Protocol Encapsulation – Forward Error Correction).

Time slicing was especially proposed for the DVB-H system where the services are transmitted in form of bursts (some sort of TDM) as shown in figure (3.10), so the receiver can switch off its demodulation in between these bursts and consequently save the battery of the handheld terminals, where it also provides the soft handover between the cells during the motion of the receiver [2].

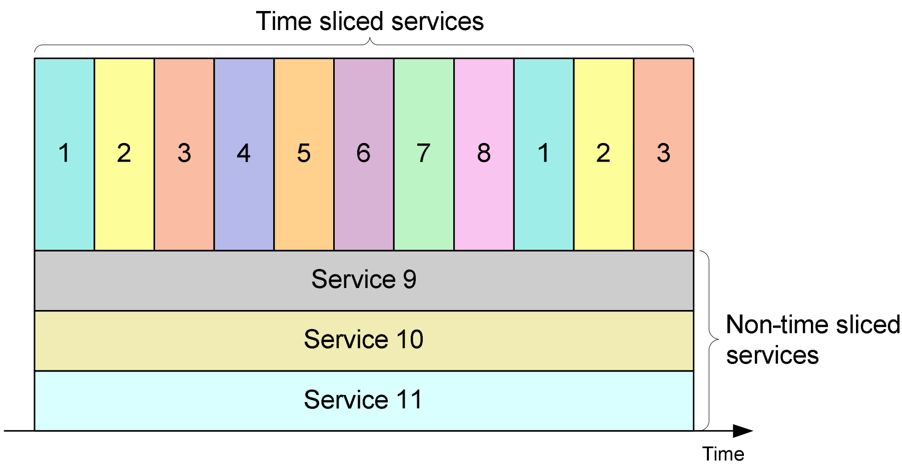


Figure 3.10: Time slicing of the DVB-H services

Similar to the time slicing, MPE-FEC was also introduced to relax the SNR requirements for the mobile receivers. Signaling of such two processes is carried on s_{48} and s_{49} according to the specifications listed in table (3-14):

Table 3-14: Format of TPS bits allocated for DVB-H signaling specifications

DVB-H Signaling	Bit s_{48}	Bit s_{49}
Time Slicing not applied	0	X
Time slicing is applied in at least one stream	1	X
MPE-FEC not applied	X	0
MPE-FEC is applied in at least one stream	X	1

Where 'X' means 'don not care' or that only value of the other bit is important whatever the value of 'X' is (0 or 1). We have to highlight that the transmission format of these signaling bits also depends upon the hierarchy mode as shown here in table (3-15):

Table 3-15: Format of DVB-H signaling bits (s_{48} and s_{49}) related to the hierarchy

<table>
<tr><th>Hierarchical Transmission</th><th>Non-Hierarchical Transmission</th></tr>
<tr><td>Frame 1 and 3 carries HP stream DVB-H signaling</td><td rowspan="2">Frame 1 to 4 carries the same signaling for the whole stream</td></tr>
<tr><td>Frame 2 and 4 carries LP stream DVB-H signaling</td></tr>
</table>

3.3.2.2.m Error Protection

So far we have defined the function of the 53 bits defined as the synchronization and information bits in table (3-3). Finally and for extra protecting these important bits (beside the frequency diversity represented before), an BCH coding is applied to it such that a set of 14 parity bits are appended to the 53 synchronization and information bits by applying the BCH shortened code (67, 53, t = 2) defined by the code generator polynomial of equation (3.10):

$$h(x) = x^{14} + x^{9} + x^{8} + x^{6} + x^{5} + x^{4} + x^{2} + x + 1 \qquad (3.10)$$

similar to the shortened RS code defined in sub-section (2.2.2), the shortened BCH code is derived from the original BCH code (127, 113, t = 2) by adding 60 zeros prior to the 53 data bits and then discard them at the output of the encoder, so we get the coded 67 bits we need.

3.3.3 Inverse Fast Fourier Transform (IFFT)

Referring back to what we stated in section (3.1), the OFDM system in its simplest form can be viewed as a transformation for a symbol stream from the serial form to the parallel one such that we have a symbol per each parallel line, then we will carry each symbol on a sub-carrier such that these carriers will be orthogonal to each other to obtain the previously mentioned advantages. From analog point of view we may say that we need an oscillator and multiplier per each symbol line as shown in figure (3.11) which is expensive and also so complicated regarding the hardware implementation and keeping the synchronization and the stability of all oscillators.

Let us try to write the equation that describes the outcome of such a system taking the 2K mode as an example as follows in equation (3.11):

$$s(t) = y_0 e^{j2\pi f_0 t} + y_1 e^{j2\pi f_1 t} + \ldots + y_{1510} e^{j2\pi f_{1510} t} + y_{1511} e^{j2\pi f_{1511} t} \qquad (3.11)$$

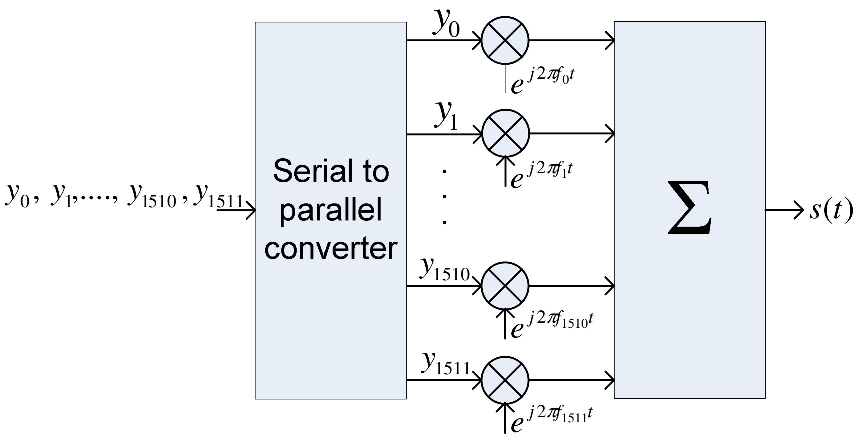


Figure 3.11: Basic structure of the OFDM signal

Comparing equation (3.11) to the basic equation that describes the IDFT (Inverse Discrete Fourier Transform) [11] written below in equation (3.12), where n, N and q are integers, we may see the similarity between them regarding that equation (3.12) may be considered as a digital representation of equation (3.11) with the scaling factor ($1/N$) and frequency difference between any two successive frequencies of ($1/N$).

$$x_n = \frac{1}{N}\sum_{q=0}^{N-1} X_q e^{\frac{j2\pi nq}{N}} \quad , \quad n = [0, N-1] \tag{3.12}$$

Consequently we may replace the OFDM sub-carriers by the harmonically related frequencies of the IDFT, so we can perform the OFDM modulation depicted in figure (3.11) in a simpler and cheaper way especially with the enormous progress in the DSP field that make it possible to make these N modulations through one step by applying the

IFFT which is a simpler approach that computes the IDFT with reduced number of mathematical operations from N^2 to $N\log_2 N$.

Revising the OFDM symbol representation stated in the DVB-H standard [1], we may note that it slightly differs than equation (3.11). In this part we will try to clarify these differences starting with writing the OFDM symbol as represented in the standard, here in equations (3.13) and (3.14):

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=K_{\min}}^{K_{\max}} c_{m,l,k} \times \psi_{m,l,k}(t) \right\} \tag{3.13}$$

where,

$$\psi_{m,l,k}(t) = \begin{cases} e^{j2\pi \frac{k'}{T_U}(t-\Delta-(l*T_s)-(68*m*T_s))} & ,(l+68*m)T_s \le t \le (l+(68*m)+1)T_s \\ 0 & ,else \end{cases} \tag{3.14}$$

$$k' = k - \left(\frac{K_{\min} + K_{\max}}{2} \right) \tag{3.15}$$

T_s : OFDM symbol duration

T_U : OFDM useful part duration = (1/sub-carriers spacing)

Δ : Guard interval duration

f_c : Central frequency of the RF signal

k' : Carrier index relative to the center frequency

Trying to illustrate what these equations represent, we will substitute in it for the 2K mode, first frame ($m=0$) and first OFDM symbol ($l=0$), so we get:

$$k^{'} = k - \left(\frac{0+1704}{2}\right) = k - 852 \qquad (3.16)$$

$$s(t) = \mathrm{Re}\begin{cases} e^{j2\pi f_c t} \sum_{k=K_{\min}}^{K_{\max}} c_{0,0,k} \times e^{j2\pi \frac{(k-852)}{T_U}(t-\Delta)} & , \ 0 \le t \le T_s \\ 0 & , else \end{cases} \qquad (3.17)$$

We will study single OFDM symbol duration only ($0 \le t \le T_s$) where in this case $s(t)$ represents single OFDM symbol in time domain, which means it has to be the sum of all sub-carriers that compose this symbol which is represented by the summation $\sum_{k=K_{\min}}^{K_{\max}}$, while $c_{0,0,k}$ is the symbol (QPSK, 16-QAM, 64-QAM) carried on each sub-carrier of the first OFDM symbol in the first frame.

The exponent of the second term inside the summation $2\pi \frac{(k-852)}{T_U}$ defines the frequencies of the different sub-carriers of the OFDM symbol where multiplying them by the carrier frequency $e^{j2\pi f_c t}$ they will be centered around the central frequency of the RF signal f_c – the up-conversion at the front end stage – because of the definition of the relative carrier index $k^{'}$ that leads to the following frequency boundaries:

for $k = K_{\min}$, first sub-carrier frequency $= f_c - \dfrac{852}{T_U}$ (3.18)

for $k = K_{\max}$, last sub-carrier frequency $= f_c + \dfrac{852}{T_U}$ (3.19)

Where the whole bandwidth of the OFDM symbol $=1704/T_U$. So as k scans from $K_{\min}$ to $K_{\max}$, the whole OFDM symbol will be constructed.

It is to be noted that as we substitute with the time domain limits in equation (3.17), the time term in the exponent of the second term inside the summation, $(t-\Delta)$ will scan the values from $-\Delta$ to $T_s - \Delta$ which is equivalent to the duration from 0 to T_s, but to highlights the guard band duration which will be from $-\Delta$ to 0 and will be discarded at the receiver, while the useful part of the OFDM symbol will be from 0 to $(T_s - \Delta) = T_U$.

Recall that all our discussion since equation (3.16) was on the first symbol in the first frame of an OFDM transmission for DVB-H on 2K mode. Continuing the substitution of l till 67 with $m = 0$, the same frequency modulation will be repeated regarding the k index explanation illustrated above, while regarding the time limits, it will be ($67T_s \le t \le 68T_s$) which means we reached the end of an OFDM frame that necessitates the increment of the frame index to $m = 1$ which in turn will update the time limits to be ($68T_s \le t \le 69T_s$) that clarifies the continuity of the signal $s(t)$.

Practically the FFT and IFFT operations are performed on number of samples with size of 2^M where M is an integer, giving the same number of samples at the output. As the number of active sub-carriers for the 2K, 4K and 8K of the DVB-H system are 1705, 3409 and 6817 respectively, where none of them is power of 2, so we choose the IFFT of size equals to the next higher power of 2, such that the IFFT size for the three modes will be 2048, 4096 and 8192 respectively and the extra added IFFT pins will be set to zero for frequency shaping as shown for the 2K mode in figure (3.12), where an IFFT pin refers to a single point in the spectrum to which IFFT will be applied.

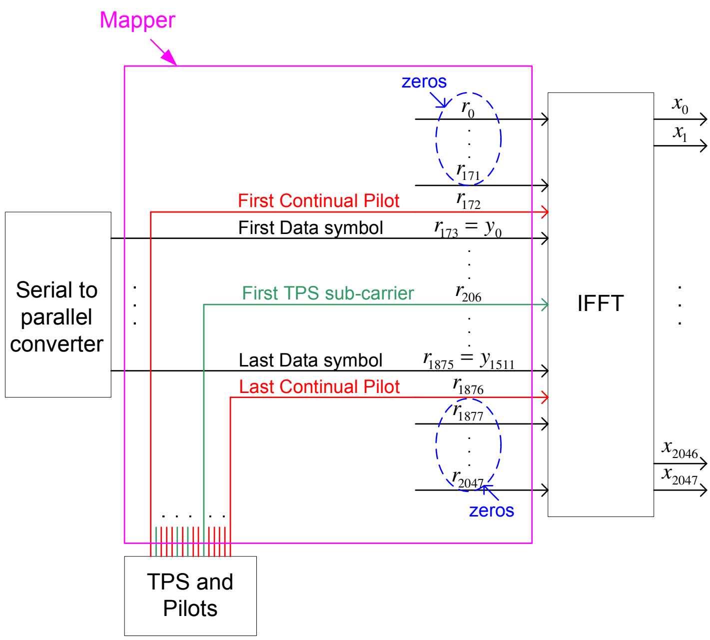


Figure 3.12: Mapping of data, pilots and TPS sub-carriers on the IFFT pins

3.3.3.1 Orthogonality Principle

As a finalization for this part we have to discuss shortly the orthogonality principle which gives the OFDM system this high immunity to interference and make it able to utilize the available band width to a great extent higher than the FDM systems.

If we try to give a general definition for orthogonality, we may say that a set of signals are orthogonal to each other if all of them can be transmitted on a single channel with the ability of easy detection without any interference between them, we may think that this definition is applicable to the traditional FDM system, but for FDM we have to insert enough frequency gaps between the sub-carriers to guarantee this easy detection, while for OFDM this can be achieved without the need of any gaps. OFDM also satisfies the mathematical definition of orthogonality which states that "two signals are orthogonal over certain interval if their multiplication and integration over this interval equals to zero" as illustrated below by equation (3.20):

$$\int_0^{T_U} x_p(t).x_q^*(t) \quad dt = \begin{cases} A & , p = q \\ 0 & , p \neq q \end{cases} \tag{3.20}$$

Where p and q are integers and represent the order of two signals in the set of signals we discuss while A is a constant. In our case we may rewrite equation (3.20) as follows:

$$\int_0^{T_U} \cos(2\pi f_p t).\cos(2\pi f_q t) \quad dt = \begin{cases} A & , p = q \\ 0 & , p \neq q \end{cases} \tag{3.21}$$

Where f_p and f_q represent two sub-carriers base band frequencies of the set of sub-carriers that compose the OFDM symbol. The condition which makes equation (3.21) holds is that f_p and f_q must be integer multiples of a fundamental frequency f_o as defined in equation (3.11) which in our case equals to $1/T_U$ as concluded from equation (3.17). Substituting for the two cases in equation (3.21) with this condition, we will get:

let $f_p = pf_o$ and $f_q = qf_o$

$$\text{for } p = q\text{, } \int_0^{T_U} \cos^2(2\pi f_p t)\ \ dt = \frac{1}{2}\int_0^{T_U} (1+\cos(2\pi(2*f_p)t))\ \ dt = \frac{T_U}{2} \qquad (3.22)$$

$$\text{for } p \neq q\text{, } \int_0^{T_U} \cos(2\pi(p+q)f_o t) + \cos(2\pi(p-q)f_o t)\ \ dt = 0 \qquad (3.23)$$

where for equations (3.22) and (3.23) the terms $(2*f_p) = 2pf_o$, $(p+q)f_o$ and $(p-q)f_o$ integrates to zero over the period $[0,T_U]$ as all these frequencies are equivalent to periods of $T_U/2p$, $T_U/(p+q)$ and $T_U/(p-q)$ respectively, so they are repeated $2p$, $(p+q)$ and $(p-q)$ times over the period $[0,T_U]$ respectively which results in average of zero over this interval as illustrated in figure (3.13).

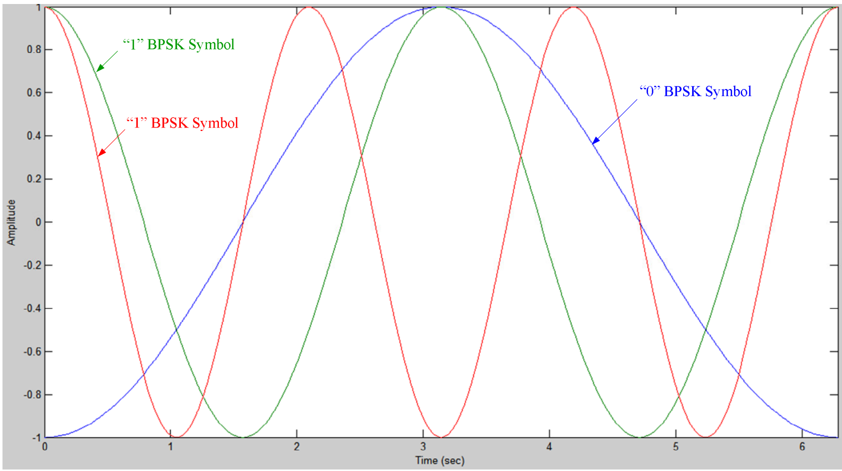


Figure 3.13: Illustration of orthogonality in time domain

This concept may be further clarified if we study the spectrum of the OFDM signal in the frequency domain. The signal shape of one OFDM sub-carrier is represented by the multiplication of square pulse of width equals to the symbol duration T_U and a sinusoidal of this sub-carrier frequency as shown in figure (3.14), which results in sinc function $(\sin c(x) = \sin(x)/x)$ centered around the sinusoidal frequency with zero crossings at the multiples of $1/T_U$ in the frequency domain as shown in figure (3.15).

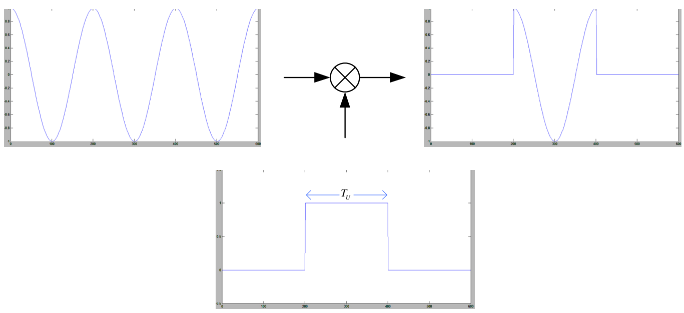


Figure 3.14: Single OFDM sub-carrier time domain Illustration

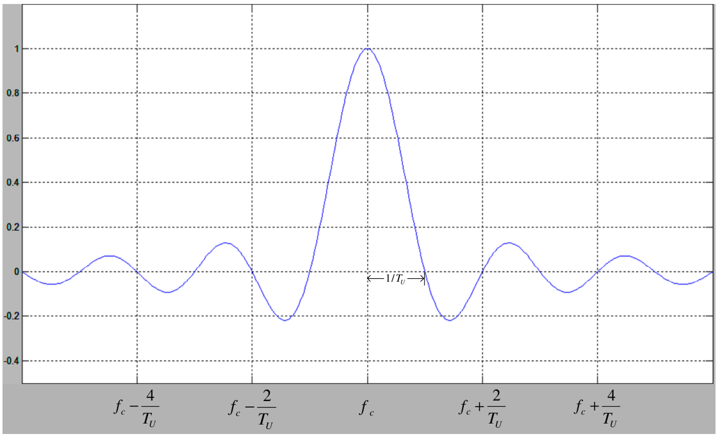


Figure 3.15: Single OFDM sub-carrier frequency domain representation

The next neighbor sub-carrier (IFFT pin) will be $1/T_U$ Hz away from this one, i.e. its fundamental peak will be at the first null of it which means that if we sample these signals at points (a) and (b) in figure (3.16), we will effectively see two individual signals with no contributions from one of them on the other one although they are overlapping in the same domain, which lighten out the concept of orthogonality to a great extent.

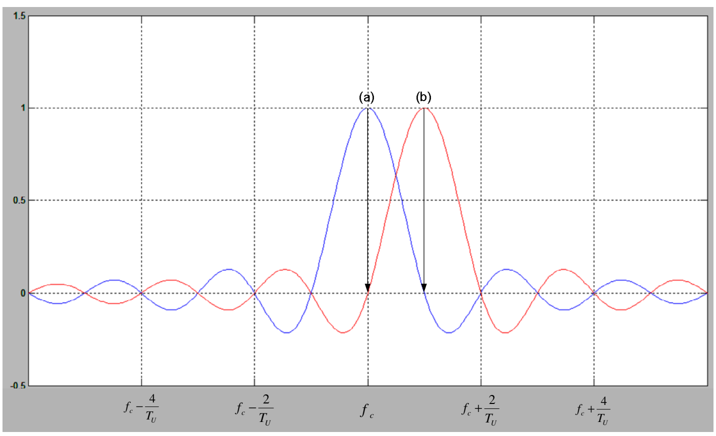


Figure 3.16: Interference cancellation due to the orthogonality principle

In a similar way, if we extend this signal in both directions, we find that each peak will always lie at the nulls of all other sub-carriers signals as previously illustrated in figure (3.1.b).

3.3.4 Guard Interval Insertion

After we perform the base band modulation of every OFDM symbol sub-carrier through applying the IFFT algorithm, we will have N discrete values that may be directly transmitted on the radio channel after being transformed into analog signal and carried on the RF carrier at the front end stage. Sending our signal in such a way, it will be affected by the channel impairments such as the delay spread that results from the arrival of many versions of the signal through many different paths with different delays, which when arrived and added at the receiver, may spread to the next adjacent symbol in the time domain causing what is known as ISI (Inter Symbol Interference) that may lead to erroneous interpretation of the symbols values and consequently increasing the BER as shown in figure (3.17) . The same phenomenon may also leads to the loss of orthogonality between the OFDM sub-carriers as we will not have multiples of the fundamental sinusoidal period over the symbol duration, consequently equation (3.23) will give non-zero value, which will cause ICI (Inter Carrier Interference) that degrades the performance of the system as the symbols on the individual sub-carriers will not be easily retrieved.

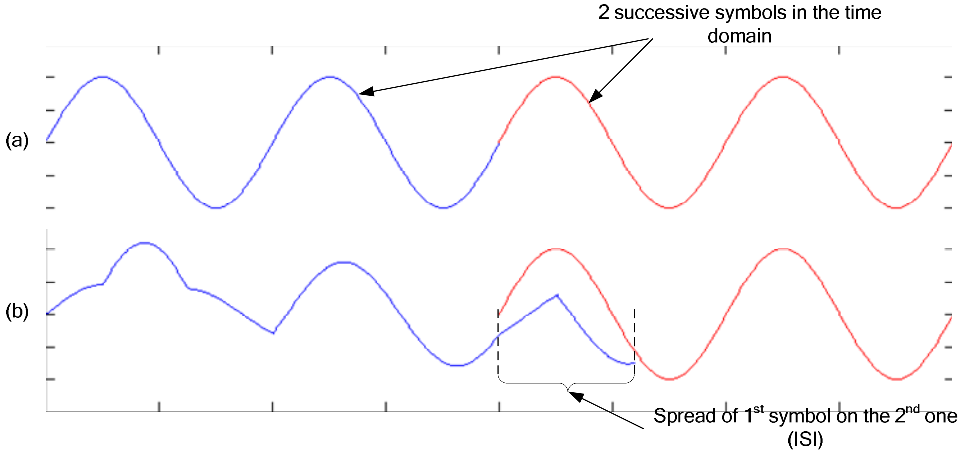


Figure 3.17: ISI phenomena

Signals before transmission, (b) Signals after channel effect

Trying to solve such problems, guard intervals are added between every two successive symbols in the time domain such that the spread of the transmitted symbol will be contained in this interval which will be discarded at the receiver. Such an idea may decrease the effect of the ISI but not the ICI as the orthogonality integration will also give non-zero values.

Trying to decrease both ISI and ICI effects, the length of the guard interval must be longer than the channel response, so the channel delay spread will be completely contained in this guard interval and will not reach the next adjacent symbol and by discarding this interval at the receiver the ISI effect may be totally eliminated as illustrated in figure (3.18).

For the ICI problem if we can add a signal during this interval which makes the orthogonality integration gives a zero-value, ICI problem can be greatly solved, which can be achieved by adding multiple cycles of the

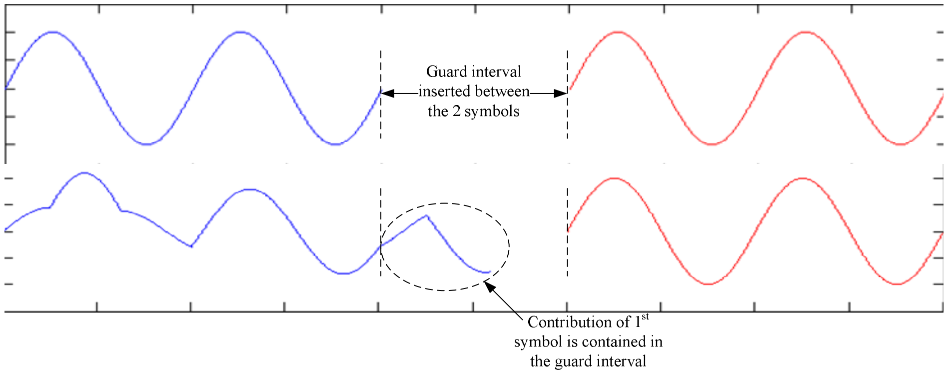


Figure 3.18: channel length and guard interval length

sub-carriers carried on the OFDM symbol itself through appending a fraction of the OFDM symbol end – conditioned to contain multiples of complete cycles – at the start of it as shown in figure (3.19). Doing so, the guard interval is also named the cyclic prefix as it is appended at the start not at the end of the symbol.

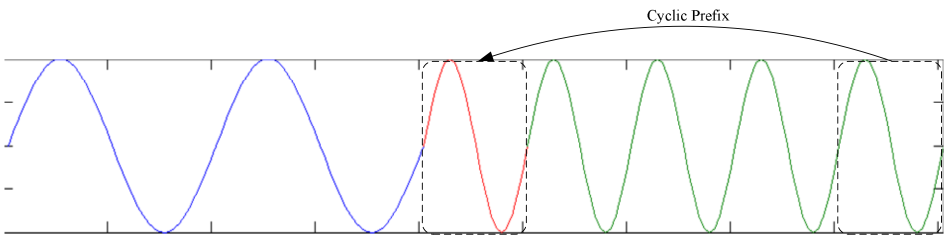


Figure 3.19: Cyclic prefix insertion with Δ = ¼

So, in figure (3.3) the number of inputs of the parallel-to-serial converter at the end of the system must be increased than the number of the IFFT pins by the number of samples that will be taken from the end of each OFDM symbol and appended before the start of the same symbol composing the cyclic prefix as shown in figure (3.20).

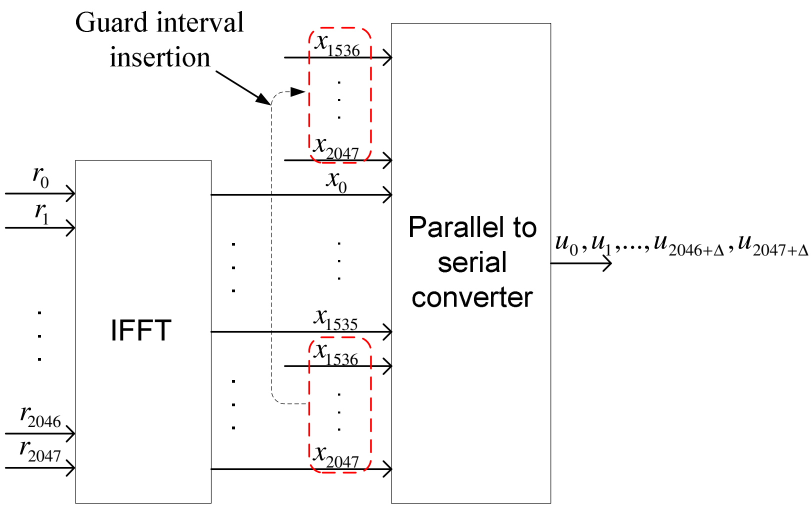


Figure 3.20: Mapping of the guard interval at the start of the OFDM symbol

Cyclic prefix also provides the continuity of the signals and consequently maintaining the synchronization instead of sending silence periods. The idea of repeating the last part of the OFDM symbol relaxes the synchronization of the window by which we read the useful part of the OFDM symbol, because the start of the window may begin earlier than its correct position and still be able to retrieve the complete data.

It can also help in the time synchronization of the OFDM stream through correlating the stream with a delayed version of itself and we will note the occurrence of two peaks at the start and end of the useful symbol duration because of the repetition.

On the other hand the insertion of the cyclic prefix between the OFDM symbols results in decreasing the efficiency of the system as it will be discarded at the receiver and consequently results in effective reduction of the overall bit rate, which enforces the designers to precisely choose the appropriate length of the guard interval such that it is not too short that the channel effect may reach the next symbol nor too long that it will degrade the system efficiency.

For DVB-H system, guard interval takes four different values (1/4, 1/8, 1/16, 1/32), each referenced to the useful duration of the OFDM symbol T_U as listed below in tables (3-16, 3-17 and 3-18) and as the smallest value of it is $T_U/32$, the least fundamental sub-carrier frequency must satisfy the existence of multiples of 32 cycles within the useful OFDM symbol duration to guarantee that we have complete number of cycles within the cyclic prefix.

Table 3-16: Time domain parameters for the 2K mode for the 8MHz channels

	2K mode			
Δ/T_U	**1/4**	**1/8**	**1/16**	**1/32**
T_U	$2048*T = 224\mu\sec$			
Δ	$512*T$ $56\mu\sec$	$256*T$ $28\mu\sec$	$128*T$ $14\mu\sec$	$64*T$ $7\mu\sec$
T_s	$2560*T$ $280\mu\sec$	$2304*T$ $252\mu\sec$	$2176*T$ $238\mu\sec$	$2112*T$ $231\mu\sec$

Table 3-17: Time domain parameters for the 4K mode for the 8MHz channels

	4K mode			
Δ / T_U	**1/4**	**1/8**	**1/16**	**1/32**
T_U	$4096 * T = 448 \mu \sec$			
Δ	$1024 * T$ $112 \mu \sec$	$512 * T$ $56 \mu \sec$	$256 * T$ $38 \mu \sec$	$128 * T$ $14 \mu \sec$
T_s	$5120 * T$ $560 \mu \sec$	$4608 * T$ $504 \mu \sec$	$4352 * T$ $476 \mu \sec$	$4224 * T$ $462 \mu \sec$

Table 3-18: Time domain parameters for the 8K mode for the 8MHz channels

	8K mode			
Δ / T_U	**1/4**	**1/8**	**1/16**	**1/32**
T_U	$8192 * T = 896 \mu \sec$			
Δ	$2048 * T$ $224 \mu \sec$	$1024 * T$ $112 \mu \sec$	$512 * T$ $56 \mu \sec$	$256 * T$ $38 \mu \sec$
T_s	$10240 * T$ $1120 \mu \sec$	$9216 * T$ $1008 \mu \sec$	$8704 * T$ $952 \mu \sec$	$8448 * T$ $924 \mu \sec$

Note that the values in the table are defined as multiples of an elementary period T which value varies according to the channel bandwidth of the DVB-H system that varies between 5, 6, 7 and 8 MHz channels where for the 8 MHz channels $T = 7/64 \, \mu \sec$ and T_s is the total symbol duration which equals $T_U + \Delta$.

Finally, after the addition of the guard interval, the output sequence will be applied to a parallel-to-serial converter as a preparation step for the digital-to-analog conversion that will transform these discrete samples into time domain continuous signal that will be then up-converted and prepared for the transmission over the radio channel in the front-end stage.

3.4 OFDM Applications

As we stated before, prior to the enormous progress in DSP and VLSI fields, the implementation of OFDM systems was so complicated which makes it rarely applied but with the ability to easily implement its systems at considerably low cost, OFDM was used in many applications such as the DAB (Digital Audio Broadcasting) that has a very fine sound quality compared to the analog one [12]. Also we have the DVB that was initially devoted for the terrestrial transmission (DVB-T) to be received on fixed terminals that then evolutes to the (DVB-H) system that enable the reception of the transmission on handheld mobile terminals that moves at relative high speeds in fast-varying radio channels. OFDM was also applied in fixed-wire applications such as the ADSL (Asynchronous Digital Subscriber Line) [13], VDSL2 (Very high speed Digital Subscriber Line 2) [14] and power-line communications systems.

Finally we may mention the WiMAX (Worldwide Interoperability for Microwave ACCess) which is a telecommunication technology that aims for providing wireless data over long distances in many ways [15].

3.5 Conclusion

OFDM system is a frequency domain multiplexing system that provides high utilization of the available bandwidth through concatenation of system sub-carriers depending on the orthogonality principle where the division of the system bandwidth into narrow sub-bands gives an added advantage as it makes the signal relatively immune to the frequency selective fading phenomenon.

The system is easily implemented through the FFT/IFFT algorithm and the introduction of the cyclic prefix concept decrease the ISI and ICI effects, so we have a system that can carry high data rates with relatively long symbol duration at the same time and a better performance compared to the traditional FDM and single carrier systems. On the other hand OFDM systems are sensitive to carrier frequency offset compared to the single carrier system.