Chapter 3
Introduction to OFDM-Based Systems

3.1 Eureka 147 DAB System

The Eureka 147 DAB [5] system has the following features: it has sound quality comparable to that of CD, it can provide maximal coverage area, it is resistant to the degradations caused by multipath propagation, and it is a widely accepted DAB standard.

3.1.1 System Overview

Eureka 147 DAB system is based on two major technologies: MUSICAM (Masking pattern adaptive Universal Sub-band Integrated Coding And Multiplexing) and COFDM (Coded OFDM).

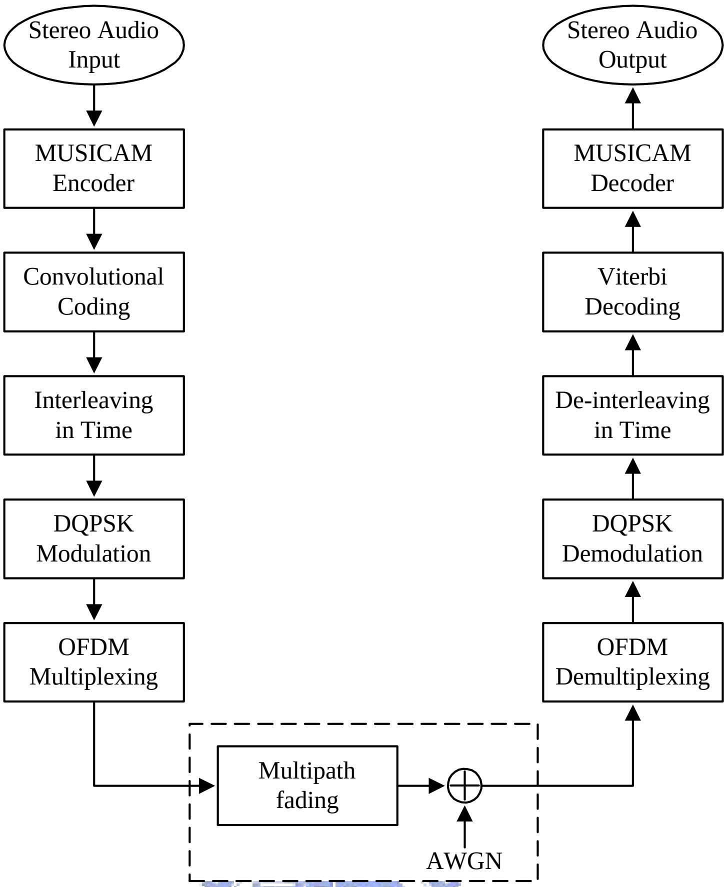

Figure 3.1 Block diagram of Eureka 147 DAB system

Figure 3.1 is a block diagram of the DAB system. In the system, audio signals are encoded by MUSICAM to reduce the data rate from 768,000 bits/sec to 128,000 bits/sec. The next step is channel coding by convolutional coding with code rate = 1/4. After breaking the data correlation by interleaving operations, signals are modulated by DQPSK (Differential Quadrature Phase Shift Keying) and become complex data. These complex data composes in frames and modulate corresponding subcarriers by using IFFT. There are 4 transmission modes in Eureka 147 DAB system, characterized by four different numbers of subcarriers. They correspond to four different IFFT lengths including 2048, 512, 256 and 1024. In the end of OFDM multiplexing block, guard intervals are inserted to form an OFDM symbol.

3.1.2 Transmission System

The DAB transmission system combines three channels which are shown in Figure

3.2: Synchronization Channel, Fast Information Channel and Main Service Channel. Synchronization channel is used internally within the transmission system for basic demodulator function, such as transmission frame synchronization, automatic frequency control, channel state estimation, and transmitter identification. It consists of the first two OFDM symbols of each frame. The first OFDM symbol of the transmission frame is the null symbol. During the time interval of null symbol, the signal power shall be equal to 0. The second OFDM symbol is the phase reference symbol. It constitutes the reference for the differential modulation of the succeeding OFDM symbols.

Fast Information Channel is used for rapid access of information by a receiver. In particular, it is used to send the Multiplex Configuration Information (MCI) and optionally Service Information and service data. The FIC is a non-time-interleaved data channel with fixed equal error protection.

Main Service Channel is used to carry audio and data service components. The MSC is a time-interleaved data channel divided into a number of subchannels which are individually and conventionally coded, with equal or unequal error protection. Each subchannel may carry one or more service components.

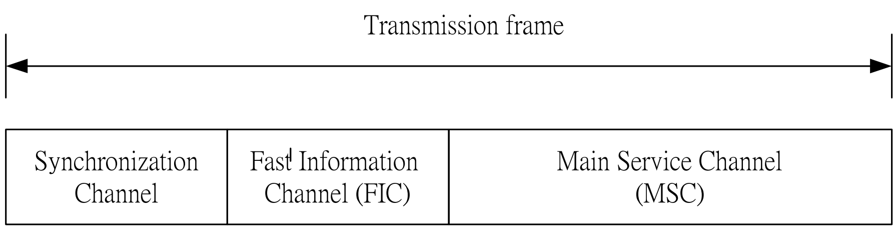

Figure 3.2 Transmission frame structure of DAB system

Each transmission frame shall consist of consecutive OFDM symbols. The number of OFDM symbols in a transmission frame is dependent on the transmission mode.

The first OFDM symbol of the transmission frame shall be the Null symbol of duration T_{null}. The remaining part of the transmission frame shall be a juxtaposition of OFDM symbols of duration T_S.

Table 3.1 DAB OFDM parameters in different modes

	Mode I	**Mode II**	**Mode III**	**Mode IV**
L	76	76	153	76
K	1536	384	192	768
T_F	$196608T$ $96\ ms$	$49152T$ $24\ ms$	$49152T$ $24\ ms$	$98304T$ $48\ ms$
T_{null}	$2656T$ $1.297\ ms$	$664T$ $324\ \mu s$	$345T$ $168\ \mu s$	$1328T$ $648\ \mu s$
T_S	$2552T$ $1.246\ ms$	$638T$ $312\ \mu s$	$319T$ $156\ \mu s$	$1276T$ $623\ \mu s$
T_U	$2048T$ $1\ ms$	$512T$ $250\ \mu s$	$256T$ $125\ \mu s$	$1024T$ $500\ \mu s$
Δ	$504T$ $246\ \mu s$	$126T$ $62\ \mu s$	$63T$ $31\ \mu s$	$252T$ $123\ \mu s$
Central frequency	375 MHz	1.5 GHz	3 GHz	1.5 GHz

Each of these OFDM symbols shall consist of a set of equally-spaced carriers, with a carrier spacing equal to $1/T_U$, where T_U is the length of useful data. The transmitted signal can be expressed as:

$$s(t) = \mathrm{Re}\left\{ e^{2j2\pi f_c t \sum_{m=-\infty}^{+\infty} \sum_{l=0}^{L} \sum_{k=-K/2}^{K/2} z_{m,l,k} \cdot g_{k,l}(t - mT_F - T_{null} - (l-1)T_S)} \right\} \tag{3.1}$$

$$g_{k,l}(t) = \begin{cases} 0 & l = 0 \\ e^{2j\pi k(t-\Delta)/T_U} \cdot \mathrm{Re}\,ct(t/T_S) & l = 1,2,\ldots,L \end{cases} \tag{3.2}$$

where $T_S = T_U + \Delta$, and Δ is the length of guard interval. Every frame includes L symbols and 1 null symbo1, and every symbol is composed of K subcarriers. $z_{m,l,k}$

is the complex DQPSK data on the k-th subcarrier of the l-th symbol in the m-th frame. These parameters are specified in Table 3.1 for transmission modes I, II, III and IV. The values of the various time-related parameters are given in multiples of the elementary period T=1/2048000 seconds, and approximately in milliseconds or microseconds.

3.2 DVB-T

Terrestrial Digital Video Broadcasting (DVB-T) [7] is based on COFDM (Coded Orthogonal Frequency Division Multiplexing). It was established by the European DVB consortium in early 1996.

3.2.1 System Overview

The system is defined by the functional blocks of a DVB equipment, which performs the adaptation of a baseband TV signal from the output of a MPEG-2 transport multiplexer, to the terrestrial channel characteristic. The whole processes are depicted in Figure 3.3.

First, a splitter is used to split the data stream into high priority-part and low-priority part. These two parts of data could have their individual channel coding and modulation methods. The way to split the data into two parts is so called Hierarchical transmission. For example, a TV program can be transmitted in both high-quality mode and low-quality mode by high-priority part and low-priority part at the same time.

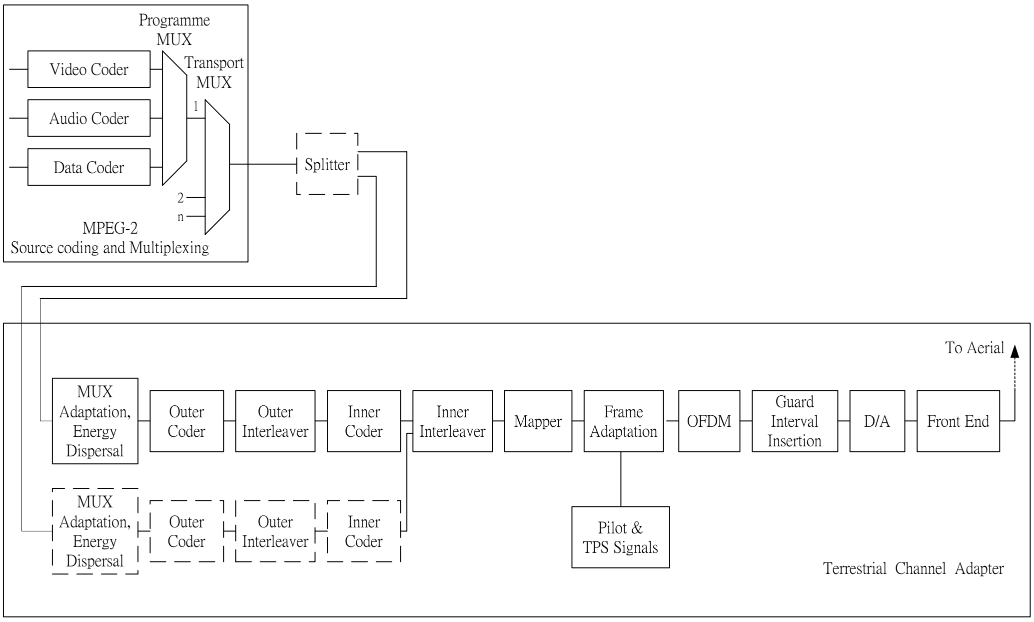

Figure 3.3 Functional block diagram of the DVB system [7]

Transport Multiplexing Adaptation will adapt the energy distribution and increase the randomization of the signal. The polynomial for the Pseudo Random Binary Sequence generator is $1+X^{14}+X^{15}$. To provide an initialization signal for the descrambler, the MPEG-2 sync byte of the first transport packet in a group of eight packets is bit-wise inverted from 47_{HEX} to $B8_{HEX}$.

There are two layers of channel coding and interleaver in the DVB-T system. The outer coding uses Reed-Solomon (204, 188, t=8) shortened code, derived from the original systematic RS (255, 239, t=8) code. Reed-Solomon coding shall also be applied to the packet sync byte. The inner channel coding is a convolutional code with code rate=1/2, 2/3, 3/4, 5/6, or 7/8. The inner interleaver is a block interleaver.

The output data of inner interleaver will be modulated to complex signal by using different modulation methods. The modulation methods specified in DVB-T systems are QPSK, 16-QAM, 64-QAM, non-uniform 16-QAM, and non-uniform 64-QAM, where the non-uniform modulations are used in hierarchical transmission mode.

After pilot and TPS (Transmission Parameter Signaling) adaptation, the signal will be handled by IFFT. There are two transmission modes in DVB-T: 2K-mode and 8K-mode. In 2K-mode, 2048-point IFFT will be used, and 8192-point IFFT will be used in 8K-mode. Transmission parameters such as transmission mode, hierarchical transmission or not, code rate of inner channel coding, and the modulation method will be recorded in the Transmission Parameter Signaling.

The system is supposed to use the traditional analog broadcasting UHF band with 8MHz bandwidth. The central frequency of the transmitter carrier is defined as:

$$470MHz + 4MHz + i \times 8Hz \qquad i = 0,1,2,3,... \tag{3.3}$$

By the way, some countries define the transmission bandwidth as 7MHz or 6MHz. We can only change the sampling period to fit these unique bandwidth regulations. The sampling period T is 7/64 μs for 8MHz channels, 1/8 μs for 7 MHZ channels and 7/48 μs for 6MHz channels.

3.2.2 The Frame Structure

The transmitted signal is organized in frames. Each frame consists of 68 OFDM symbols. Four frames constitute one super-frame. Each symbol is constituted by a set of K=6817 carriers in the 8K mode and K=1705 carriers in the 2K mode and transmitted with a duration of T_S seconds It is composed of two parts: a useful part with duration T_U and a guard interval with a duration of Δ. The guard interval consists of a cyclic tail replica of the useful part T_U. The emitted signal at time t can be expressed as:

$$S(t) = \mathrm{Re}\{e^{j2\pi f_c t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=K_{\min}}^{K_{\max}} C_{m,l,k} \times \psi_{m,l,k}(t)\} \tag{3.4}$$

where

$$\psi_{m,l,k}(t) = e^{j2\pi \frac{k'}{T_u}(t-\Delta-l\times T_{total}-68\times m\times T_{total})}, \quad (l+68\times m)\times T_{total} \le (l+68\times m+1)\times T_{total}$$

$$\psi_{m,l,k}(t) = 0, \qquad elsewhere$$

and k denotes the subcarriers number, $k' = k - (K_{\max} + K_{\min})/2$ is carrier index relative to the centre frequency, l denotes the OFDM symbol number, m denotes the transmission frame number, $C_{m,l,k}$ is the complex data on each subcarrier, and T_{total} is an OFDM symbol duration composed of two parts: a useful part with duration T_u and a guard interval with duration Δ. Each mode can choose four different kinds of guard interval duration, (i.e., 1/4, 1/8, 1/16 or 1/32 of a useful symbol duration).

Table3.2 Specifications of the 8K and 2K modes of an 8MHz DVB-T channel

Parameters	8K mode	2K mode
Number of carriers number K	6817	1705
Value of carriers $K_{\min}$	0	0
Value of carrier number $K_{\max}$	6816	1704
Duration T_U	896 μs	224 μs
Carrier spacing $1/T_U$	1116 Hz	4464 Hz
Spacing between $K_{\min}$ to $K_{\max}$	7.61 MHz	7.61 MHz

3.2.3 Reference Signals

DVB-T has two kinds of reference signals: continual pilot and scattered pilot. Each of them is derived from a PRBS (Pseudo Random Binary Sequence) $w_k = X^{11} + X^2 + 1$.We can use these reference signals to find correct symbol and frame timing, estimate the frequency offset, and do channel estimation.

-Scattered Pilots

Scattered pilot cells are always transmitted with “boosted” power level. Thus the corresponding modulation is given by:

$$\text{Re}\{C_{m,l,k}\} = 4/3 \times 2(1/2 - w_k)\ ;\ \ \text{Im}\{C_{m,l,k}\} = 0$$

where m is the frame index, k is the frequency index of the carriers and l is the time index of the symbol.

Positions of the scattered pilots are specified by:

$$k = K_{\min} + 3 \times (l \bmod 4) + 12p \mid p \ \text{ integer}, \ \ p \geq 0, k \in [K_{\min}, K_{\max}] \tag{3.5}$$

where $K_{\min}$ =0 for both 2K and 8K modes, $K_{\max}$ =1704 for 2K mode and $K_{\max}$ =6816 for 8K mode. Since $(l \bmod 4)$ is used, the scattered pilot locations will repeat every four symbols as shown in Figure 3.4.

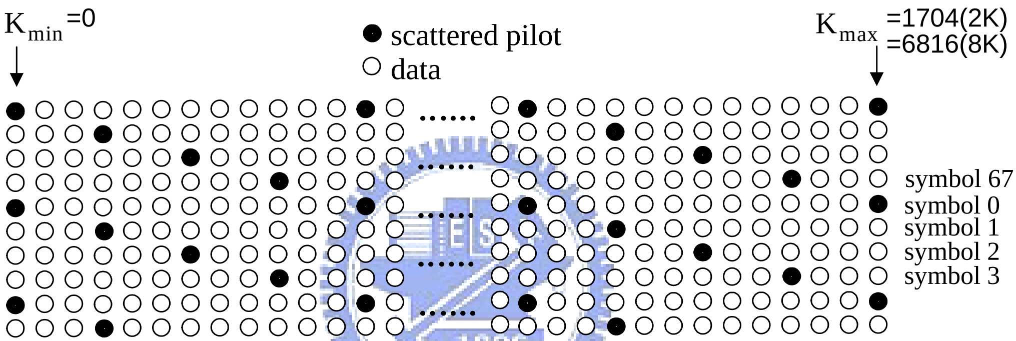

Figure 3.4 Scattered pilot locations of DVB-T system.

- Continual Pilots

There are 177 continual pilots in 8K mode and 45 in the 2K mode. The continual pilots are placed in the fixed subcarriers at each symbol as shown in Figure 3.5. The continual pilots are transmitted with “boosted” power level. The value of continual pilot on subcarrier k is given by:

$$\text{Re}\{C_{m,l,k}\} = 4/3 \times 2(1/2 - w_k);\ \ \text{Im}\{C_{m,l,k}\} = 0 \tag{3.6}$$

Integral frequency offset can be estimated by matching the continual pilot of each symbol.

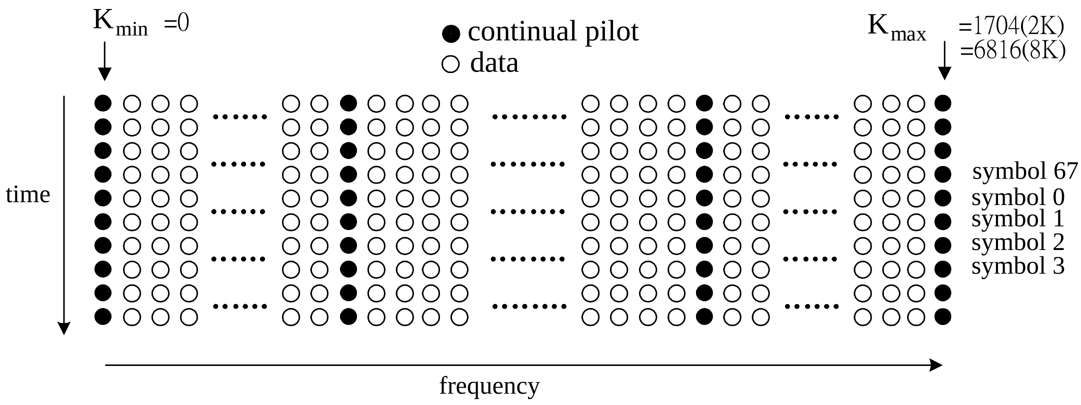

Figure 3.5 Continual pilot locations of DVB-T system

Table 3.3 Carrier indices for continual pilot carriers of DVB-T system

Continual pilot carrier position (index number k)	
2K mode	8K mode
0 48 54 87 141 156	0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 636 714 759
192 201 255 279	765 780 804 873 888 918 939 942 969 984 1050 1101 1107 1110 1137 1140 1146
282 333 432 450	1206 1269 1323 1377 1491 1683 1704 1752 1758 1791 1845 1860 1896 1905 1959
483 525 531 618	1983 1986 2037 2136 2154 2187 2229 2235 2322 2340 2418 2463 2469 2484 2508
636 714 759 765	2577 2592 2622 2643 2646 2673 2688 2754 2805 2811 2814 2841 2844 2850 2910
780 804 873 888	2973 3027 3081 3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687
918 939 942 969	3690 3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212 4281
984 1050 1101 1107	4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548 4554 4614 4677
1110 1137 1140	4713 4785 4899 5091 5112 5160 5166 5199 5253 5268 5304 5313 5367 5391 5394
1146 1206 1269	5445 5544 5562 5595 5637 5643 5730 5748 5826 5871 5877 5892 5916 5985 6000
1323 1377 1491	6030 6051 6054 6081 6096 6162 6213 6219 6222 6249 6252 6258 6318 6381 6435
1683 1704	6489 6603 6795 6816

3.2.4 Transmission Parameter Signaling (TPS)

TPS carriers are used for the purpose of signaling parameters related to the transmission schemes, coding and modulation. TPS is composed of 17 TPS carriers for the 2K mode and on 68 carriers for the 8K mode. Every TPS carrier in the same symbol conveys the same differentially encoded information bit. The sub-carriers carrying the TPS information are the same in every symbol just like the continual pilots.

Every TPS carrier is DBPSK modulated, which conveys the same message. The DBPSK is initialized at the beginning of each TPS block. The following rule applies to the differential modulation of carrier k of symbol l ($l > 0$) in frame m:

$$\mathrm{Re}\{C_{m,l,k}\} = (-1)^{S_l} \times \mathrm{Re}\{C_{m,l,k-1}\}; \;\; \mathrm{Im}\{C_{m,l,k}\} = 0; \qquad (3.7)$$

The absolute modulation of the TPS carriers in the first symbol in a frame is derived from the PRBS $w_k = X^{11} + X^2 + 1$ as follows:

$$\mathrm{Re}\{C_{m,l,k}\} = 2(1/2 - w_k); \; \mathrm{Im}\{C_{m,l,k}\} = 0; \qquad (3.8)$$

TPS is defined over 68 consecutive OFDM symbols, referred to as one OFDM frame. The reference sequence corresponding to the TPS carriers of the first symbol of each OFDM frame are used to initialize the TPS modulation on each TPS carrier. Each OFDM symbol conveys one TPS bit. Each TPS block (corresponding to one OFDM frame) contains 68 bits, defined as: 1 initialization bit; 16 synchronization bits; 37 information bits and 14 redundancy bits for error protection. We can find the start of a frame by matching 16 synchronization bits. The transmission parameter information shall be transmitted as shown in Table 3.4.

Table 3.4 TPS signaling information of DVB-T system

Bit number	**Purpose/Content**
s_0	Initialization
$s_1 - s_{16}$	Synchronization word
$s_{17} - s_{22}$	Length indicator
s_{23}, s_{24}	Frame number
s_{25}, s_{26}	Constellation
s_{27}, s_{28}, s_{29}	Hierarchy information
s_{30}, s_{31}, s_{32}	Code rate, HP stream
s_{33}, s_{34}, s_{35}	Code rate, LP stream
s_{36}, s_{37}	Guard interval
s_{38}, s_{39}	transmission mode
$s_{40} - s_{53}$	Reserved for future use
$s_{54} - s_{67}$	Error protection

3.3 IEEE 802.16a

IEEE 802.16-2001, completed in October 2001 and published on 8 April 2002 [3], defines the WirelessMan^{TM} air interface specification for wireless metropolitan area network (MANs). The IEEE 802.16 standard addresses the "first-mile/last-mile" connection in wireless metropolitan area network. It focuses on the efficient use of bandwidth between 10 and 66 GHz, where extensive spectrum is currently available worldwide but at which the short wavelengths introduce significant deployment challenges.

IEEE 802.16a amended in 2003 located the transmission band to lower frequencies from 2 GHz to 11 GHz. Its main content includes MAC (medium access control) and Physical Layer Specifications for 2-11 GHz [2]. IEEE 802.16a has four modes of physical layers: Wireless MAN-SCa (Single Carrier for IEEE 802.16a), Wireless MAN-OFDM, and Wireless MAN-OFDMA (OFDM with Multiple Access), Wireless HUMAN (High Speed Unlicensed MAN). The Wireless MAN-OFDMA PHY layer is discussed here.

3.3.1 Operation and Considerations of OFDMA

In OFDMA, there are many aspects to be considered, like its pilot allocation, pilot modulation, frame structure, and maximum frequency offset and clock offset that system can tolerate. In IEEE 802.16a, the subscriber station (SS) is known as the mobile station or the user and the base station (BS) is the service provider. The direction of transmission from the BS to the SS is called downlink (DL), and the opposite direction is uplink (UL). At initialization, a SS should search for all possible lengths of the GI until it finds the GI being used by the BS. Once a specific CP duration has been selected by the BS for operation, it should not be changed. Changing the CP lengths would force the SSs to resynchronize to the BS. The SS shall use the same GI on the uplink (UL).

3.3.1.1 Time-Domain Description

For convenience, Figure 3.6 again shows guard interval structure of an OFDM symbol discussed before. The transmitter energy increases with the length of the guard interval while the receiver energy remains the same. Such inclusion of GI causes SNR degradation by an amount of 10log $(1+T_g/T_u)$. GI lengths of $1/32T_u$, $1/16T_u$, $1/8T_u$, and $1/4T_u$ are supported in 802.16a.

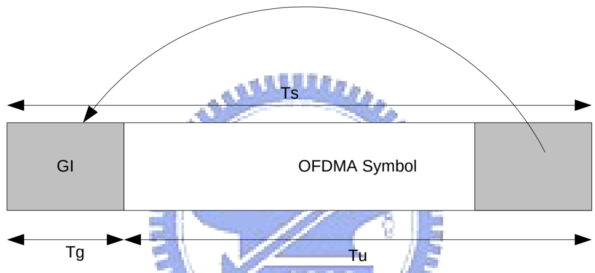

Figure 3.6 802.16a OFDMA symbol structure

3.3.1.2 Frequency-Domain Description

An OFDMA symbol is made up of 2048 carriers. There are three carrier types: data carriers that are for data transmission, pilot carriers that are for various estimation purposes, and null carriers without transmission at all which are guard and DC carriers. The goal of the guard bands is to enable the signal to naturally decay. In the DL, a subchannel may be intended for many receivers to do broadcasting. In the

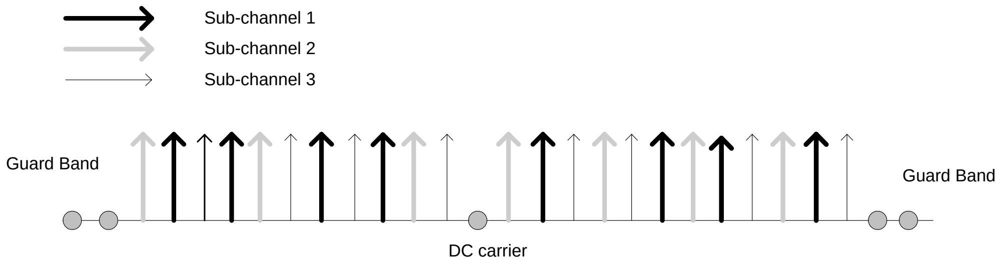

Figure 3.7 OFDMA frequency description

UL, a transmitter may be assigned one or more subchannels. The carriers forming one subchannel are not adjacent, as shown in Figure 3.7.

3.3.2 OFDMA Carrier Allocation

For both downlink and uplink the used carriers are divided into pilot carriers and data carriers. However, there is some difference between downlink and uplink. For downlink, data carriers are partitioned into several subchannels. In downlink, there is one set of common pilot carriers. Besides, downlink does not have preamble with all pilots. For uplink, used carriers are firstly partitioned into subchannels, each has four specified varying-location pilots and one fixed-location pilot located in the middle of each subchannel. Uplink may use an all-pilot preamble symbol.

3.3.2.1 Downlink Pilot Allocation

In downlink, pilots are partitioned into variable-location pilots and fixed-location pilots. The carrier indices of the fixed-location pilots never change. The variable-location pilots change their location in every symbol and repeat the same location per 4 symbols, according to the formula:

$$Var\_Loc\_Pilot = 3L + 12P_k \quad (3.9)$$

where P_k belong to the set {0,1,2,……,141} and the periodic sequence L is [0 2 1 3] which is indexed symbol by symbol. In some cases, a variable-location pilot will coincide with a fixed-location pilot. The allocation of pilot carriers is illustrated in Figure 3.8.

Table 3.5 OFDMA 802.16a DL carrier allocations

Parameter	Value
Number of DC carriers	1
Number of left guard carriers	173
Number of right guard carriers	172
Number of used carriers	1702
Total number of carriers	2048
$N_{varLocPilots}$	142
Number of fixed-location pilots	32
Number of variable-location pilots which coincide with fixed-location pilots	8
Total number of pilots	166
Number of data carriers	1536
$N_{subchannel}$	32
$N_{subcarriers}$	48
Number of data carriers per subchannel	48

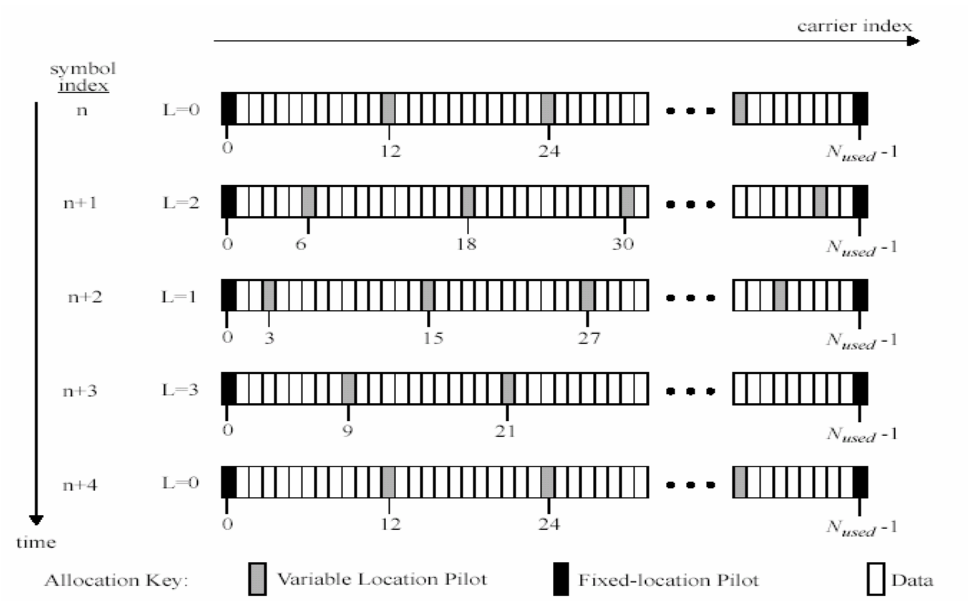

Figure 3.8 Carrier allocation in the OFDMA DL

3.3.2.2 Uplink Pilot Allocation

In uplink, the used carriers are first partitioned into subchannels and each subchannel has 53 subcarriers. Within each subchannel, there are 48 data carriers, 1 fixed-location pilot carriers, and 4 variable-location pilot carriers. In every subchannel, pilot carriers and data carriers are partitioned according to the following formula:

$$Var\_Loc\_Pilot=[0\ 13\ 27\ 40]+L_k \qquad (3.10)$$

Since the periodic sequence L_k is [0,2,4,6,8,10,12,1,3,5,7,9,11], it will repeat every 13 symbols. The fixed-location pilot is always at carrier 26 in the subchannel. The allocation of pilot carriers is illustrated in Figure 3.9.

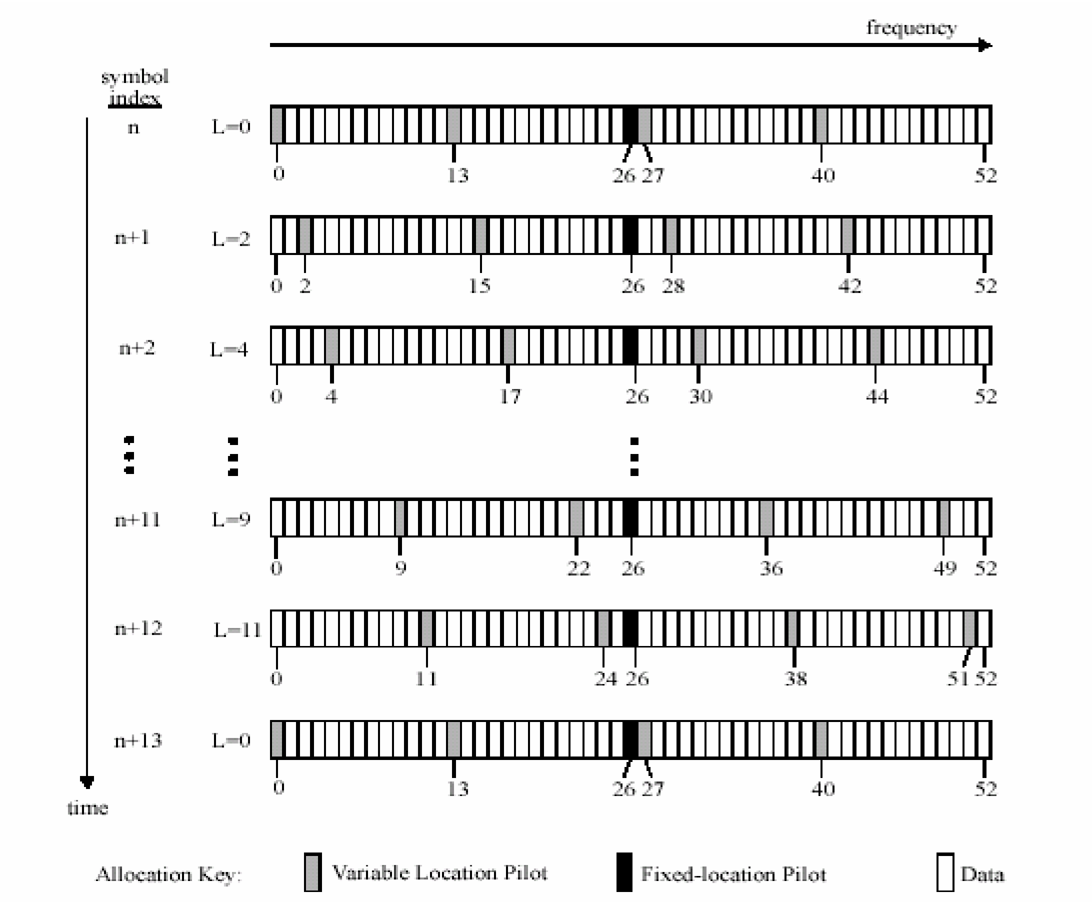

Figure 3.9 Carrier allocation in the OFDMA UL

Table 3.6 OFDMA 802.16a UL carrier allocations

Parameter	Value
Number of DC carrier	1
Number of used carriers	1696
Number of left carriers	176
Number of right carriers	175
$N_{subchannel}$	32
$N_{subcarriers}$	53
Number of data carriers per subchannel	48

3.3.3 OFDMA Frame Structure

In the licensed band, the duplexing method of OFDMA system shall be either TDD or FDD modes. However, IEEE 802.16a just support TDD mode in the license-exempt band. We consider the TDD mode in this thesis. When implementing a TDD system, the frame structure is built from BS and SS transmissions. In each frame, the Tx/Rx transition gap (TTG) and Rx/Tx transition gap (RTG) shall be inserted between the downlink and the uplink and at the end of each frame respectively to allow the BS to

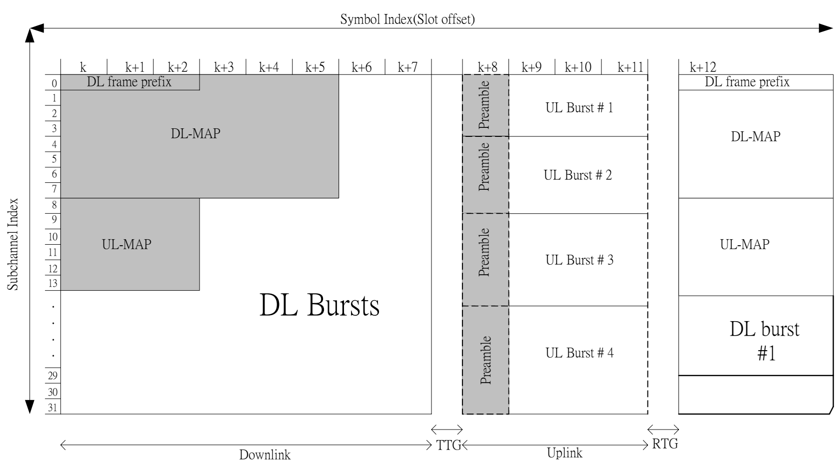

Figure 3.10 Illustration of TDD time frame of IEEE 802.16a

turn around. Each TGG and RTG duration should last for $5\mu s$ at least. After the TGG, the BS receiver shall look for the first symbol of a UL burst. After the RTG, the SS receivers shall look for the first symbol of QPSK modulated data in the DL burst. This mechanism is illustrated in Figure 3.10.

The first three OFDM DL symbols are all-pilot preamble in the sense that they indicate where the OFDMA frame starts. However, the DL preamble is not composed of all-pilot symbols.

3.3.4 Modulation

3.3.4.1 Data modulation

After bit interleaving, the data bits are entered serially to the constellation mapping block, where QPSK and 16-QAM modulations shall be supported, while 64-QAM is optional. The constellations shall be normalized by multiplying the constellation point with a factor to achieve equal averaged power. The constellations are shown in Figure 3.11.

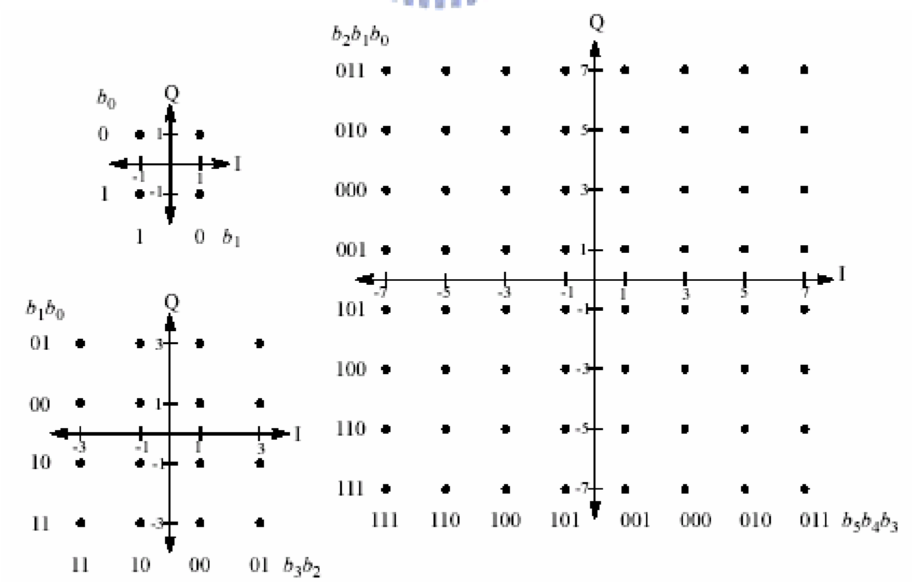

Figure 3.11 QPSK, 16-QAM and 64-QAM constellations

3.3.4.2 Pilot modulation

Pilot carriers shall be inserted into each data burst in order to constitute the symbol and they shall be modulated according to their carrier locations within the OFDMA symbol. Figure 3.12 shows the PRBS used for pilot modulation.

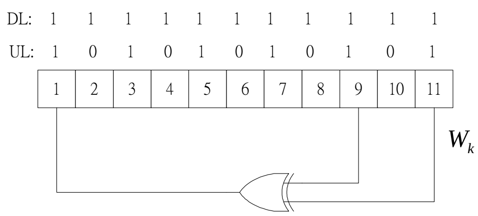

Figure 3.12 PRBS for Pilot Modulation

When transmitting data on DL, the initialization vector of the PRBS is: [1 1 1 1 1 1 1 1 1 1 1], except for the OFDMA DL preamble. When transmitting data on UL, the initialization vector of the PRBS shall be: [1 0 1 0 1 0 1 0 1 0 1]. The PRBS shall be initialized so that its first output bit coincides with the first usable carrier. A new value shall be generated by the PRBS on every usable carrier. Besides, each pilot shall be transmitted with a boosted power of 2.5dB over the averaged power of each data carrier but not on uplink preamble. As such the modulated pilots have the following form:

$$\mathrm{Re}\{C_k\} = \frac{8}{3}(\frac{1}{2} - W_k); \mathrm{Im}\{C_k\} = 0$$

3.3.4.3 Preamble Pilot Modulation

For DL, the first three symbols serve as the OFDMA DL preamble, where the initialization vector of the pilot modulation PRBS is [0 1 0 1 0 1 0 1 0 1 0]. The pilots shall be boosted and shall be modulated according to the following formula:

$$\mathrm{Re}\{C_k\} = \frac{8}{3}(\frac{1}{2} - W_k); \mathrm{Im}\{C_k\} = 0$$

For UL preamble, the pilots shall not be boosted and is modulated as

$$\mathrm{Re}\{C_k\} = 2(\frac{1}{2} - W_k); \mathrm{Im}\{C_k\} = 0$$