Chapter 8
OFDM Applications

Contents

8.1 Digital Audio Broadcasting (DAB)

8.1.1 Introduction to DAB

- **Current analog FM radio broadcasting system cannot satisfy the demands of the future, which are**
  - excellent sound quality
  - large number of stations
  - small portable receivers
  - no quality impairment due to multipath propagation or signal fading

8.1.1 Introduction to DAB

- **Current analog FM radio broadcasting systems have reached the limits of technical improvement.**
- **DAB is a digital technology offering considerable advantages over today's FM radio.**

8.1.1 Introduction to DAB

Eureka project EU 147: DAB

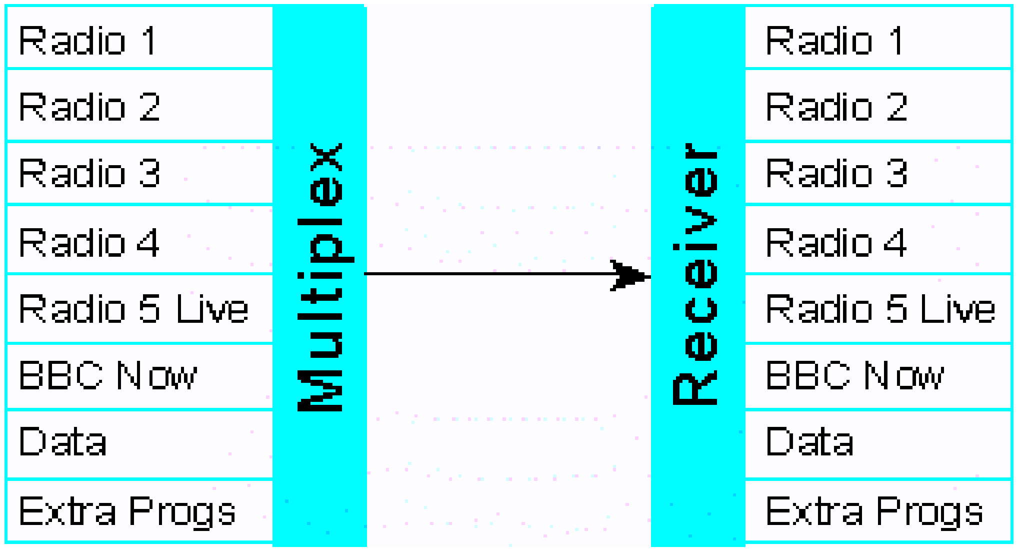
- Launched at 1986
- First phase: 4 year plan (1987-1991) of research and development
- Participants from Germany, France, Netherlands and United Kingdom
- Second phase (1992-1994, 170 man-years) :completion development of individual system specifications, development of ASICs, and considerations of additional services

8.1.1 Introduction to DAB

- Ability to deliver CD-quality stereo sound.
- Ease of use of DAB receivers.
- Switch between the eight or more stations carried by every single multiplex.

8.1.1 Introduction to DAB

- No need for drivers to retune as they cross a country.
- Wider choice of programs.
- Each multiplex is able to carry up to six full-quality stereo programs.



8.1.1 Introduction to DAB

Figure 1: DAB Transmission

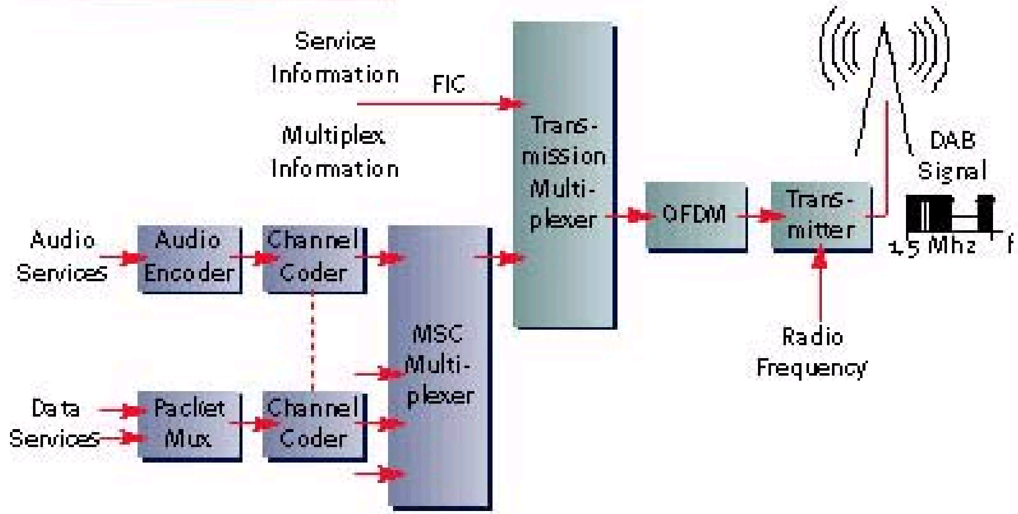
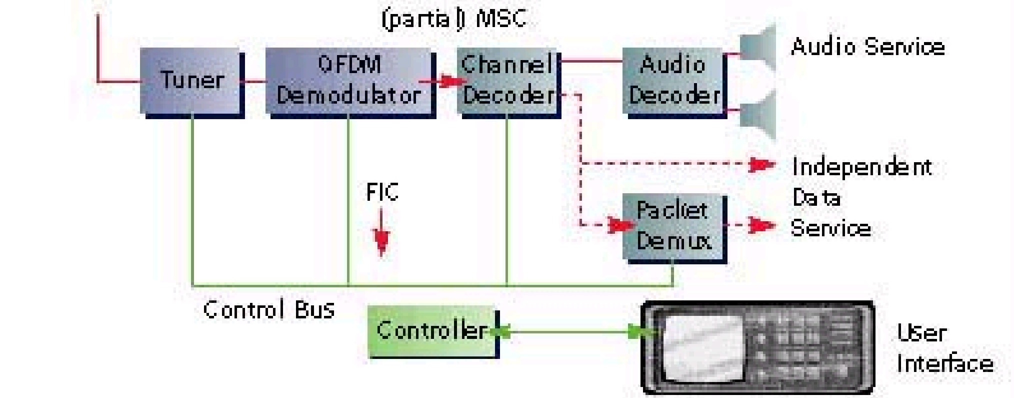


Figure 2: DAB Receiver



8.1.1 Introduction to DAB

- DAB can carry text and images as well as sound.
- All but the smallest will be able to display at least two 16-character lines of text.
- Selection by name or programme type.
- Enabling broadcasters to transmit programme-associated data (PAD) such as album title, song lyrics, or contact details.
- DAB can be transmitted at lower power than today's FM and AM services without loss of coverage

8.1.1 Introduction to DAB

- **DAB combines two advanced digital technologies to achieve robust and spectrum-efficient transmission of high-quality audio and other data.**
- **DAB uses the MPEG Audio Layer II system to achieve a compression ratio of 7:1 without perceptible loss of quality.**
- **The signal is then encoded at a bit rate of 8-384 kbit/s, depending on the desired sound quality and the available bandwidth.**

8.1.1 Introduction to DAB

- **Signal is individually error protected and labeled prior to multiplexing. Independent data services are similarly encoded.**
- **The Coded Orthogonal Frequency Division Multiplex (COFDM) technology is used for transmission.**
- **2.3 million bits of the multiplexed signal in time and across 1,536 distinct frequencies within the 1.5 MHz band.**

8.1.1 Introduction to DAB

- **An conventional FM network must use different frequencies in each area. In a DAB network, all transmitters operate on a single frequency.**
- **Such a Single Frequency Network (SFN) makes DAB's use of the radio spectrum over three times more efficient than conventional FM.**
- **DAB is designed for terrestrial, cable and for future satellite broadcasts**

8.1.1 Introduction to DAB

- **Technical characteristics**
  - **frequency range up to 20 kHz**
  - **48 kHz sampling rate; 18-bit resolution**
  - **4 audio modes: mono, stereo, dual channel, and joint stereo**
  - **bit rates from 32 kbit/s mono to 384 kbit/s stereophonic programme**
  - **audio frame 24 ms corresponding 1152 PCM audio samples**
  - **digital I/O conform AES/EBU standard**
  - **2 kbit/s (bytes of data per frame) for Program Associated Data (PAD)**

8.1.1 Introduction to DAB

- **Transmission system**
  - **Radio signal is normally distorted by**
    - **physical conditions**
    - **multipath propagation**
  - **Interference can be avoided by using COFDM**
  - **COFDM with error detection and correction provides a digital transparent channel allowing transmission of a stereo program or any other data.**
  - **Programs are divided into a total of 1536 carrier frequencies bandwidth 1.5 Mhz.**

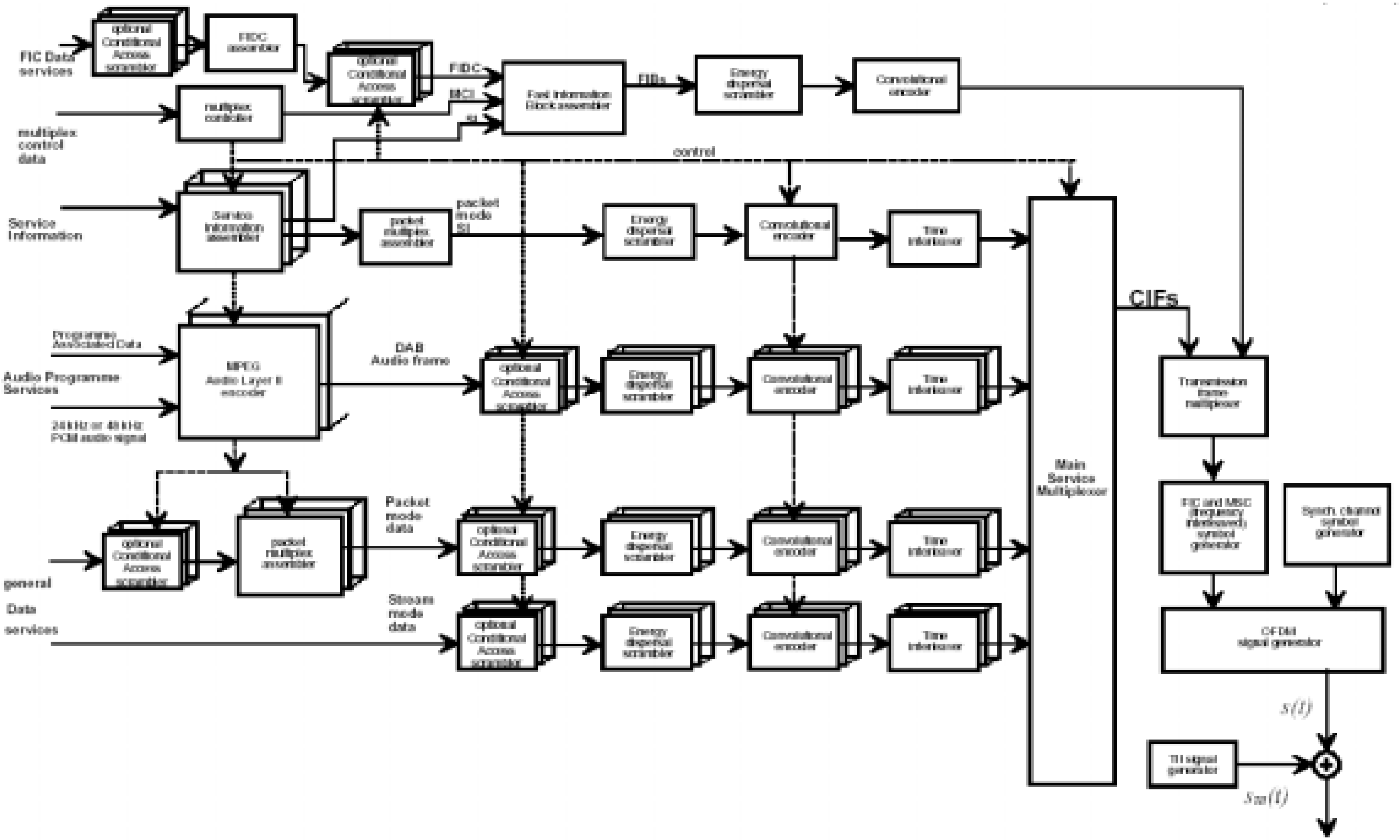
8.1.2 DAB System Overview

- **Audio, control information, and digital data service are multiplexed together to form OFDM signal on the air.**
- **The audio is encoded by MPEG Audio Layer II.**
- **The control information is used to interpret the configuration of the Main Service Channel (MSC).**

8.1.2 DAB System Overview

- **The control information is transmitted over the Fast Information Channel (FIC), which is made up of Fast Information Block (FIB).**
- **See the block diagram shown below.**

8.1.2 DAB System Overview



Conceptual DAB emission block diagram

8.1.3 DAB Channel Coding

- **Channel coding is based on a convolutional code with constraint length 7.**
- **Punctured convolutional coding allows Unequal Error Protection (UEP).**
- **Several convolutional coded stream are then combined and mapped into OFDM symbols.**

8.1.3 DAB Channel Coding

☞ **The mother code generates from the vector** $(a)_{i=0}^{I-1}$ **a codeword**

$\{(x_{0,i}, x_{1,i}, x_{2,i}, x_{3,i})\}_{i=0}^{I+5}$

$$x_{0,i} = a_i \oplus a_{i-2} \oplus a_{i-3} \oplus a_{i-5} \oplus a_{i-6}$$

$$x_{1,i} = a_i \oplus a_{i-1} \oplus a_{i-2} \oplus a_{i-3 \oplus} a_{i-6}$$

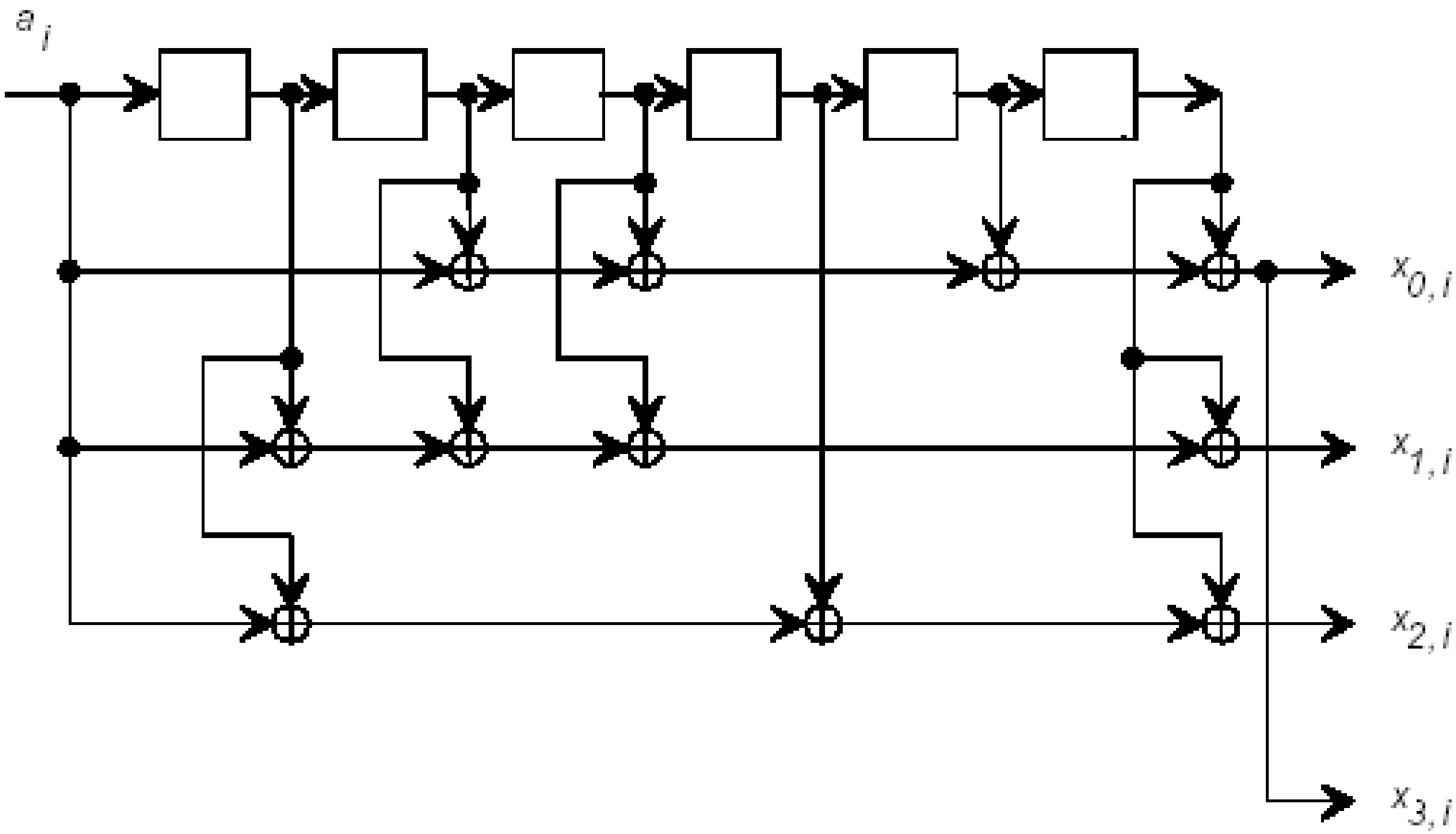
$$x_{2,i} = a_i \oplus a_{i-1} \oplus a_{i-4} \oplus a_{i-6}$$

$$x_{3,i} = a_i \oplus a_{i-2} \oplus a_{i-3} \oplus a_{i-5} \oplus a_{i-6}$$

for $i = 0,1,2,\ldots,I+5$

8.1.3 DAB Channel Coding

☞ **Convolutional Encoder**



8.1.3 DAB Channel Coding

- **Puncturing procedure: Some predefined coded bits generated by the mother code are not transmitted.**
- **The first *4I* bits are divided into consecutive sub-blocks of 32 bits.**
- **The *i*th bit in each sub-block is process according to the puncturing vector**

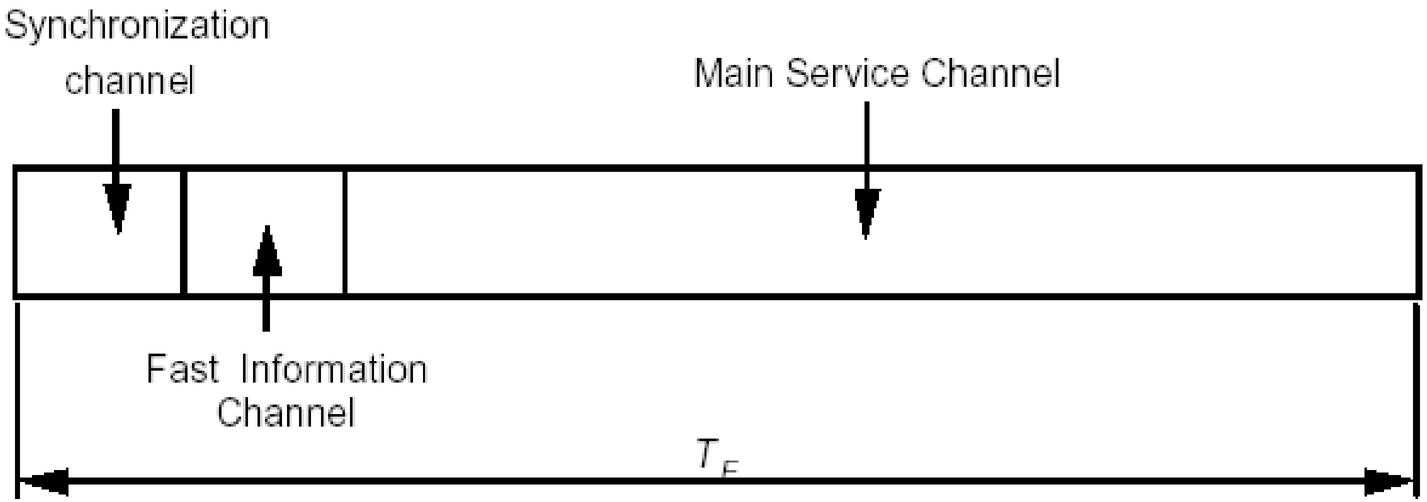
$$v_{PI} = (v_{PI,0}, v_{PI,1}, \ldots, v_{PI,31})$$

8.1.3 DAB Channel Coding

- **For $v_{PI,i} = 0$, the corresponding bit shall be taken out of the sub-block and shall not be transmitted.**
- **For $v_{PI,i} = 1$, the corresponding bit shall be retrained in the sub-block and shall be transmitted.**
- **There are total 24 possible puncturing vectors so the rate of the punctured convolutional code varies from 8/9 to ¼.**

8.1.4 DAB Modulation

☞ **Transmission frame structure**



8.1.4 DAB Modulation

- **Four transmission modes are defined**
- **Each transmission frame is divided into a sequence of OFDM symbols.**
- **The first OFDM symbol of the transmission frame shall be the Null symbol of duration T_{NULL}. The remaining part is OFDM symbols of duration T_S.**

8.1.4 DAB Modulation

☞Each OFDM symbol can be expressed as

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

with

$$g_{k,l}(t) = \begin{cases} 0 & \text{for } l = 0 \\ e^{j2\pi k(t-\Delta)/T_U}\,\mathrm{Rect}(t/T_S) & \text{for } l = 1,2,\ldots,L \end{cases}$$

L: Number of OFDM symbols per frame

K: Number of transmitted carriers

T_F: Transmission frame duration

T_{NULL}: Null symbol duration

f_c: Central frequency of the signal

T_U: Inverse of the carrier spacing

Δ: Guard interval

$T_S = T_U + \Delta$: Duration of OFDM symbols

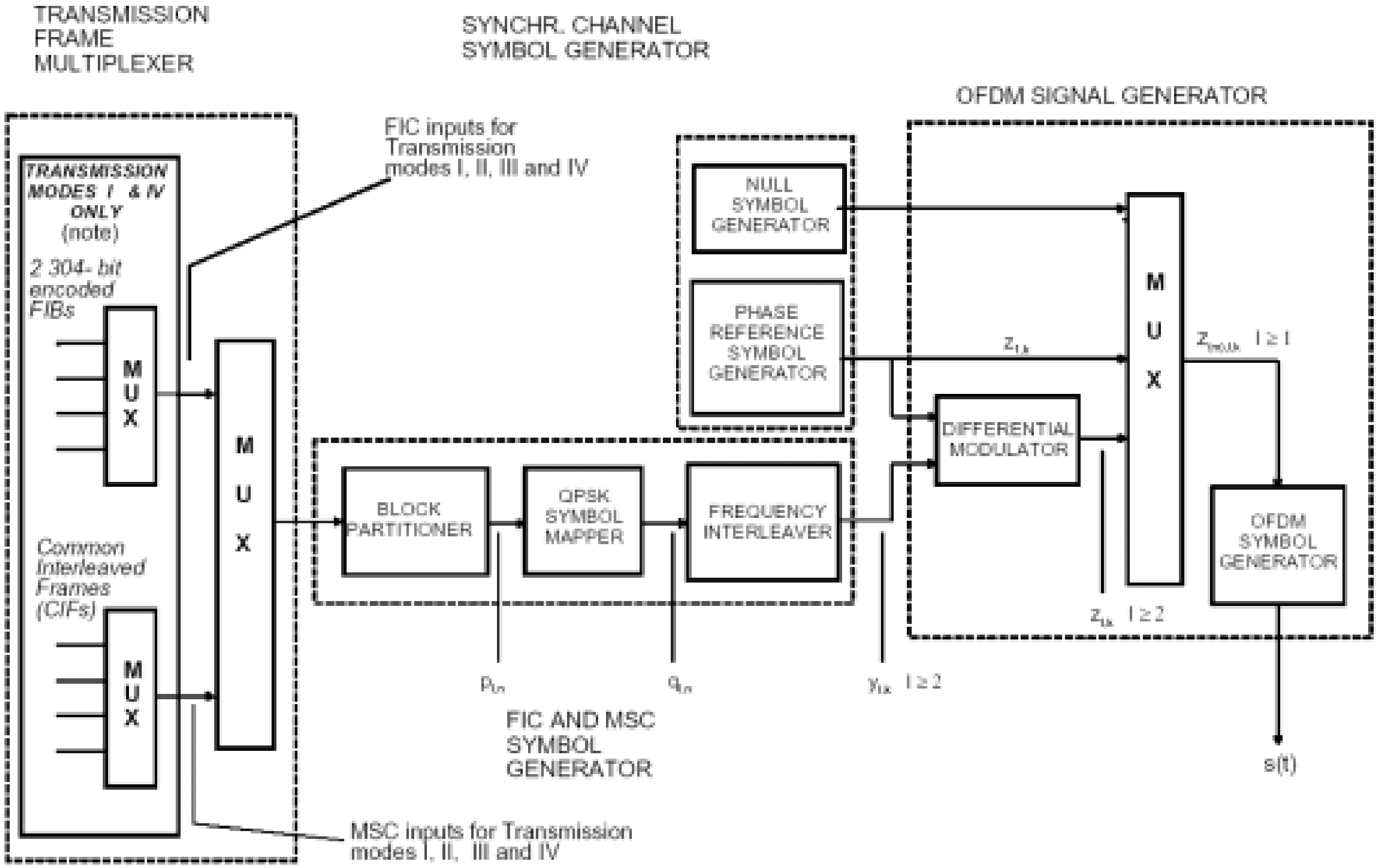
$Z_{m,l,k}$: Complex D-QPSK symbol for carrier k of OFDM symbol l during transmission frame k.

8.1.4 DAB Modulation

Parameter	Transmission mode I	Transmission mode II	Transmission mode III	Transmission mode IV
L	76	76	153	76
K	1536	384	192	768
T_F	196608 T 96 ms	49152 T 24 ms	49152 T 24 ms	98304 T 48 ms
T_{NULL}	2656 T ~1,297 ms	664 T ~324 μs	345 T ~168 μs	1328 T ~648 μs
T_S	2552 T ~1,246 ms	638 T ~312 μs	319 T ~156 μs	1276 T ~623 μs
T_U	2048 T 1 ms	512 T 250 μs	256 T 125 μs	1024 T 500 μs
Δ	504 T ~246 μs	126 T ~62 μs	63 T ~31 μs	252 T ~123 μs

Definition of the parameters for transmission modes I,II,III, and IV.

8.1.4 DAB Modulation



NOTE: In transmission mode I, the 4 inputs of each MUX are used.
In transmission mode IV, only 2 inputs of each MUX are used.

Conceptual block diagram of the generation of the main signal

8.1.4 DAB Modulation

- **Synchronization Channel: the first two OFDM symbols**
- **During the time interval [$0, T_{NULL}$], the main signal $s(t)$ shall be equal to zero.**
- **The second OFDM symbol is the phase reference symbol defined by the value of $z_{l,k}$ for $l=1$:**

$$z_{1,k} = \begin{cases} e^{j\varphi_k} & \text{for } -K/2 \le k < 0 \text{ and } 0 < k \le K/2 \\ 0 & \text{for } k = 0 \end{cases}$$

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8.1.4 DAB Modulation

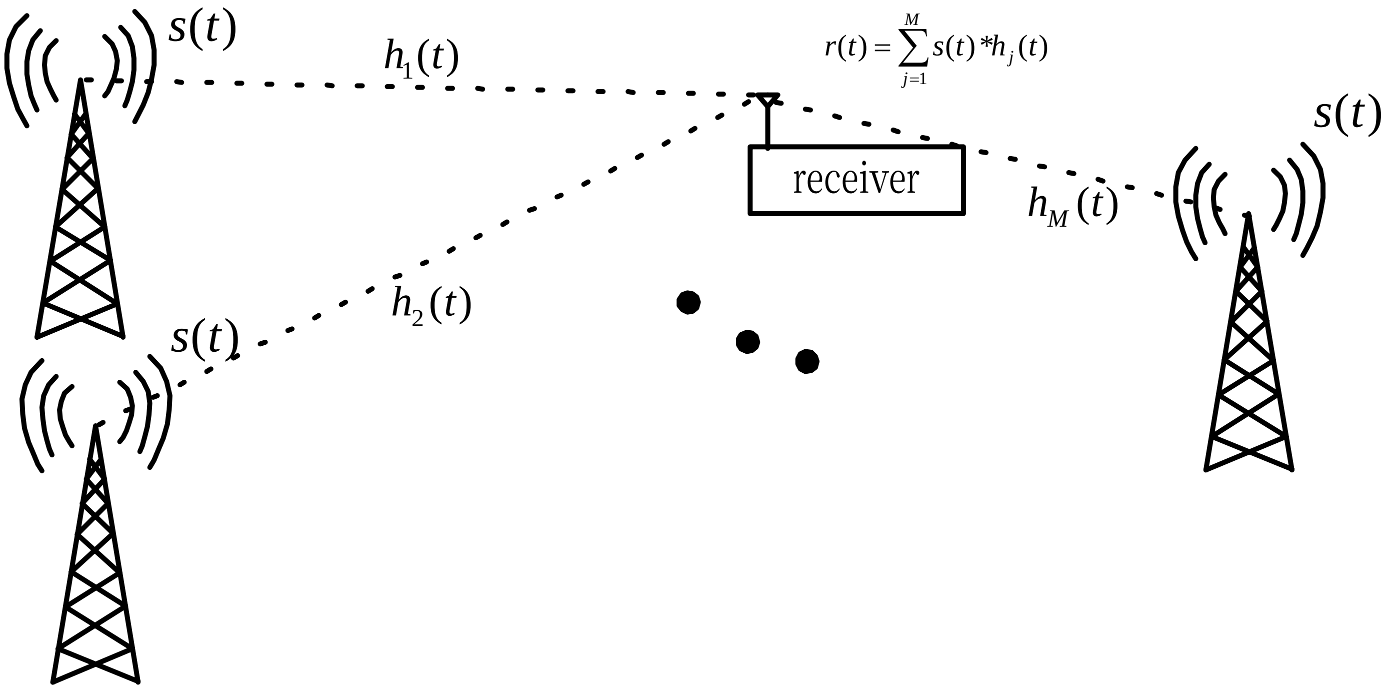
- **The values of φ_k shall be obtained from the following formulae**

$$\varphi_k = \frac{\pi}{2}(h_{i,k-k'} + n)$$

- **The values of the parameter $h_{i,j}$ as a function of indices i and j are specified in the standard**

8.1.5 Channel for DAB OFDM System

☞ **Assume that there are *M* stations that transmit synchronous OFDM frame *s(t)*.**



8.1.5 Channel for DAB OFDM System

- **The signal from the station j propagates to the receiver. The received signal from the jth station can be expressed as**

$$r_j(t) = s(t) * h_j(t)$$

where * denotes the convolution and $h_j(t)$ **is the channel impulse response from station j to the receiver.**

- **The overall received signal from all stations can be expressed as**

$$r(t) = \sum_{j=1}^{M} r_j(t) = \sum_{j=1}^{M} s(t) * h_j(t)$$

$$= s(t) * \sum_{j=1}^{M} h_j(t)$$

8.1.5 Channel for DAB OFDM System

- **Now we may define the overall channel impulse response as**

$$h(t) = \sum_{j=1}^{M} h_j(t)$$

- **The received signal can be expressed as**

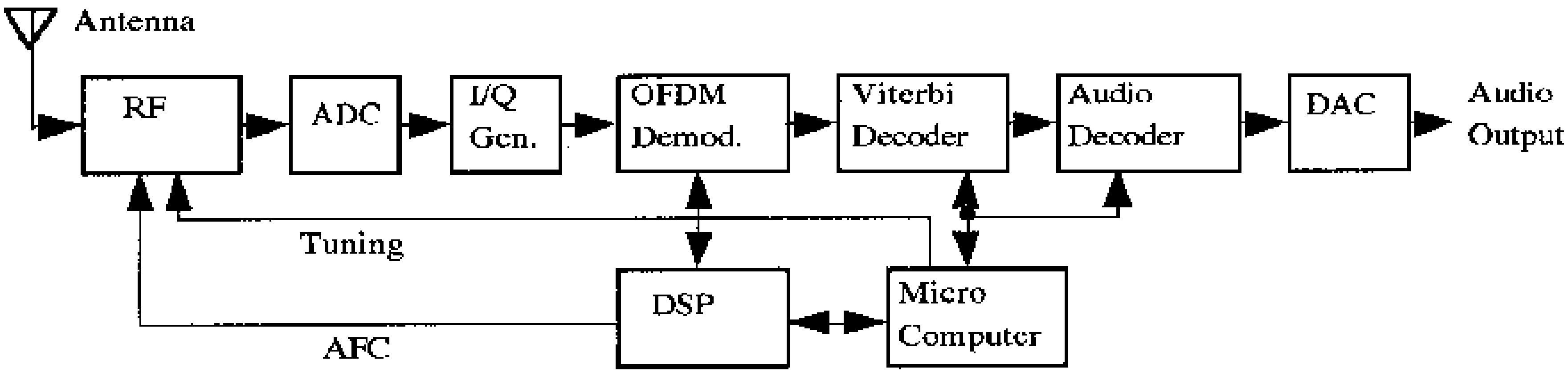
$$r(t) = s(t) * h(t)$$

- **No inter-symbol interference (ISI) if the spreading of *h(t)* is less then the guard interval.**

8.1.6 Receiver for DAB OFDM System

- **Tuning (frequency) accuracy required is 5%.**
- **Robust frequency tracking is required.**
- **Fast channel and timing tracking to overcome the rapidly change condition.**

8.1.6 Receiver for DAB OFDM System



Block diagram of DAB receiver

8.2 HDTV-Digital Video Broadcasting (DVB)

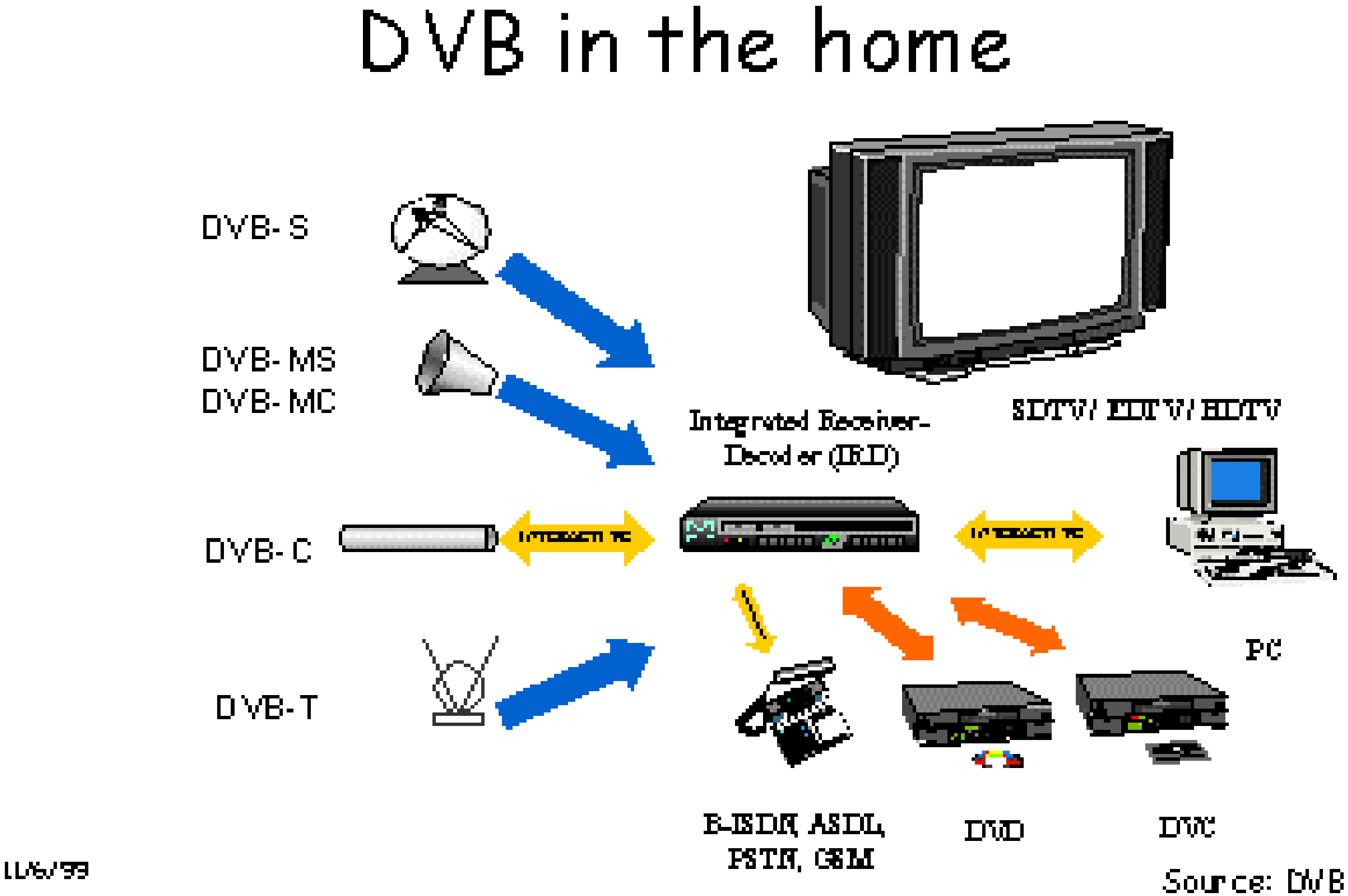
8.2.1 Introduction to DVB

- Audio and Video-centric
- Very large files transmission.
- Quality of service issues.
  - Guaranteed bandwidth
  - Jitter
  - Delay
- Large, scalable audience
- Broadband downstream, narrowband up
- Satellite: DVB-S
- Terrestrial: ATSC, DVB-T

8.2.1 Introduction to DVB

- **European standard for transmission of digital TV via satellite, cable or terrestrial**
  - DVB-S (satellite)
    - QPSK – Quadrature Phase-Shift Keying
  - DVB-T (terrestrial)
    - COFDM – Coded Orthogonal Frequency Division Multiplexing
- **MPEG-2 compression and transport stream**
- **Support for multiple, encrypted program stream.**

8.2.1 Introduction to DVB



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8.2.1 Introduction to DVB

- **Digital Video Combines Traditional and Interactive Content and Applications**

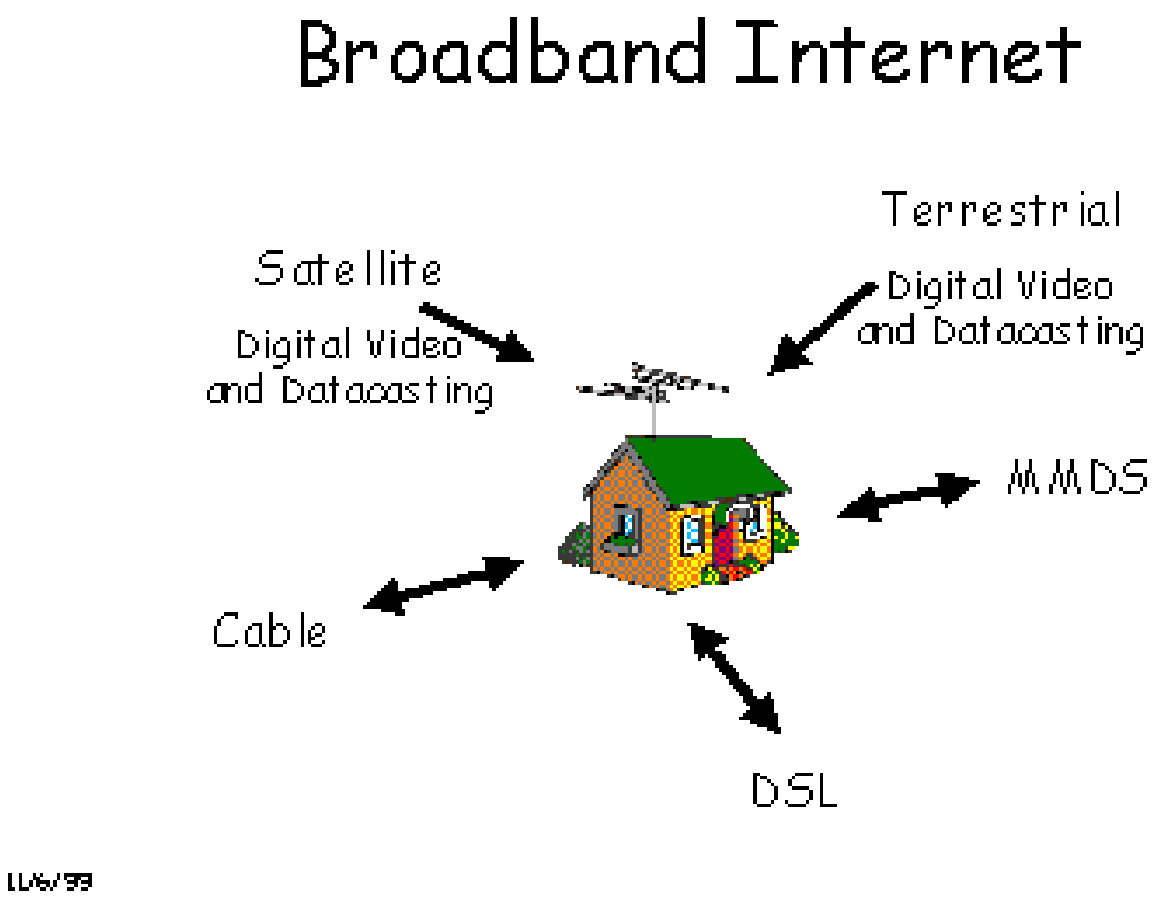
Traditional

- **Film**
- **TV**
- **Music**
- **Books**
- **Magazines**
- **Board games**

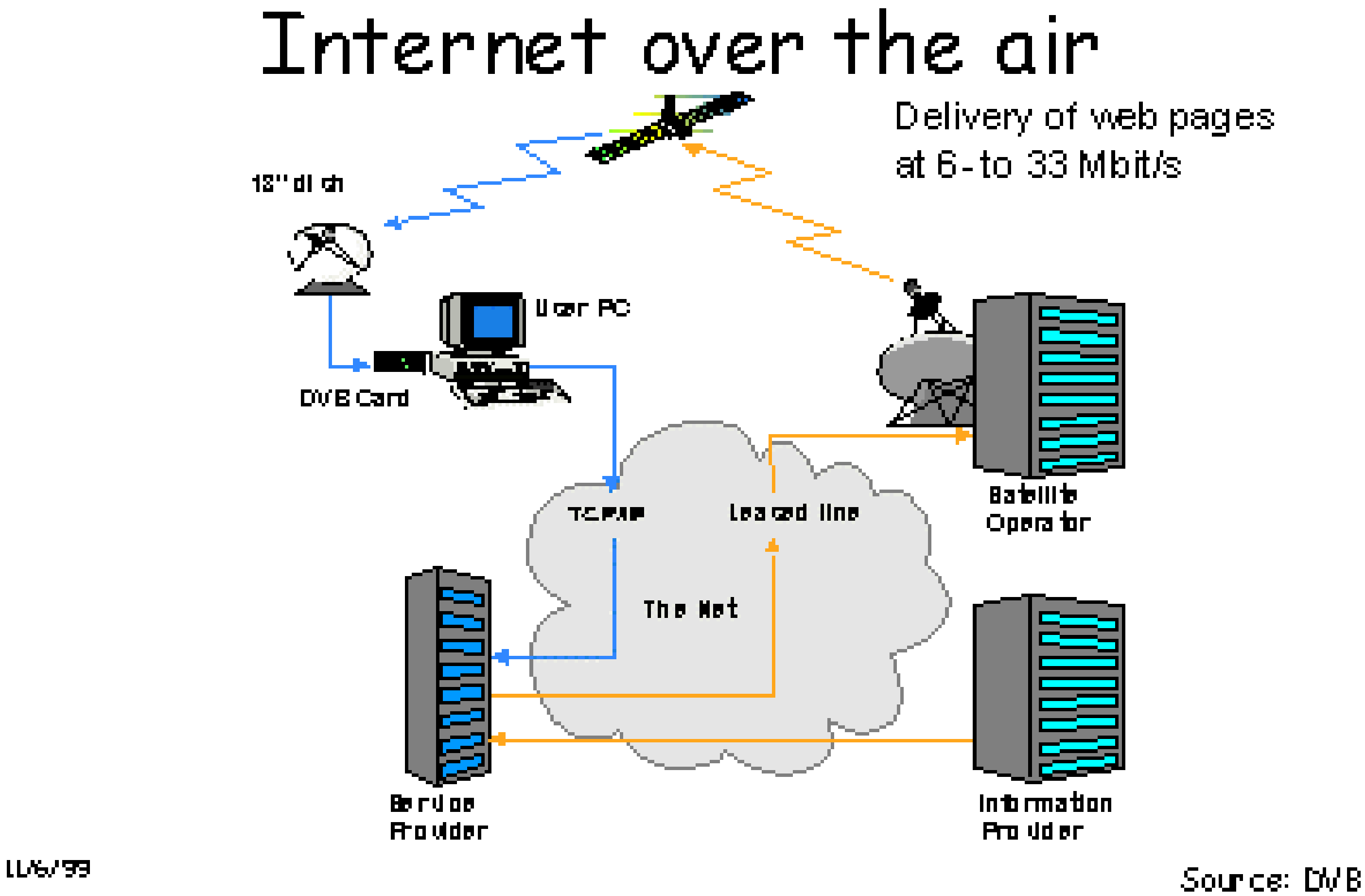
Interactive

- **Enhanced DVD**
- **Movies/music**
- **Interactive games**
- **Videophone**
- **Creating and sharing documents**
- **Online E-commerce**

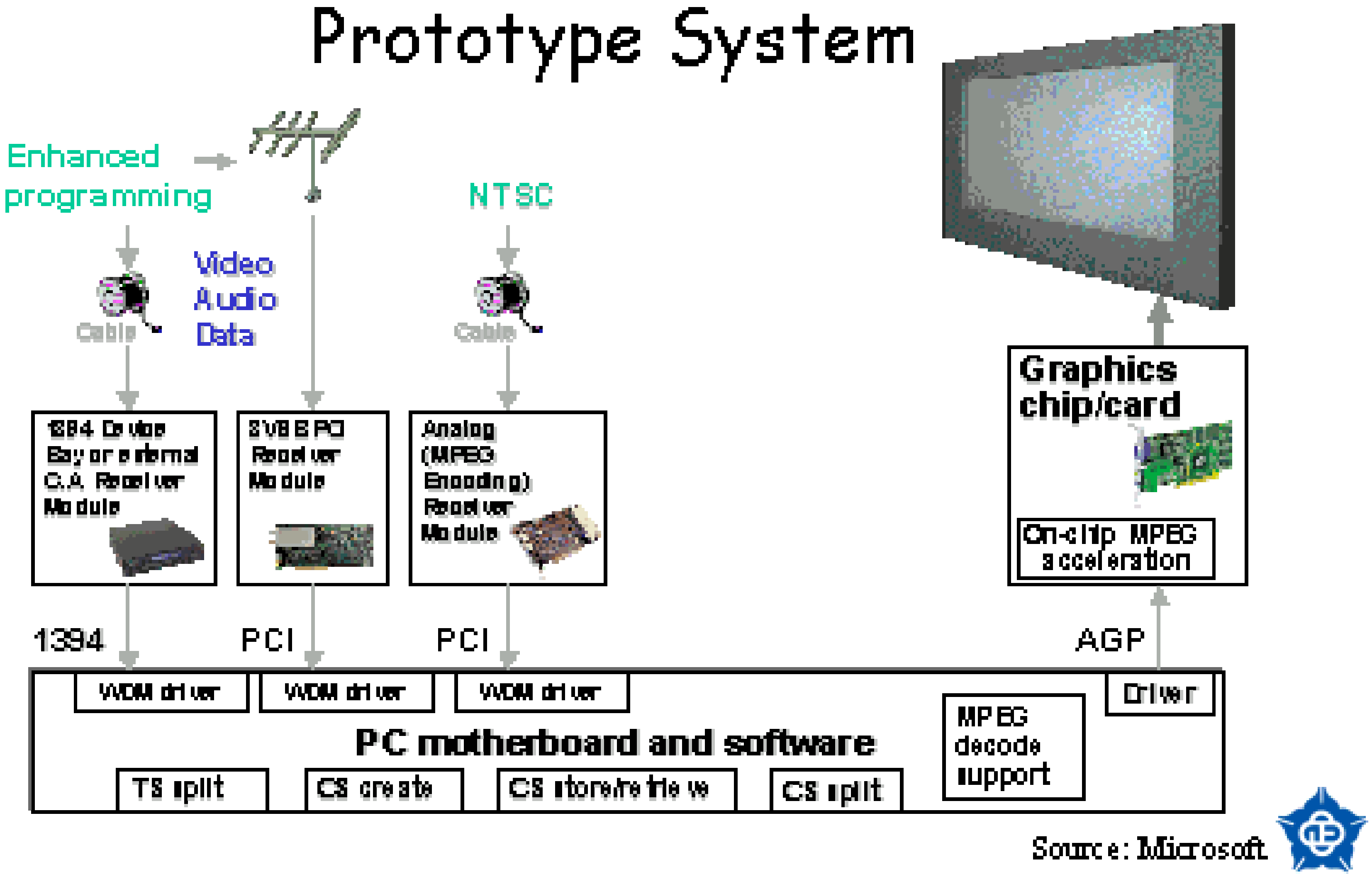
8.2.1 Introduction to DVB



8.2.1 Introduction to DVB



8.2.1 Introduction to DVB



8.2.2 DVB System Overview

- **MPEG-2 source coding and multiplexing**
- **Outer coding (Reed-Solomon code)**
- **Outer interleaving (convolutional interleaving)**
- **Inner coding (punctured convolutional code)**
- **Inner interleaving**
- **Mapping and modulation (BPSK,QPSK,16-QAM, 64-QAM)**
- **Transmission – Orthogonal Frequency Division Multiplexing (OFDM)**

8.2.2 DVB System Overview

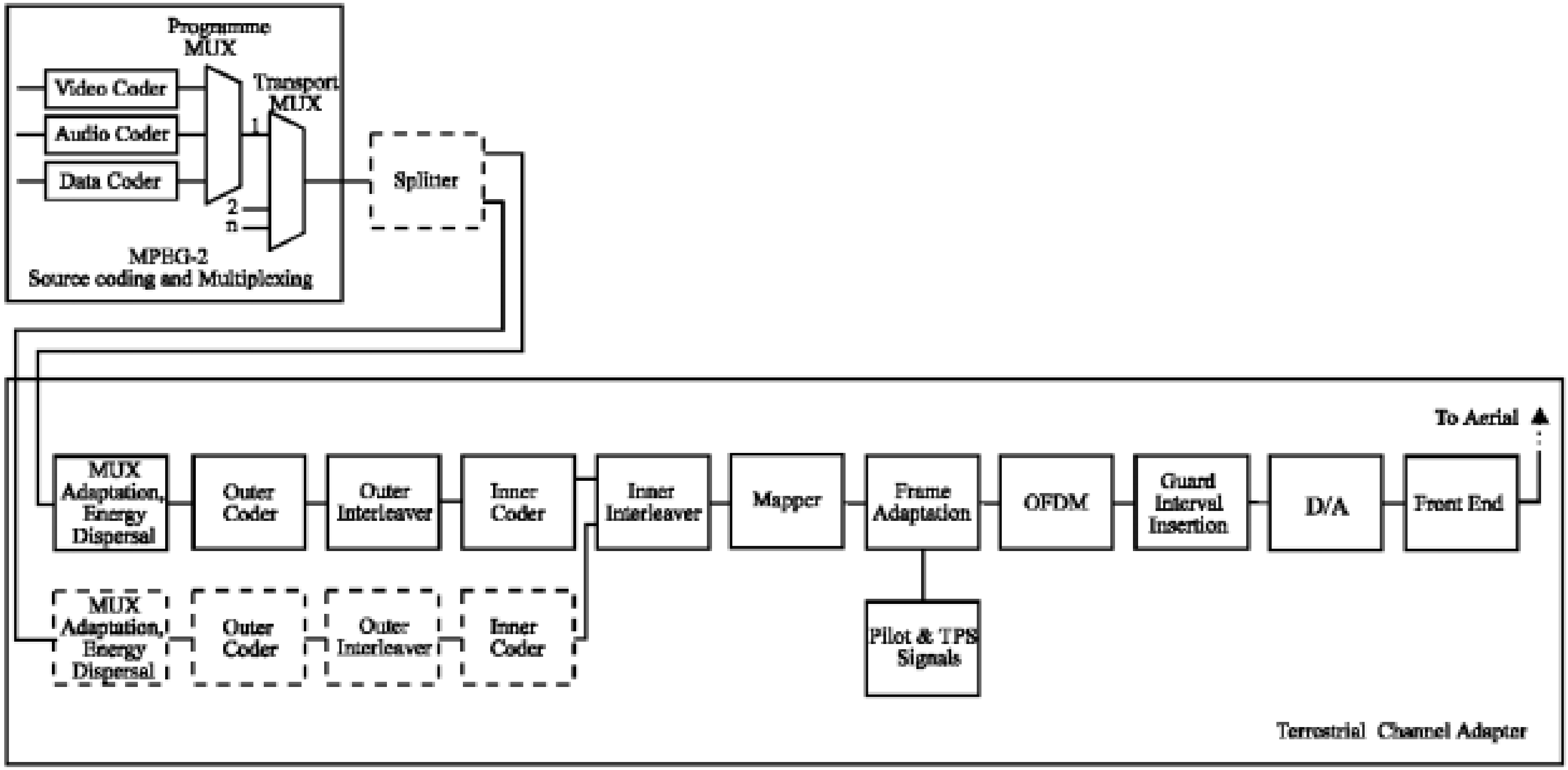
- **Operate within existing VHF and UHF spectrum**
  - The system must provide sufficient protection against Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI)
- **OFDM with concatenated error correcting coding is being specified.**
- **Flexible guard interval is specified**
- **Two mode of operations:**
  - 2K mode: suitable for single transmitter operation for small SFN networks.
  - 8K mode: used both for single transmitter operation and for small and large SFN networks.

8.2.2 DVB System Overview

- **Multi-level QAM modulation**
- **Different inner code rates (punctured convolutional code)**
- **MPEG stream is separated into**
  - High-priority stream
  - Low-priority stream
- **Unequal Error Protection (UEP)**
  - High-priority stream is high-level protected.
  - Low-priority stream is low-level protected.

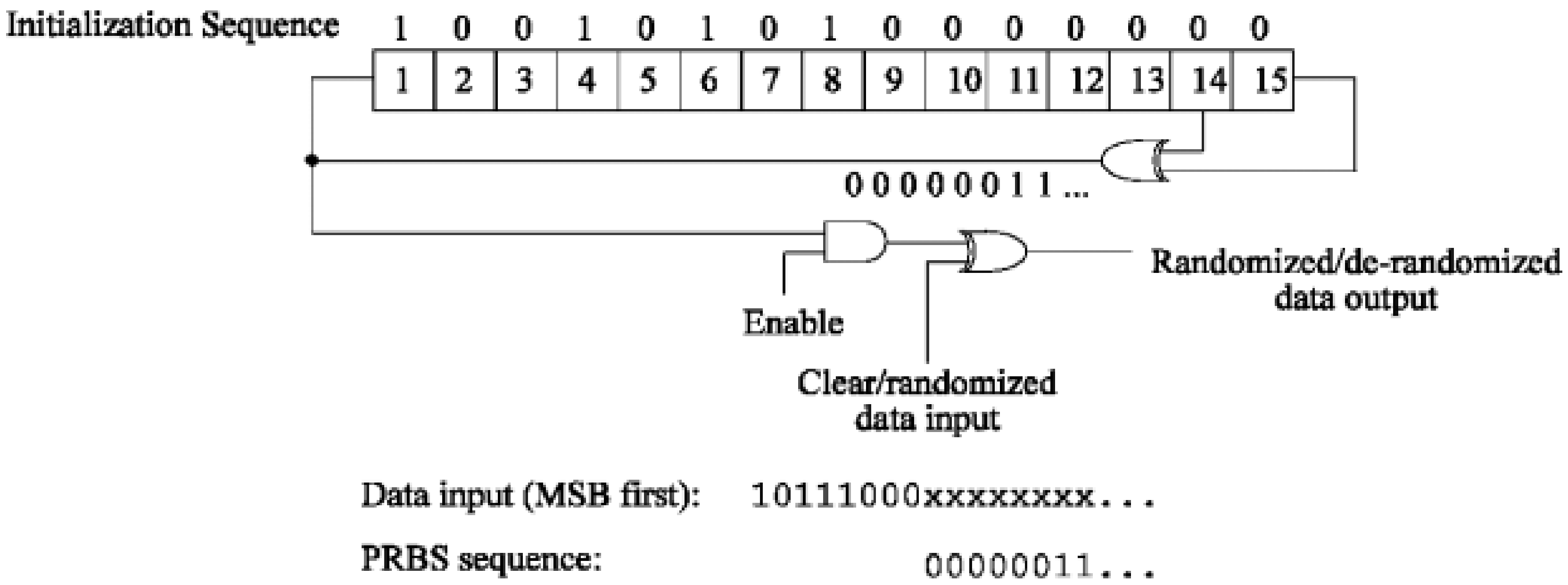
8.2.2 DVB System Overview

☞ **Functional block diagram of the DVB transmitter**



8.2.3 Channel Coding and Modulation

- ☞ **Transport multiplex adaptation and randomization (scrambler)**

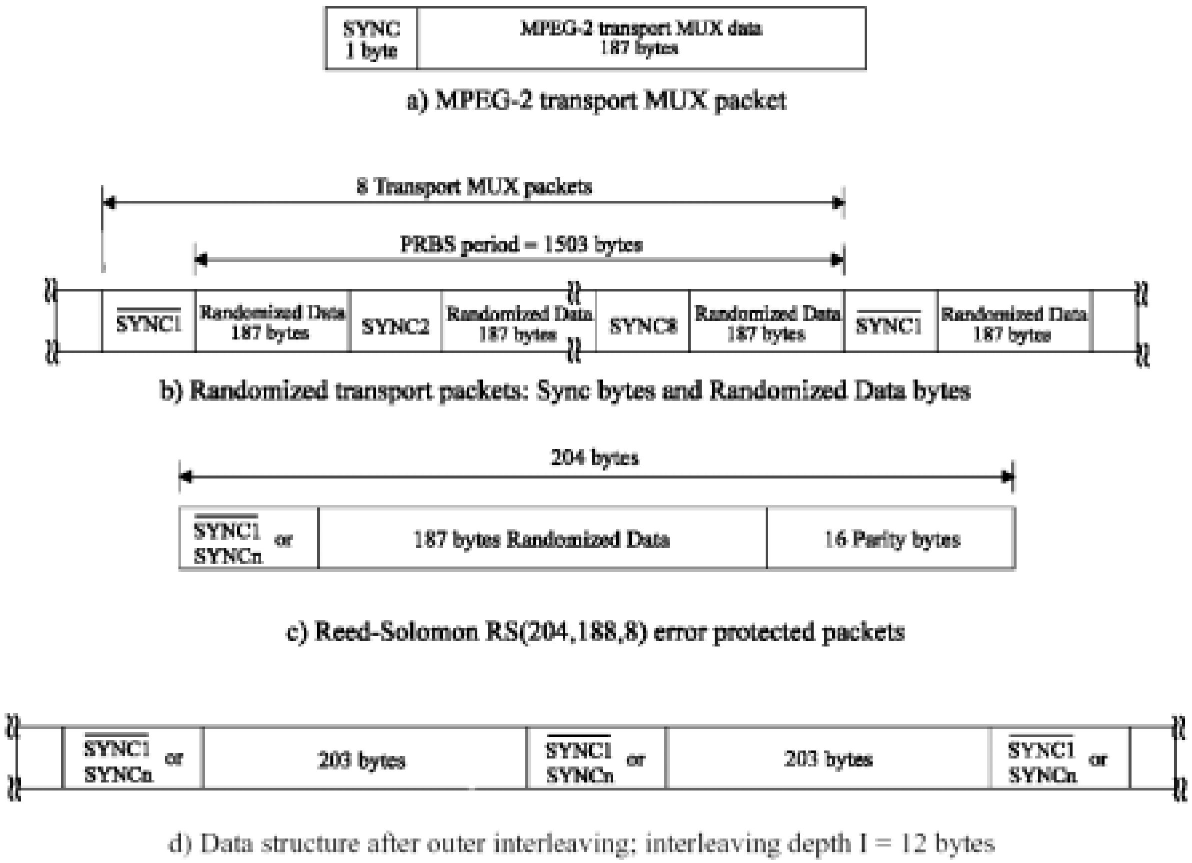


8.2.3 Channel Coding and Modulation

- **The total packet length of the MPEG-2 MUX packet is 188 bytes.**
- **The data of the input MPEG-2 multiplex shall be randomized with the above circuit.**

8.2.3 Channel Coding and Modulation

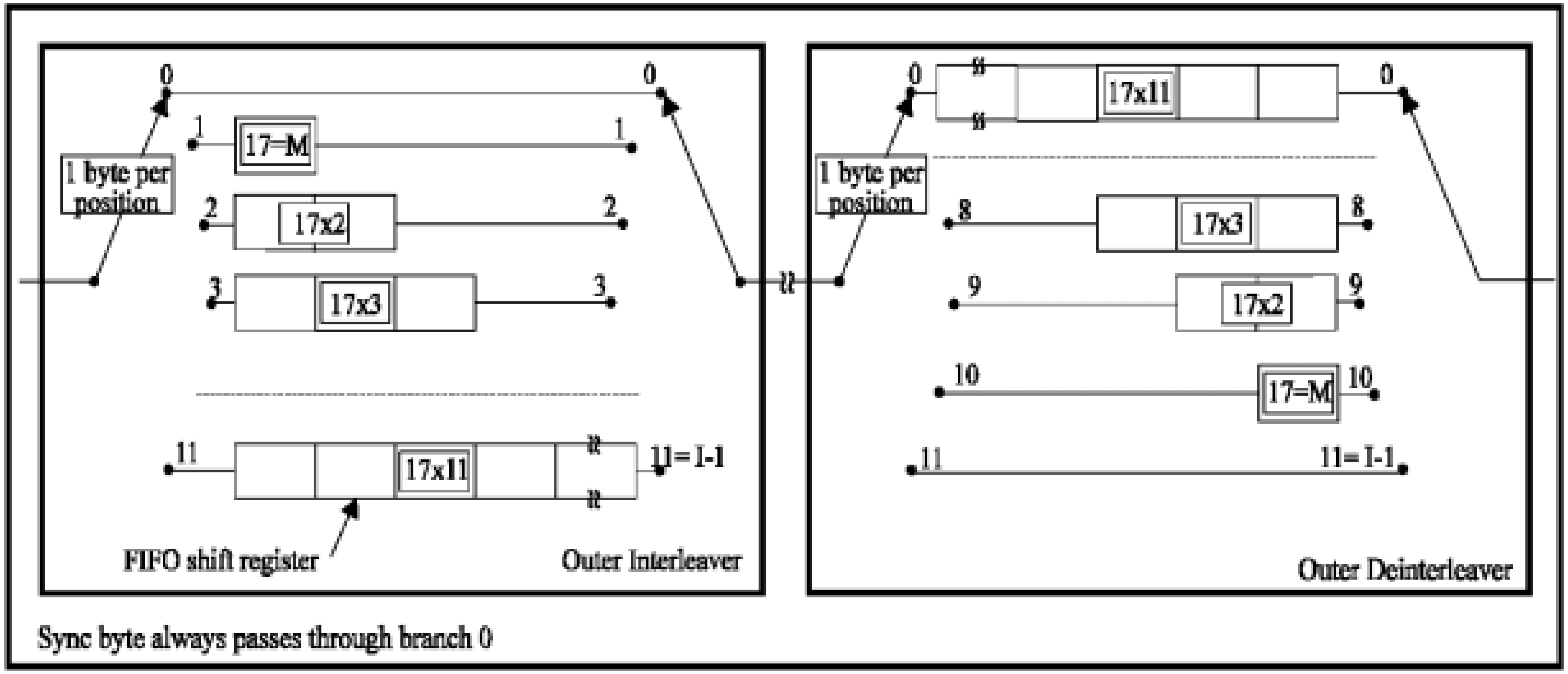
- **Outer coding and outer interleaving**
  - **RS (204,188) shortened code from RS (255,239) is adopted.**



8.2.3 Channel Coding and Modulation

Convolutional interleaving

- Convolutional byte-wise interleaving with depth I=12



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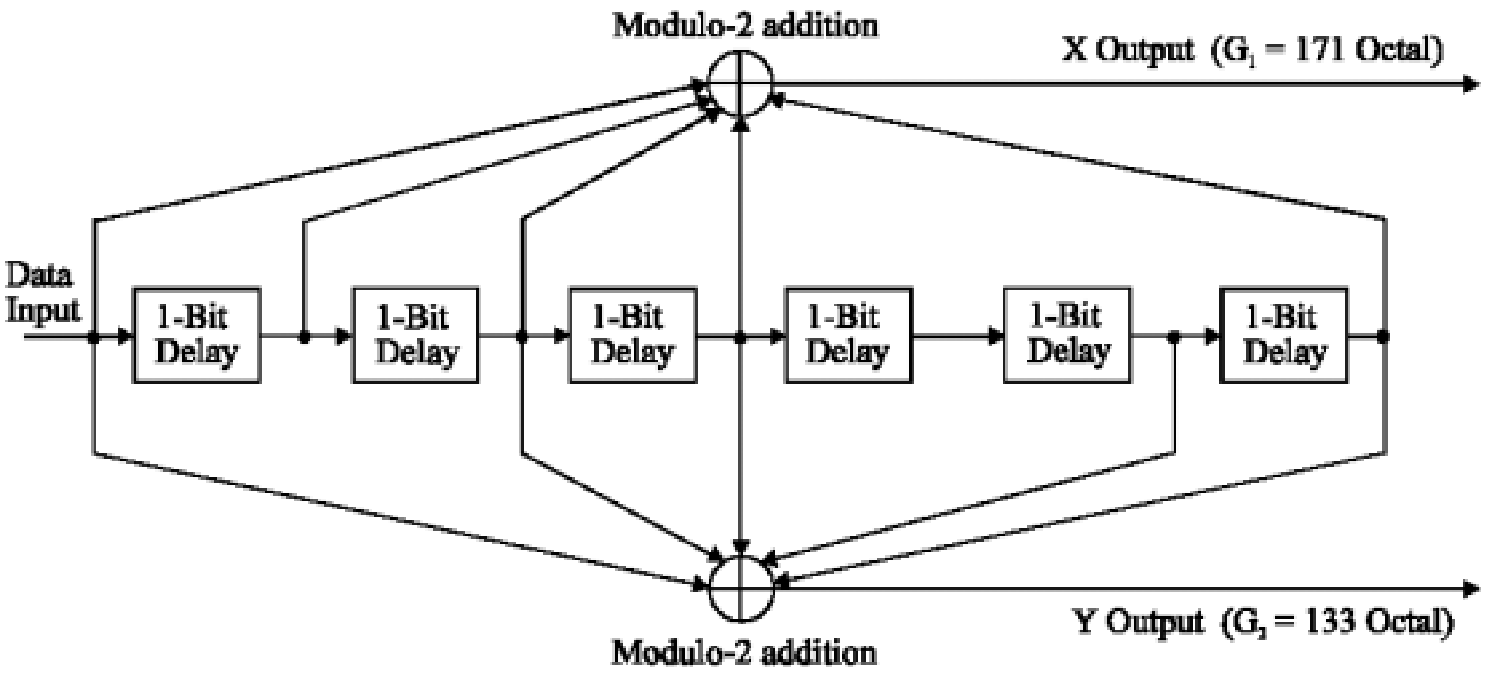
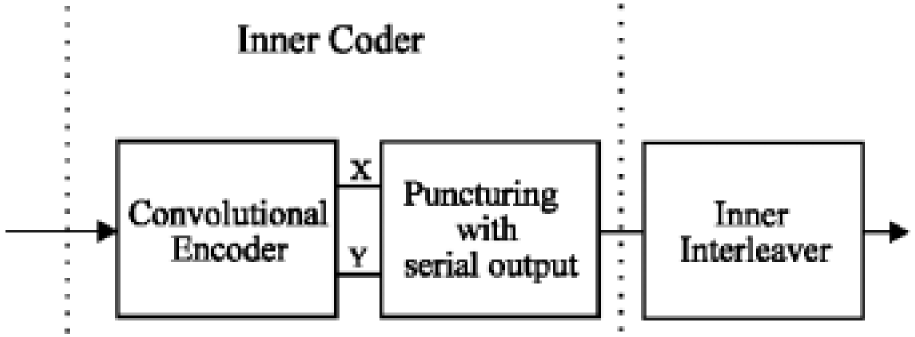
8.2.3 Channel Coding and Modulation

- **Inner coding**
  - **Convolutional code of rate ½ with 64 states.**
  - **Generator polynomial $G_1=171_{OCT}$ and $G_2=133_{OCT}$**



8.2.3 Channel Coding and Modulation

☞ **Punctured convolutional code**



☞ **Puncturing pattern and transmitted sequence after parallel-to-serial conversion for the possible code rate**

Code Rates r	Puncturing pattern	Transmitted sequence (after parallel-to-serial conversion)
1/2	X: 1 Y: 1	X_1Y_1
2/3	X: 1 0 Y: 1 1	$X_1\ Y_1\ Y_2$
3/4	X: 1 0 1 Y: 1 1 0	$X_1\ Y_1\ Y_2\ X_3$
5/6	X: 1 0 1 0 1 Y: 1 1 0 1 0	$X_1\ Y_1\ Y_2\ X_3\ Y_4\ X_5$
7/8	X: 1 0 0 0 1 0 1 Y: 1 1 1 1 0 1 0	$X_1\ Y_1\ Y_2\ Y_3\ Y_4\ X_5\ Y_6\ X_7$

8.2.3 Channel Coding and Modulation

- **Inner interleaving**
  - **Bit-wise interleaving followed by symbol interleaving .**
  - **Both the bit-wise interleaving and the symbol interleaving processes are block-based.**
- **Define a mapping (demultiplexing) of the input bits** x_{di} **onto the output bits** $b_{e,do}$
- **In non-hierarchical mode:**

$$x_{di} = b_{[di(\mathrm{mod})v](\mathrm{div})(v/2)+2[di(\mathrm{mod})(v/2)],di(\mathrm{div})v}$$

8.2.3 Channel Coding and Modulation

☞ **In non-hierarchical mode:**

- **High-priority input**

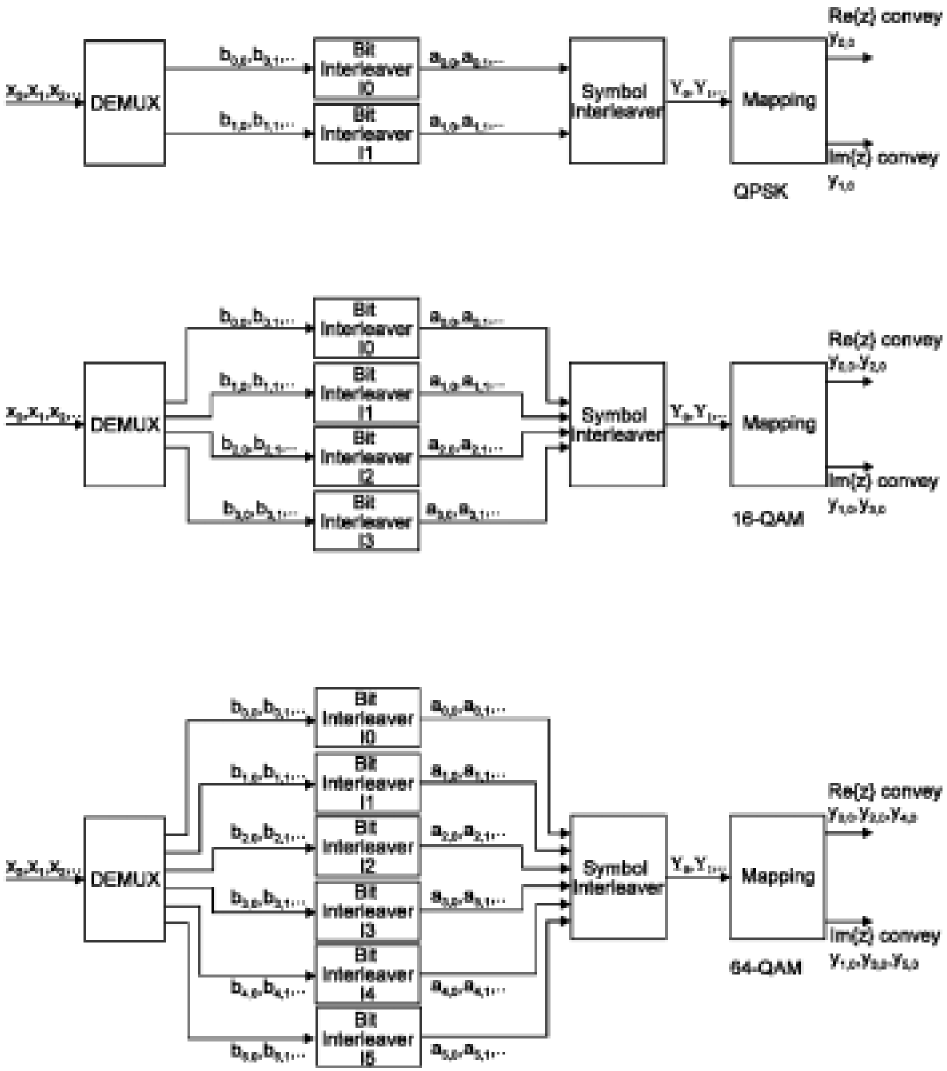
$$x'_{di} = b_{di(\mathrm{mod})2,\,di(\mathrm{div})2}$$

- **Low-priority input**

$$x''_{di} = b_{[di(\mathrm{mod})(v-2)](\mathrm{div})((v-2)/2)+2[di(\mathrm{mod})((v-2)/2)]+2,\,di(\mathrm{div})(v-2)}$$

8.2.3 Channel Coding and Modulation

☞ Non-hierarchical modulation mapping



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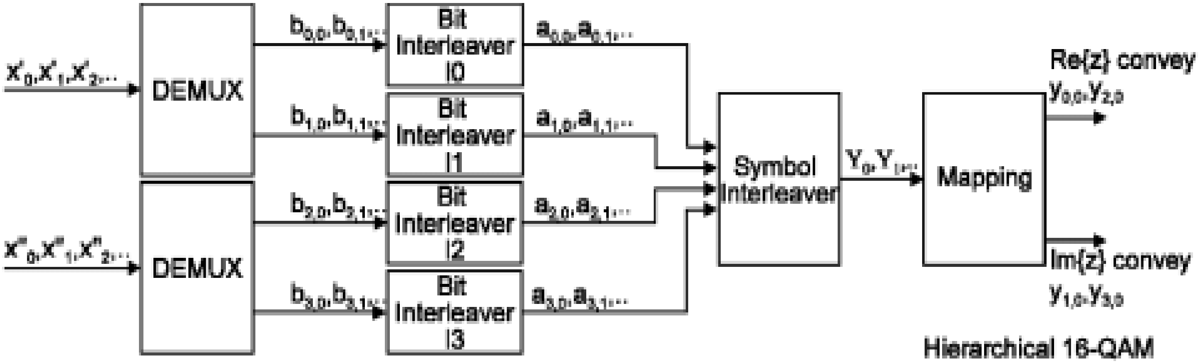
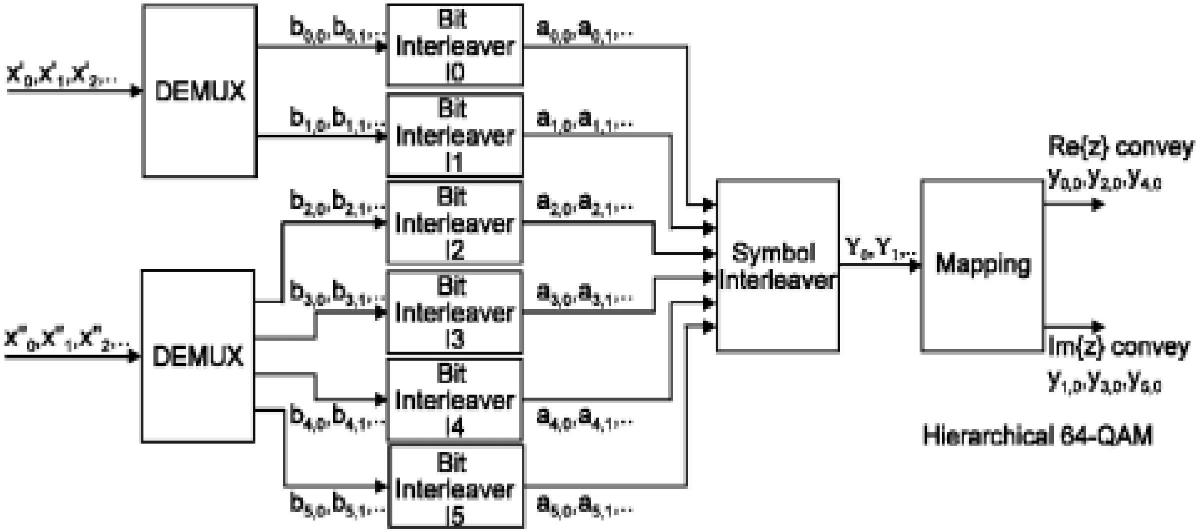
8.2.3 Channel Coding and Modulation

☞ Hierarchical modulation mapping





8.2.3 Channel Coding and Modulation

Bit interleaver

- **For each bit interleaver, the input bit vector is defined by**

$$B(e) = (b_{e,0}, b_{e,1}, b_{e,2}, \ldots, b_{e,125})$$

where *e* ranges from 0 to *v-1*.

- **The interleaved output vector**

$$A(e) = (a_{e,0}, a_{e,1}, a_{e,2}, \ldots, a_{e,125})$$

is defined by

$$a_{e,w} = b_{e,H_e(w)}$$

where $He(w)$ is a permutation function which is different for each interleaver.

8.2.3 Channel Coding and Modulation

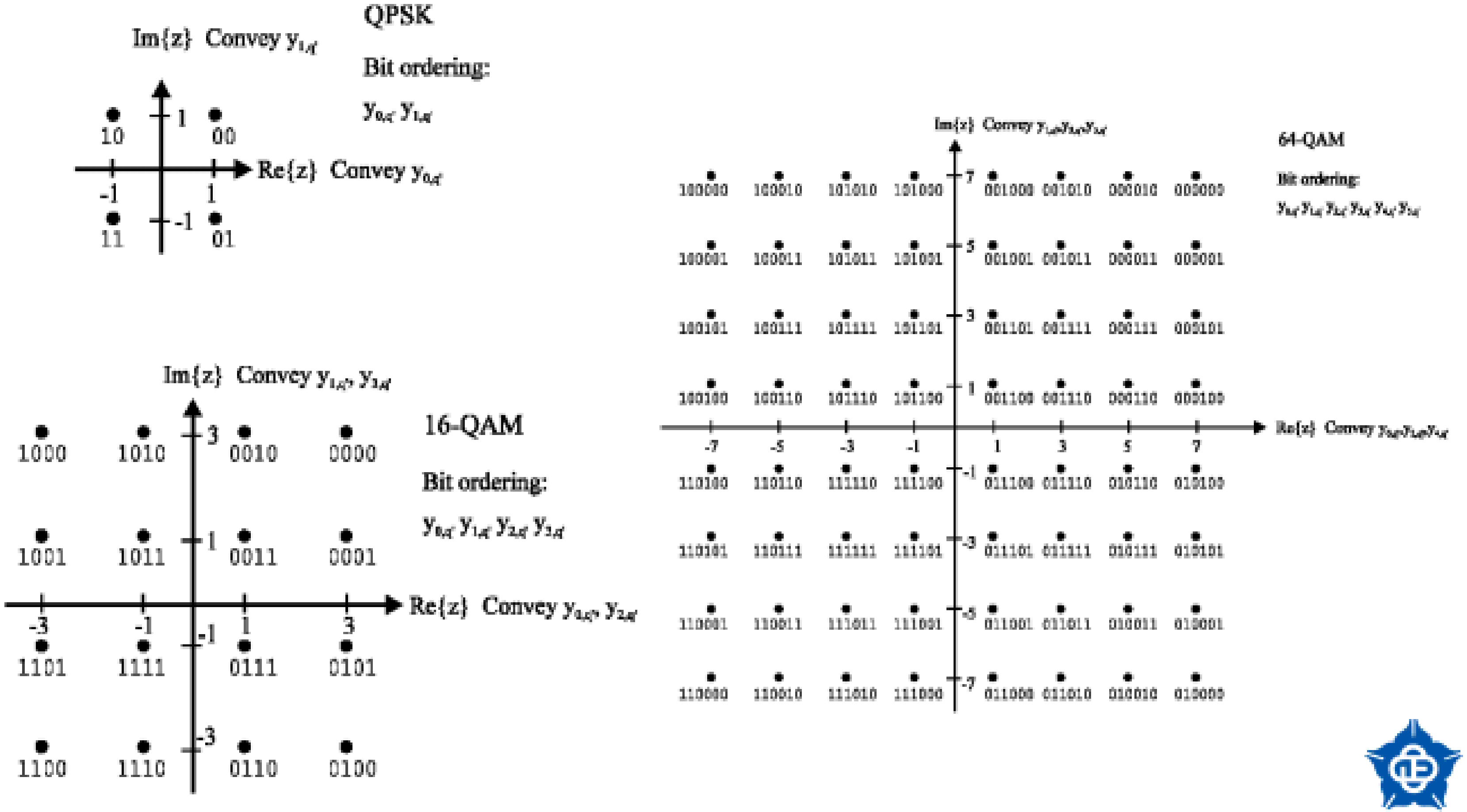
- **Symbol interleaver**
  - **Map *v* bit words onto the 1512 (2K mode) or 6048 (8K mode) active carriers per OFDM symbol.**
  - **To spread consecutive poor channels into random-like fading.**
  - **Symbol interleaver address generation schemes are employed for the symbol interleaver.**

8.2.3 Channel Coding and Modulation

- **Signal constellations and mapping**
  - **OFDM transmission**
  - **All data carries in one OFDM frame are modulated using either QPSK, 16-QAM, 64QAM, non-uniform 16-QAM or non-uniform 64-QAM.**
  - **The non-uniform signal constellation provides Unequal Error Protection (UEP).**

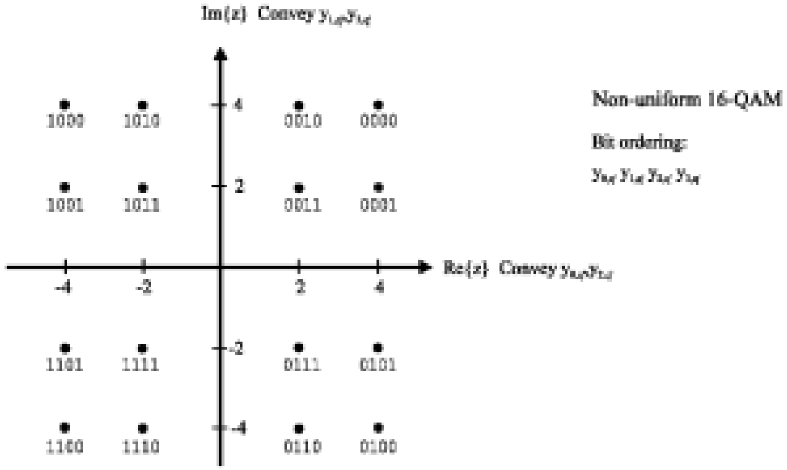
8.2.3 Channel Coding and Modulation

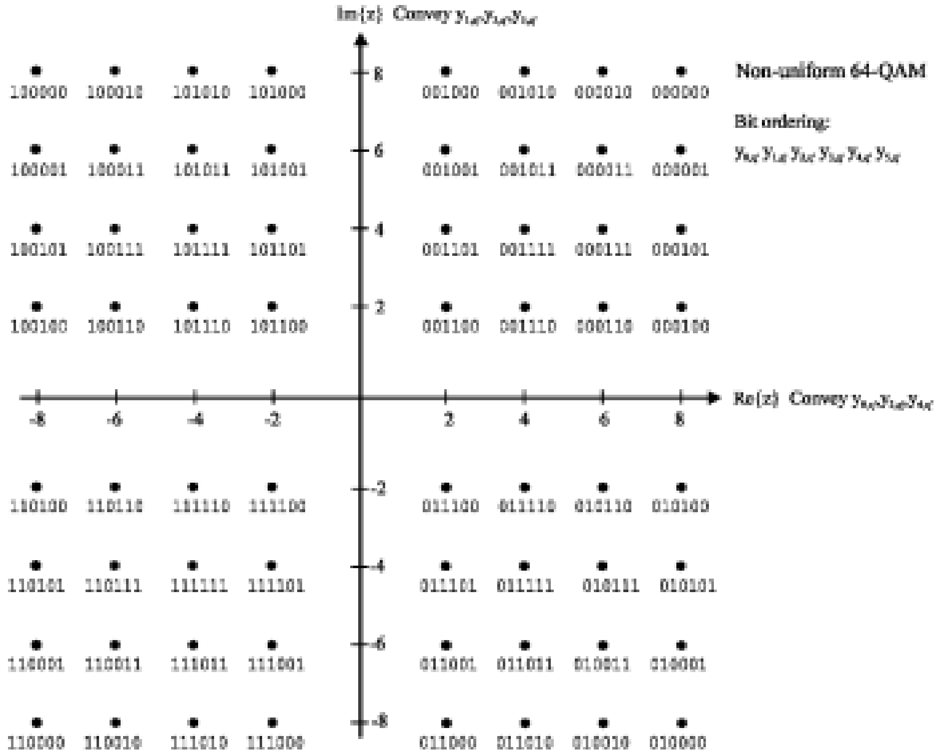
- **The QPSK, 16-QAM and 64-QAM mapping and the corresponding bit patterns**



8.2.3 Channel Coding and Modulation

☞ The Non-uniform 16-QAM and 64-QAM mappings





8.2.3 Channel Coding and Modulation

- **OFDM frame structure**
  - **Each frame has duration T_F**
  - **Consists of 68 OFDM symbols**
  - **Four frames constitute one super-frame**
  - **Each OFDM symbol contains *K*=6817 (8K mode) or *K*=1705 (2*K* mode) carriers**
  - **The duration of each OFDM symbol is $T_S = T_U + \Delta$ where Δ is the guard interval and T_U is the useful part.**
  - **The symbols in an OFDM frame are numbered from 0 to 67**
  - **Scattered pilot cells (carrier)**
  - **Continual pilot carriers**
  - **TPS carriers**

8.2.3 Channel Coding and Modulation

- The pilot can be used for frame synchronization, frequency synchronization, time synchronization, channel estimation, transmission mode identification.
- The carriers are indexed by $k \in [K_{\min}; K_{\max}]$ where K_{min}=0 and K_{max}=1704 or 6816.
- Numerical values for the OFDM parameters for the 8K and 2K modes for the 8Mhz channels.

Parameter	8K mode	2K mode
Number of carriers K	6 817	1 705
Value of carrier number K_{min}	0	0
Value of carrier number K_{max}	6 816	1 704
Duration T_U (note 2)	896 μs	224 μs
Carrier spacing $1/T_U$ (note 1) (note 2)	1 116 Hz	4 464 Hz
Spacing between carriers K_{min} and K_{max} $(K-1)/T_U$ (note 2)	7,61 MHz	7,61 MHz

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8.2.3 Channel Coding and Modulation

☞The emitted signal is described by the following expression:

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

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

***k*: carrier number**

***l*: OFDM symbol number**

***m*: frame number**

***K*: number of transmitted carriers**

T_S: symbol duration

T_U: inverse of the carrier spacing

Δ : Guard interval

***fc*: central frequency of the RF signal**

k': $k'=k-(K_{max} - K_{min})/2$

$c_{m,l,k}$: complex symbol for carrier *k* of data symbol number *l* in frame number *m*

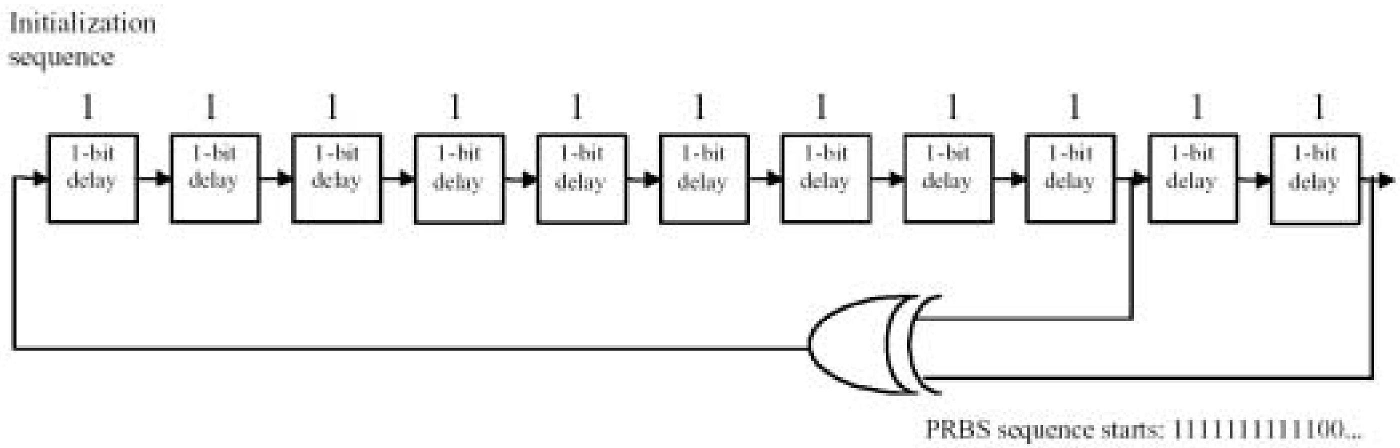
8.2.3 Channel Coding and Modulation

☞Duration of symbol part for the guard intervals for 8Mhz channel

Mode	8K mode				2K mode			
Guard interval Δ∈ T_U	1/4	1/8	1/16	1/32	1/4	1/8	1/16	1/32
Duration of symbol part T_U	8 192 × T 896 µs (note)				2 048 × T 224 µs (note)			
Duration of guard interval Δ	2 048 × T 224 µs	1 024 × T 112 µs	512 × T 56 µs	256 × T 28 µs	512 × T 56 µs	256 × T 28 µs	128 × T 14 µs	64 × T 7 µs
Symbol duration $T_S = \Delta + T_U$	10 240 × T 1 120 µs	9 216 × T 1 008 µs	8 704 × T 952 µs	8 448 × T 924 µs	2 560 × T 280 µs	2 304 × T 252 µs	2 176 × T 238 µs	2 112 × T 231 µs

8.2.3 Channel Coding and Modulation

- **Reference signal**
  - **Various cells within the OFDM frame are modulated with reference information whose transmitted values is known to the receiver**
  - **The value of the pilot information is derived from a Pseudo Random Binary Sequence (PRBS)**
  - **Two kinds of pilots: scattered pilot and continual pilot**



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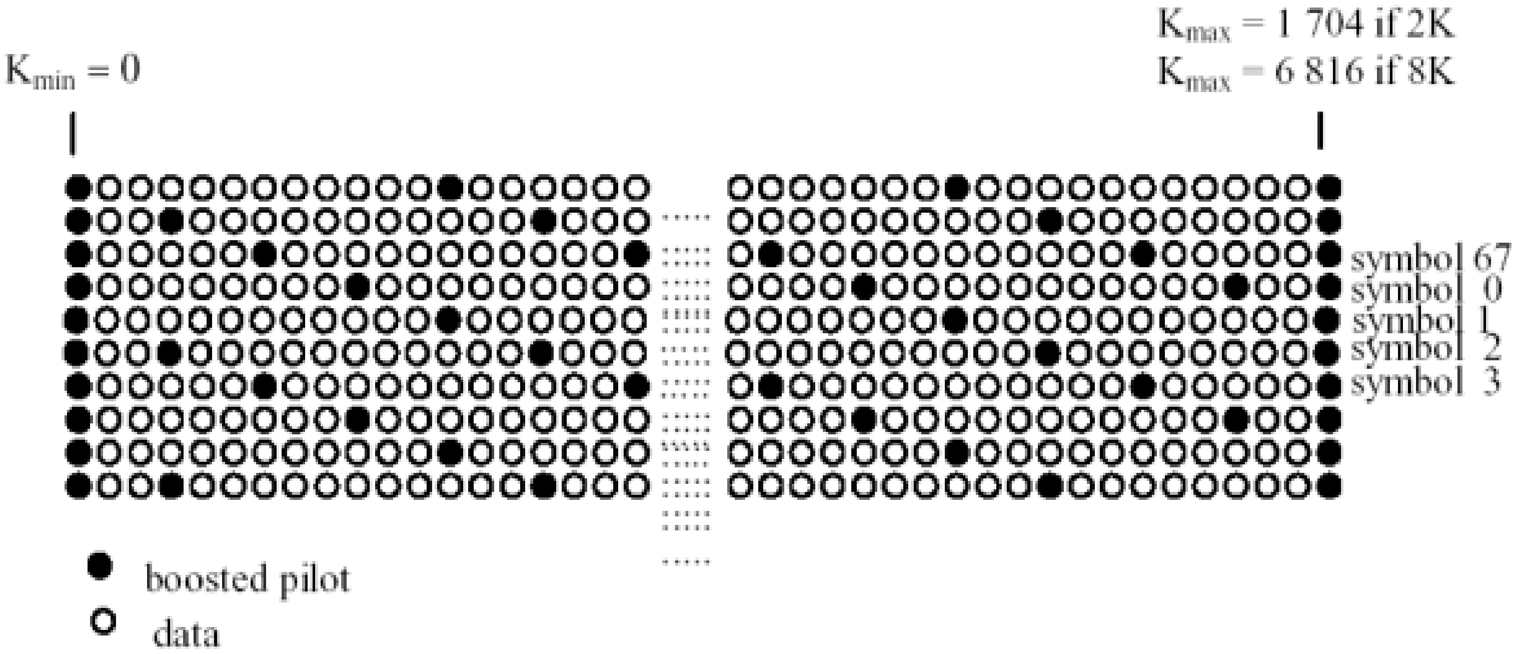
8.2.3 Channel Coding and Modulation

- **Location of scattered pilot cells**
- **pilot is modulated according to**

$$\mathrm{Re}\{c_{m,l,k}\} = 4/3 \times 2(1/2 - w_k)$$

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



8.2.3 Channel Coding and Modulation

- **Location of continual pilot carriers**
- **Pilot is modulated according to**

$$\mathrm{Re}\{c_{m,l,k}\} = 4/3 \times 2(1/2 - w_k)$$

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

Continual pilot carrier positions (index number k)	
2K mode	**8K mode**
0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704	0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758 1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229 2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646 2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081 3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690 3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212 4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548 4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268 5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748 5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162 6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816

8.2.3 Channel Coding and Modulation

- **Transmission Parameter Signaling (TPS)**
  - **The TPS carriers are used for the purpose of signaling parameters related to the transmission scheme.**
  - **The TPS is transmitted in parallel on 17 TPS carriers for 2K mode and on 68 carriers for the 8K mode.**

2K mode	8K mode
34 50 209 346 413 569 595 688 790 901 1073 1219 1262 1286 1469 1594 1687	34 50 209 346 413 569 595 688 790 901 1073 1219 1262 1286 1469 1594 1687 1738 1754 1913 2050 2117 2273 2299 2392 2494 2605 2777 2923 2966 2990 3173 3298 3391 3442 3458 3617 3754 3821 3977 4003 4096 4198 4309 4481 4627 4670 4694 4877 5002 5095 5146 5162 5321 5458 5525 5681 5707 5800 5902 6013 6185 6331 6374 6398 6581 6706 6799

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8.2.3 Channel Coding and Modulation

- **The TPS carriers convey information on:**
  - **a) Modulation of the QAM constellation pattern**
  - **b) Hierarchy information**
  - **c) Guard interval**
  - **d) Inner code rate**
  - **e) 2K or 8K transmission mode**
  - **f) Frame number in a super-frame**
  - **g) Cell identification.**

8.3 Wireless LAN Networks

8.3.1 Introduction to Wireless LAN Networks

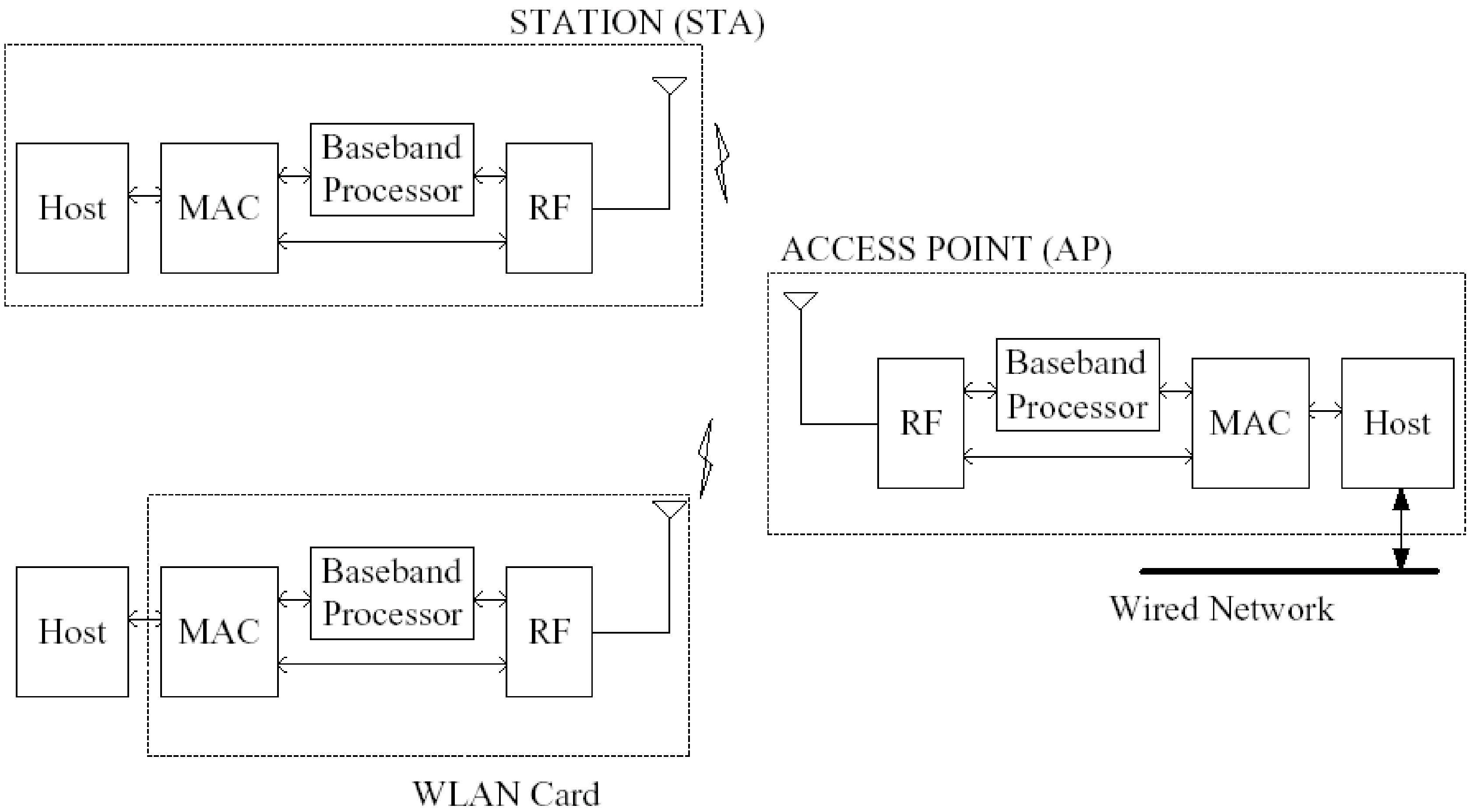
- **IEEE 802.11 - The first international standard for WLAN, 1997.**
  - **Infrared (IR) baseband PHY (1Mbps, 2Mbps)**
  - **Frequency hopping spread spectrum (FHSS) radio in 2.4GHz band (1Mbps, 2Mbps)**
  - **Direct sequence spread spectrum (DSSS) radio in the 2.4GHz band (1Mbps, 2Mbps)**
- **IEEE 802.11a, 1999**
  - **5GHz band**
  - **Orthogonal frequency division multiplexing (OFDM)**
  - **6Mbps to 54Mbps**

8.3.1 Introduction to Wireless LAN Networks

- **IEEE 802.11g**
  - **(802.11b + 80211a) operating at 2.4GHz band**
  - **ERP-DSS/CCK: IEEE 802.11b-1999**
  - **ERP-OFDM: IEEE 802.11a-1999**
  - **PBCC (optional)**
  - **CCK-OFDM (optional)**
- **IEEE 802.11h/D2.2, September 2002**
  - **Radar detection in 5GHz band**
  - **Regulatory (ETSI EN 301 893 v.1.2.1)**
  - **Power control**

8.3.1 Introduction to Wireless LAN Networks

☞ **Typical Wireless System**

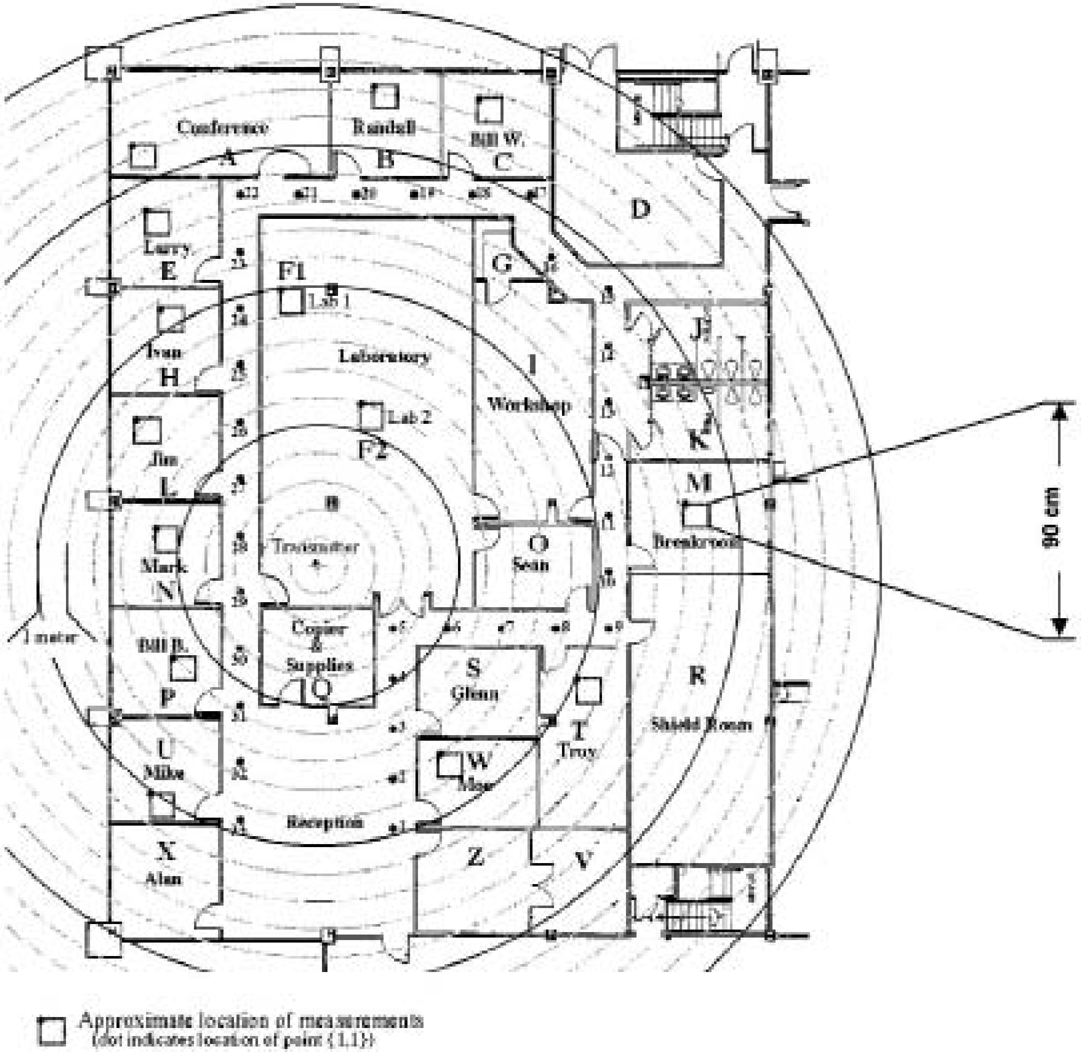


8.3.2 Indoor Environment

- **Delay Spread - refection of RF signal from wall, furniture, etc.**
- **Path loss**
- **Interference - microwave oven, Bluetooth, cordless phone, etc.**
- **Statistic channel model for WLAN**

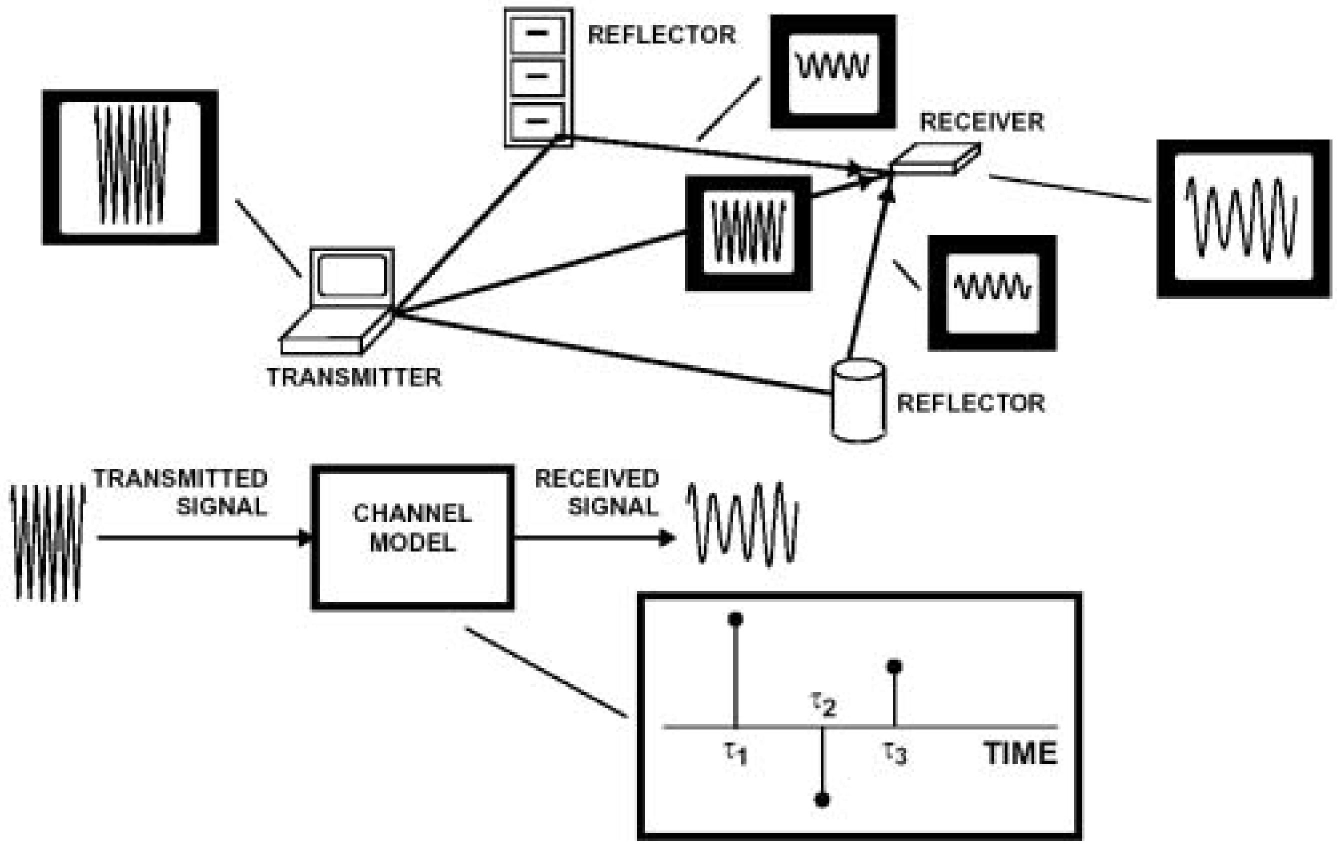
8.3.2 Indoor Environment

Typical Indoor Environment



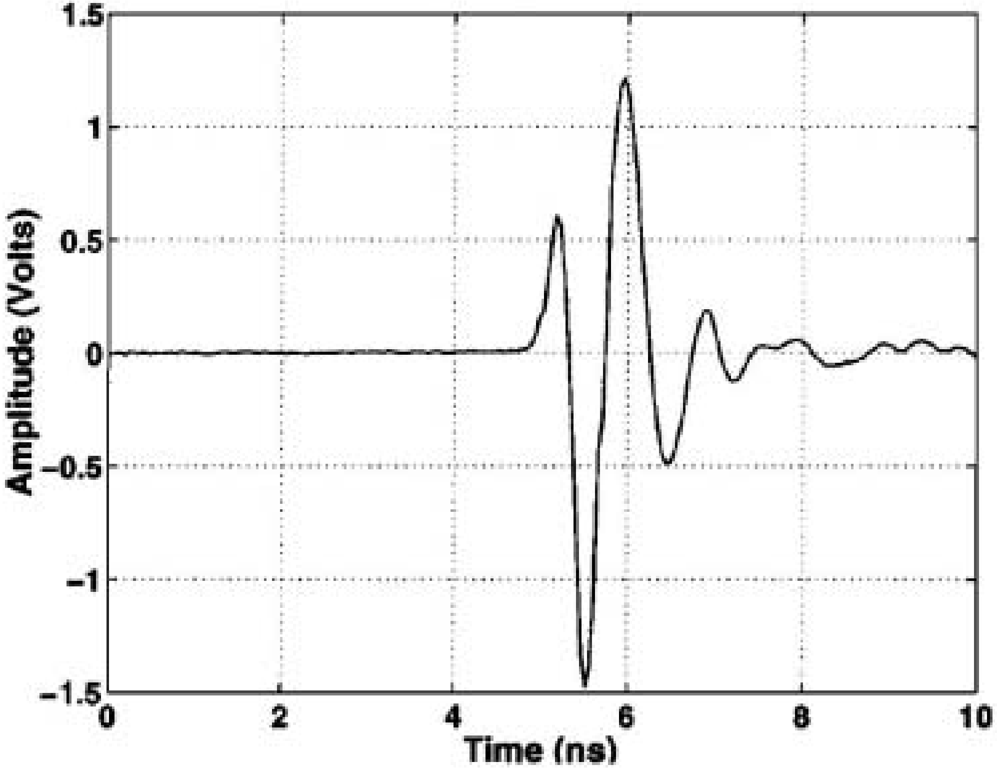
8.3.2 Indoor Environment

☞ **Delay Spread**



8.3.2 Indoor Environment

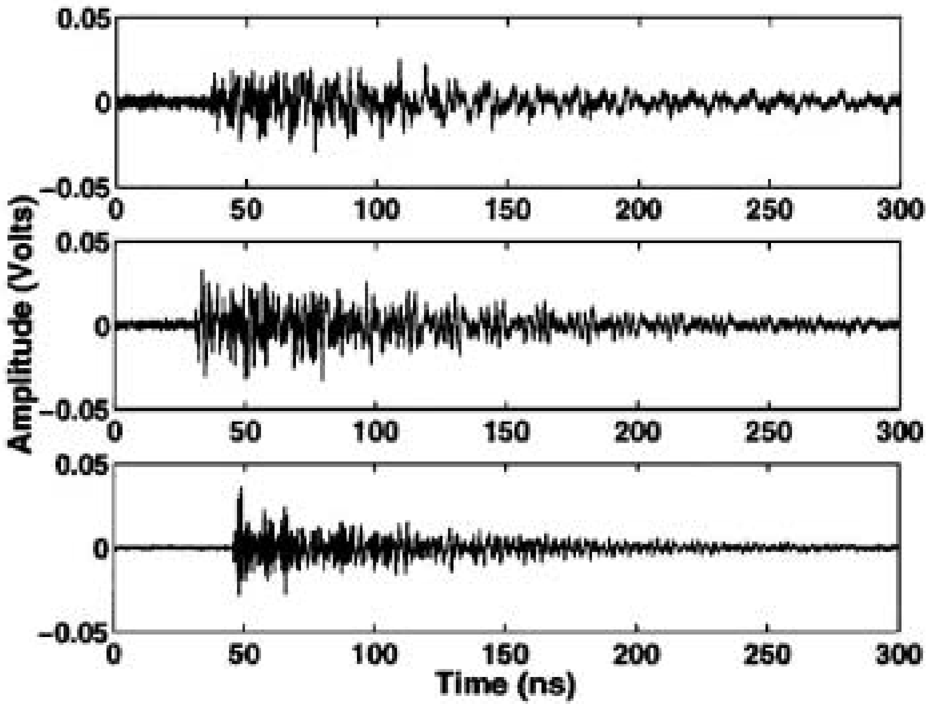
☞ **Typical Measurement Results I - 1 m away from the transmitter**



1 m away from the transmitter

8.3.2 Indoor Environment

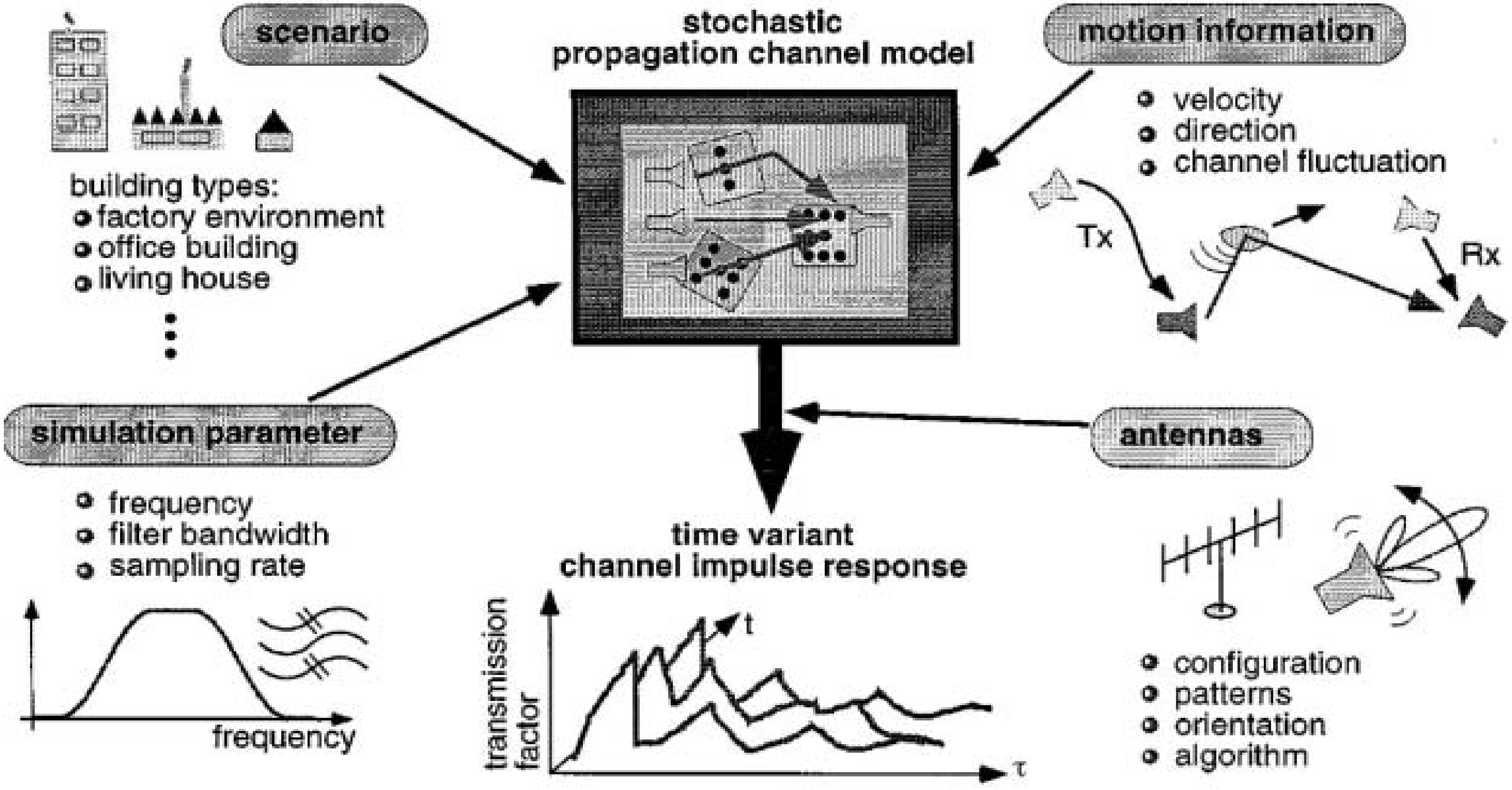
☞ **Typical Measurement Results II - 10m, 8m, and 13.5m away from the transmitter**



U.W.M:10m, 8m, and 13.5m away from the transmitter

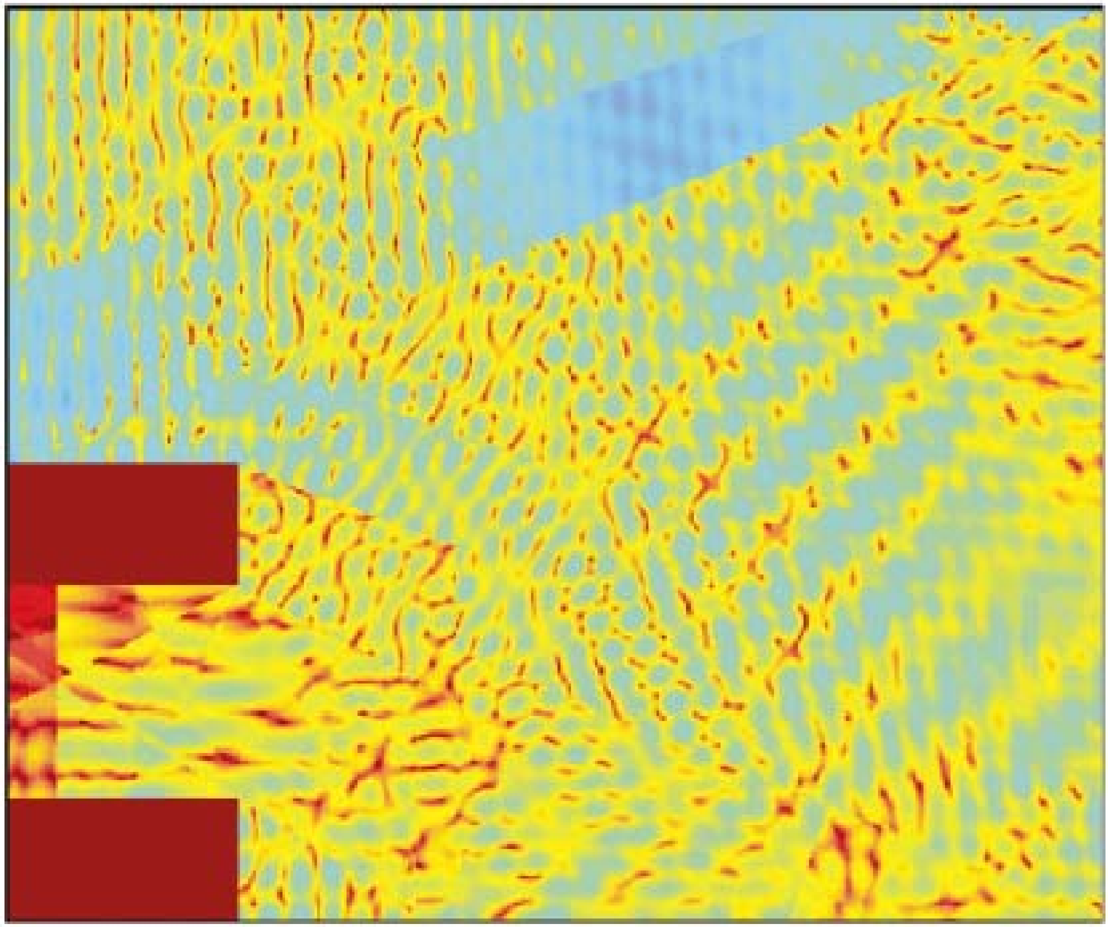
8.3.2 Indoor Environment

☞ Computer model for indoor channels



8.3.2 Indoor Environment

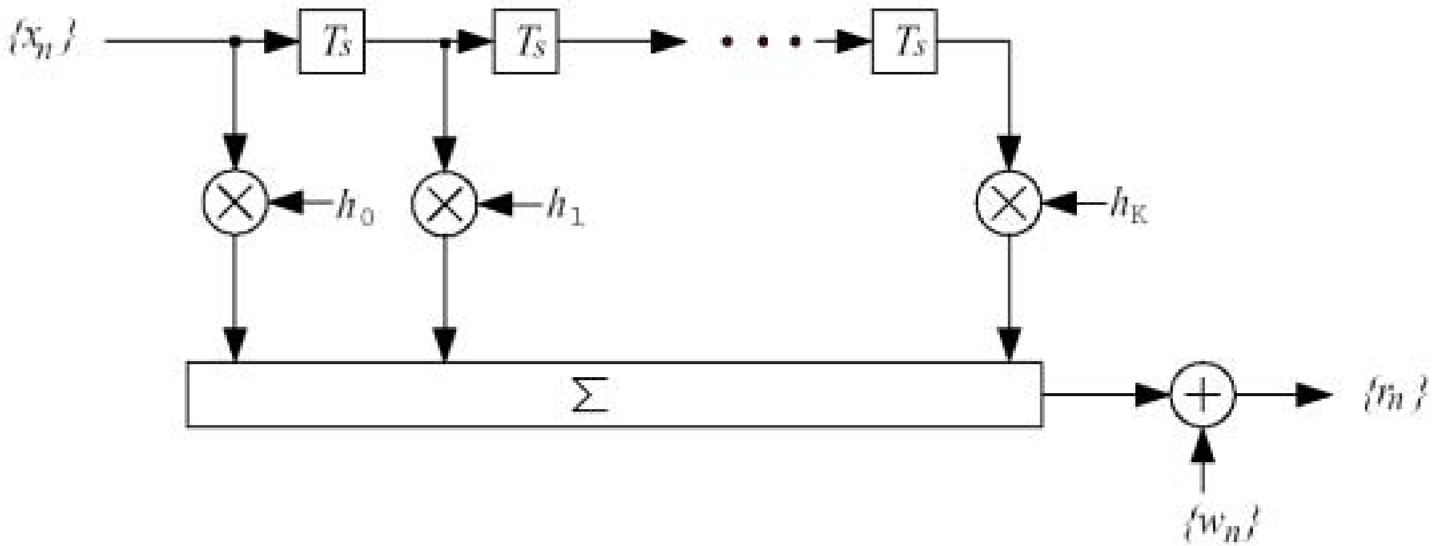
☞ **Ray Tracing Simulation Result**



8.3.3 Statistic Channel Model for WLAN

- **This channel model was agreed to be a baseline model for comparison of modulation methods.**
- **Simple mathematical description and in the possibility to vary the RMS delay spread.**
- **The channel is assumed static throughout the packet and generated independently for each packet.**

8.3.3 Statistic Channel Model for WLAN



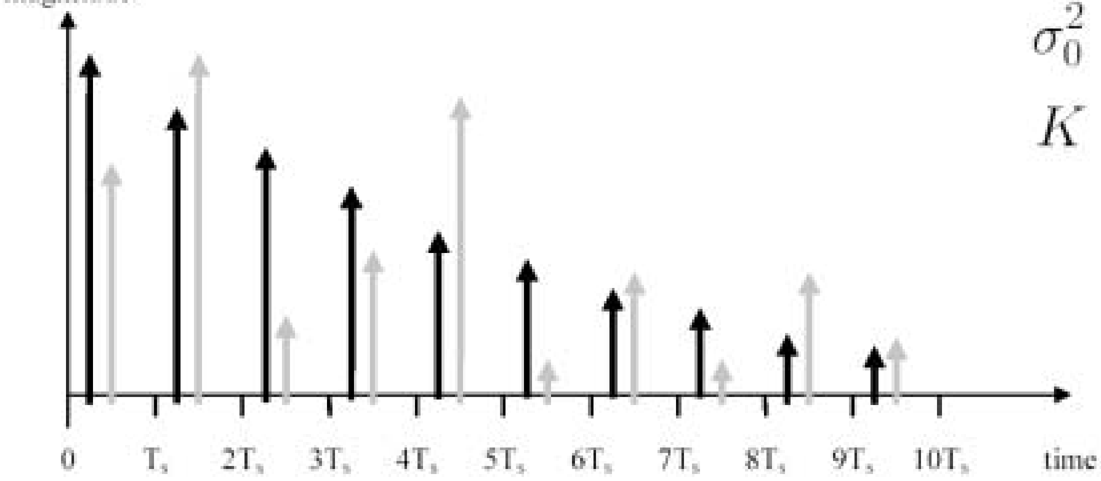
☞ **The received signal**

$$r_n = \sum_{k=0}^{K} x_{n-k} h_k^* + w_n$$

where *wn* is the additive white Gaussian noise, *xn* is the transmitted signal and *hk* is the baseband complex impulse response

8.3.3 Statistic Channel Model for WLAN

☞ **Channel Impulse response**



$$
\begin{aligned}
h_k &= N(0, \frac{1}{2}\sigma_k^2) + jN(0, \frac{1}{2}\sigma_k^2) \\
\sigma_k^2 &= \sigma_0^2 e^{-kT_s/T_{\text{RMS}}} \\
\sigma_0^2 &= 1 - e^{-T_s/T_{\text{RMS}}} \\
K &= k_{\max} = 10T_{\text{RMS}}/T_s
\end{aligned}
$$

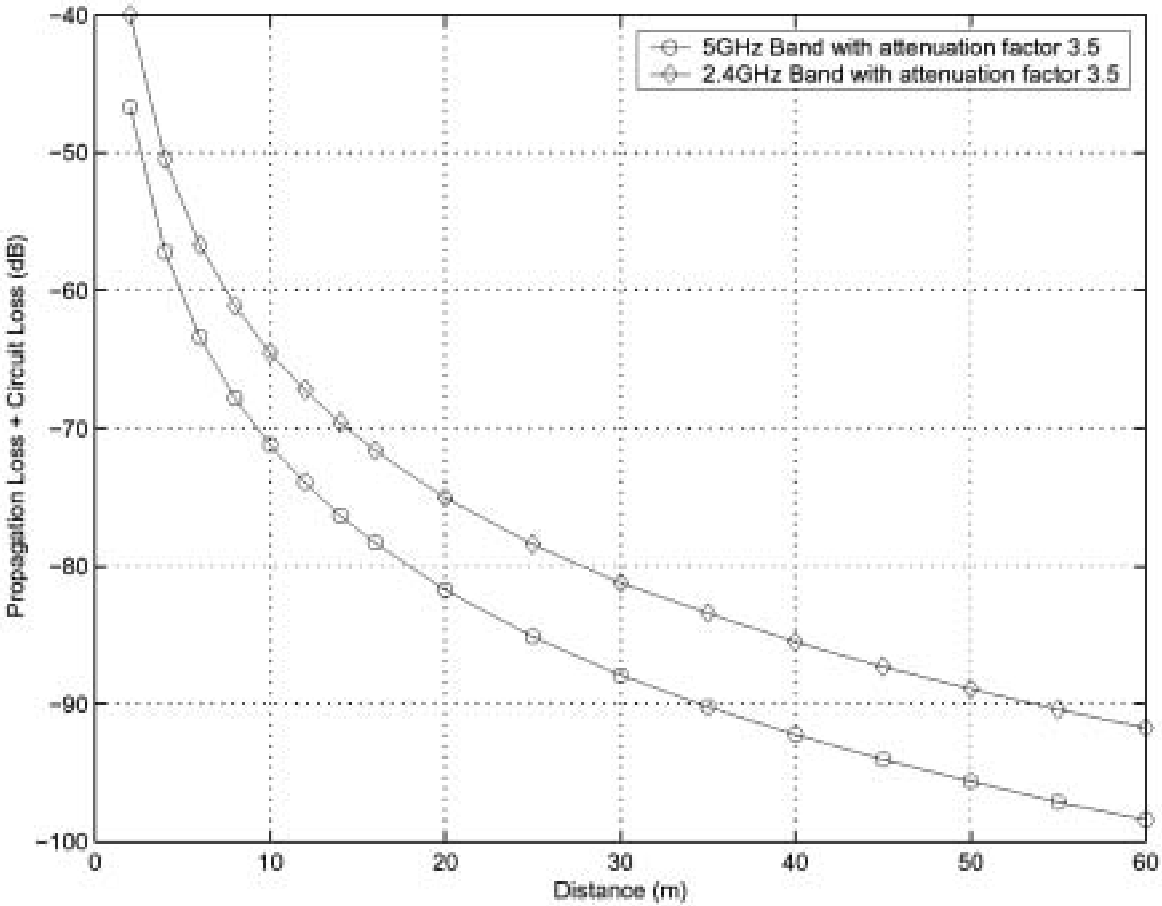
8.3.3 Statistic Channel Model for WLAN

☞ **Typical Multipath Delay Spread**

Enviroment	Delay Spread
Home	< 50 nsec
Office	$\approx$100 nsec
Manufacture floor	200-300 nsec

8.3.3 Statistic Channel Model for WLAN

☞ **Path loss**



8.3.4 802.11a WLAN Standard

- ☞ **OFDM system with punctured convolutional code.**
- ☞ **52 carriers with 4 pilot tones.**
- ☞ **Date rate from 6Mbps to 54Mbps**

8.3.4 802.11a WLAN Standard

☞ **Rate dependent parameters**

Data rate (Mbits/s)	Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

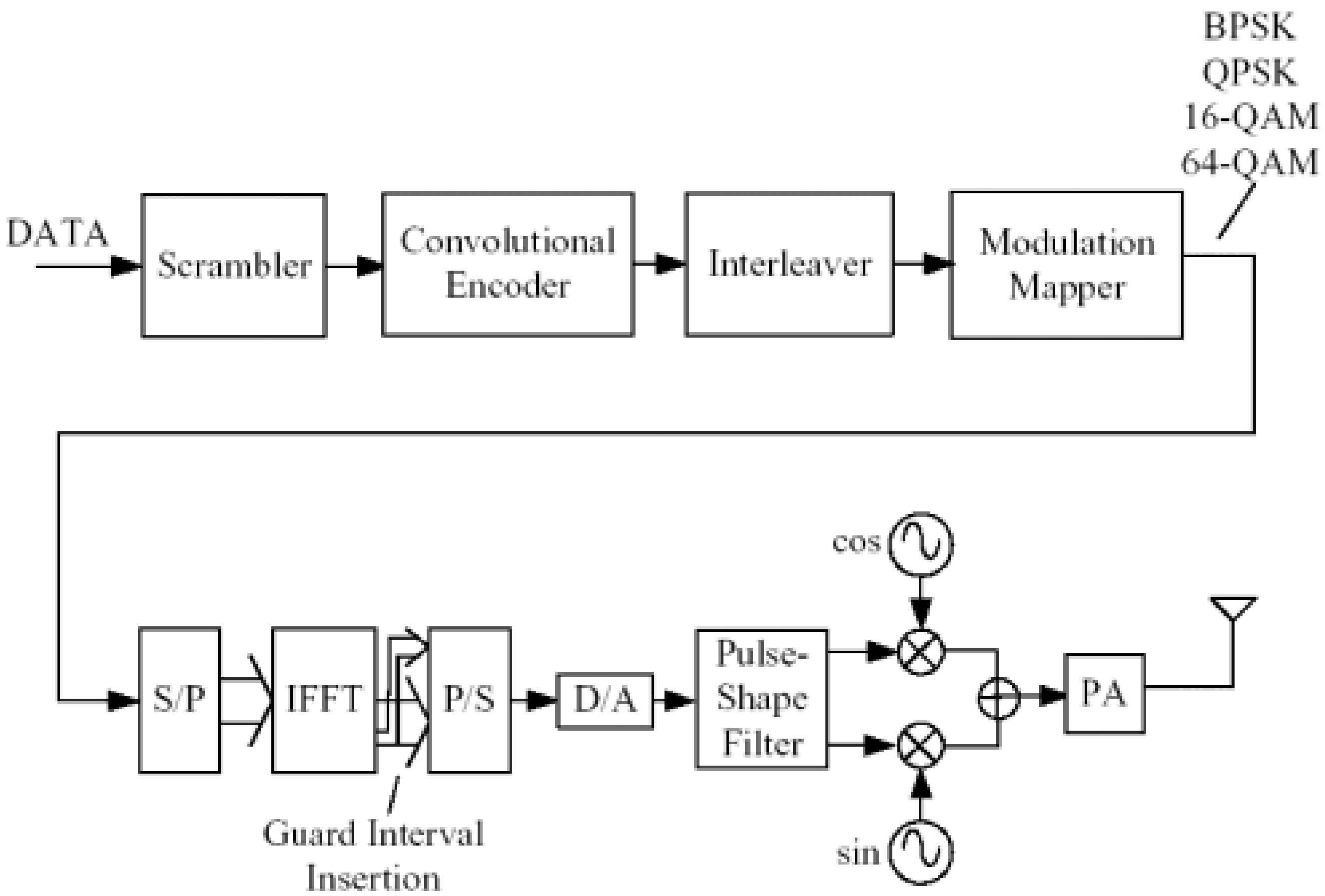
8.3.4 802.11a WLAN Standard

☞ **Timing related parameters**

Parameter	Value
N_{SD}: Number of data subcarriers	48
N_{SP}: Number of pilot subcarriers	4
N_{ST}: Number of subcarriers, total	52 ($N_{SD} + N_{SP}$)
Δ_F: Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
T_{FFT}: IFFT/FFT period	3.2 μs ($1/\Delta_F$)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{GI} + T_{FFT}$)
T_{GI}: GI duration	0.8 μs ($T_{FFT}/4$)
T_{GI2}: Training symbol GI duration	1.6 μs ($T_{FFT}/2$)
T_{SYM}: Symbol interval	4 μs ($T_{GI} + T_{FFT}$)
T_{SHORT}: Short training sequence duration	8 μs ($10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	8 μs ($T_{GI2} + 2 \times T_{FFT}$)

8.3.4 802.11a WLAN Standard

☞ **Transmitter of 802.11a**



8.3.4 802.11a WLAN Standard

- **All the subframes of the signal are constructed as an inverse Fourier transform of a set of coefficients, C_k , with C_k defined as data, pilots, or training symbols.**

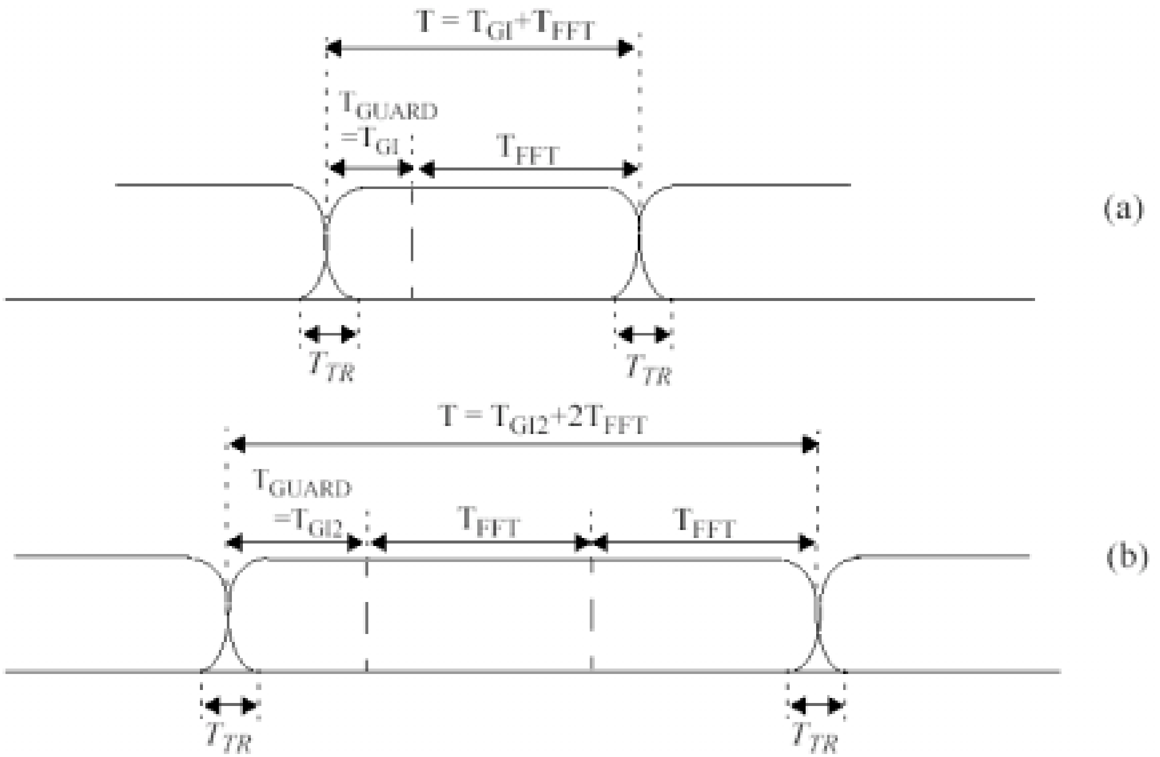
$$r_{SUBFRAME}(t) = w_{TSUBFRAME}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} C_k \exp(j2\pi k\Delta_f)(t - T_{GUARD})$$

Where $w_T(t)$ is a time window function defined by

$$w_T(t) = \begin{cases} \sin^2\left(\frac{\pi}{2}(0.5 + t/T_{TR})\right) & (-T_{TR}/2 < t < T_{TR}/2) \\ 1 & (T_{TR}/2 \le t < T - T_{TR}/2) \\ \sin^2\left(\frac{\pi}{2}(0.5 - (t-T)/T_{TR})\right) & (T - T_{TR}/2 \le t < T + T_{TR}/2) \end{cases}$$

8.3.4 802.11a WLAN Standard

☞ **Cyclic extension and window function (a) single reception and (b) two receptions**



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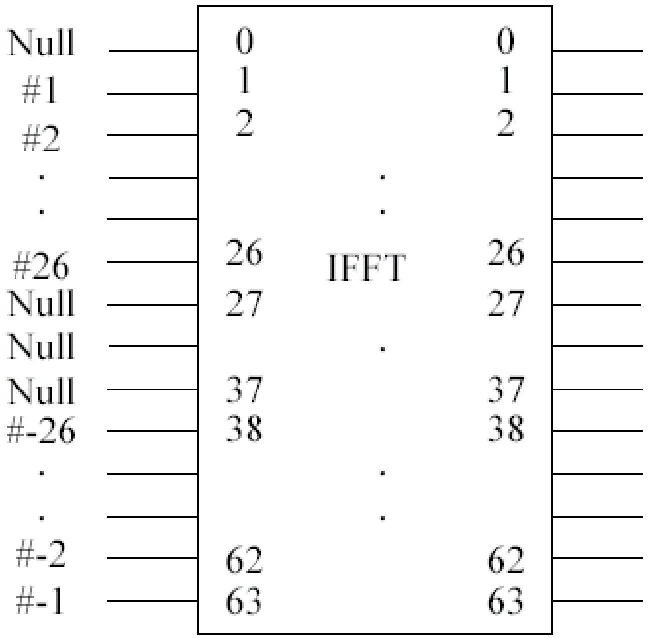
8.3.4 802.11a WLAN Standard

☞ **Implemented by IFFT**

frequency-domain input



time-domain output

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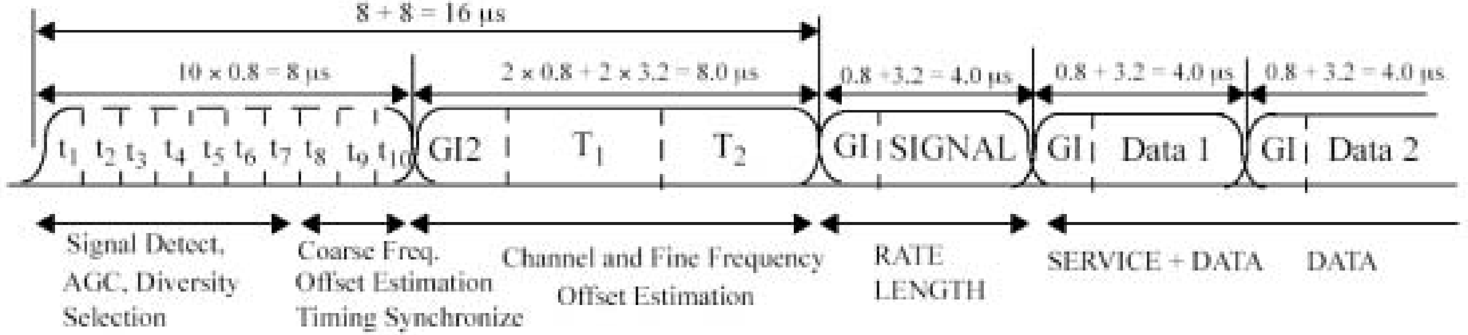
8.3.4 802.11a WLAN Standard

☞OFDM packet structure



☞A short OFDM training symbol consists of 12 subcarriers, which are modulated by the elements of the sequence S, given by

$$S_{-26,26} = \sqrt{(13/6)} \times \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0,0\}$$

☞The short training signal shall be generated according to

$$r_{SHORT}(t) = w_{TSHORT}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} S_k \exp(j2\pi k \Delta_f)$$

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8.3.4 802.11a WLAN Standard

☞A long OFDM training symbol consists of 53 subcarriers given by

$$L_{-26,26} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\}$$

☞The long training signal shall be generated according to

$$r_{LONG}(t) = w_{TLONG}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} L_k \exp(j2\pi k \Delta_F (t - T_{G12}))$$

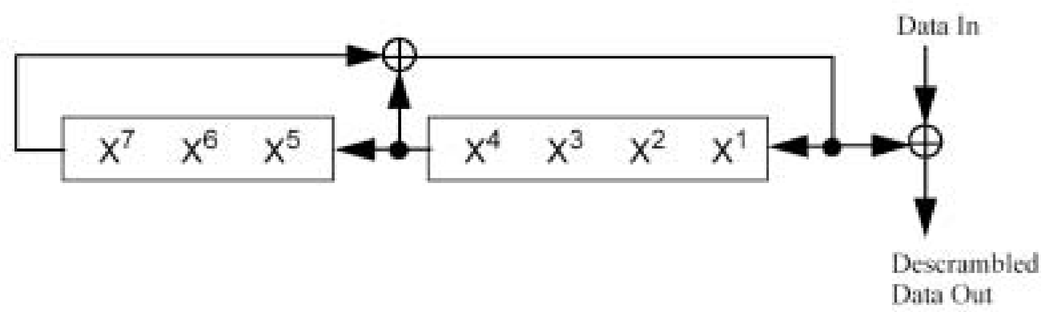
☞Signal field - modulation with 6Mbps

RATE (4 bits)					LENGTH (12 bits)												SIGNAL TAIL (6 bits)					
R1	R2	R3	R4	R	LSB										MSB	P	"0"	"0"	"0"	"0"	"0"	"0"
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

Transmit Order →

8.3.4 802.11a WLAN Standard

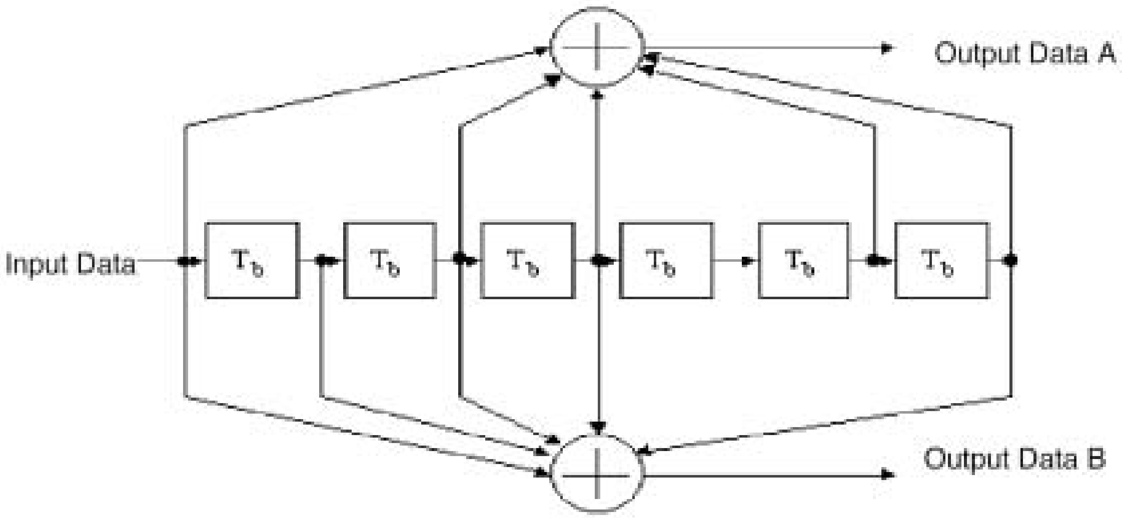
- **Data field includes**
  - **Service field - scrambler initialization**
  - **PSDU - carry the data to be transmitted.**
  - **Tail bit field - 6 bits of zero to return the convolutional encoder to zero state.**
  - **Pad bits (PAD) - zero bits.**
- **DATA scrambler and descrambler**
  - **scrambler and descrambler use the same module.**



8.3.4 802.11a WLAN Standard

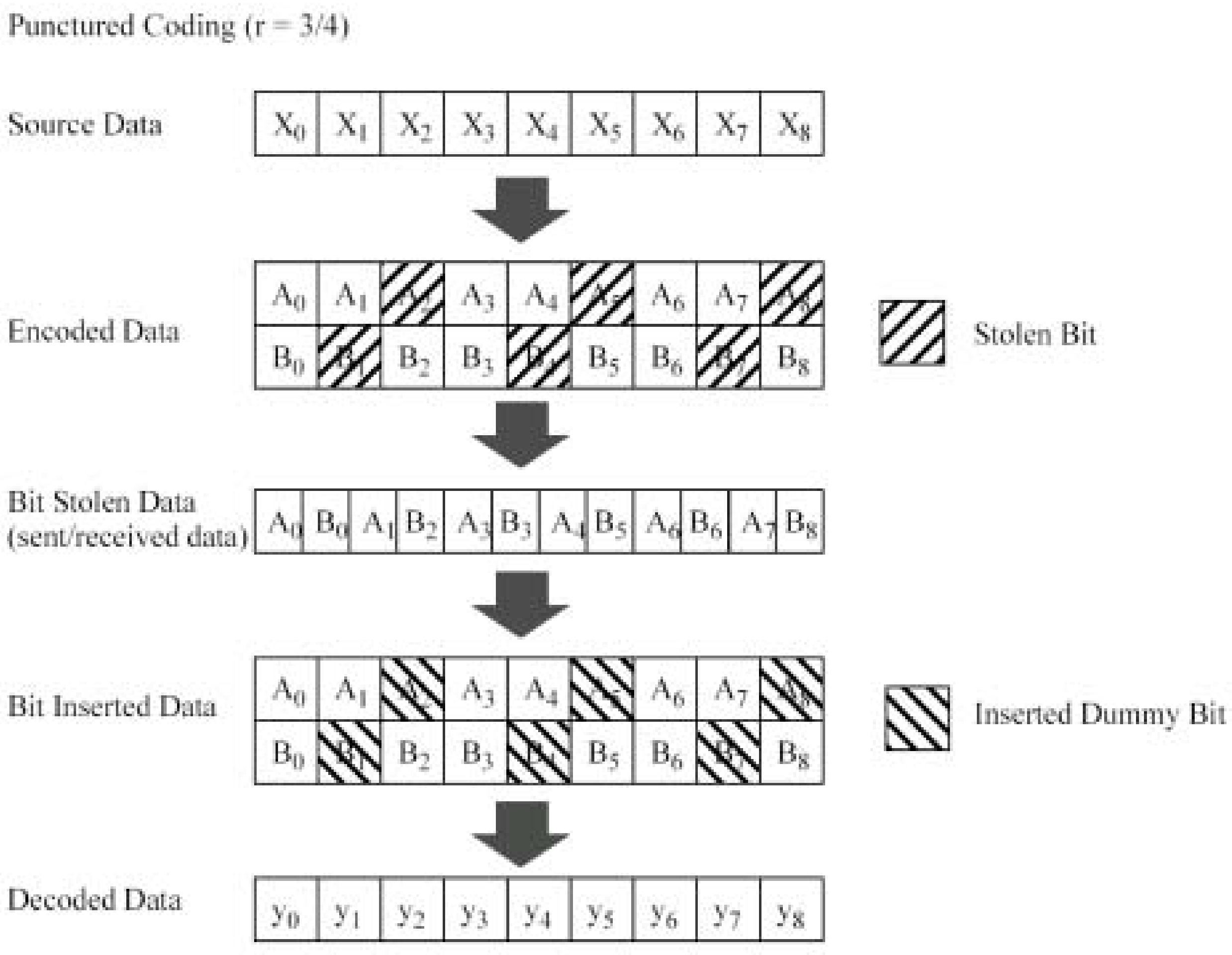
☞ **Convolutional encoder**

- **DATA field should be coded with a convolutional encoder of coding rate** ***R = 1/2, 2/3, 3/4*****.**
- **The rate** ***2/3*** **and** ***3/4*** **code is generated by puncturing the rate** ***1/2*** **convolutional code with generator polynomial** $g_0 = 133_8$ **and** $g_1 = 171_8$**.**



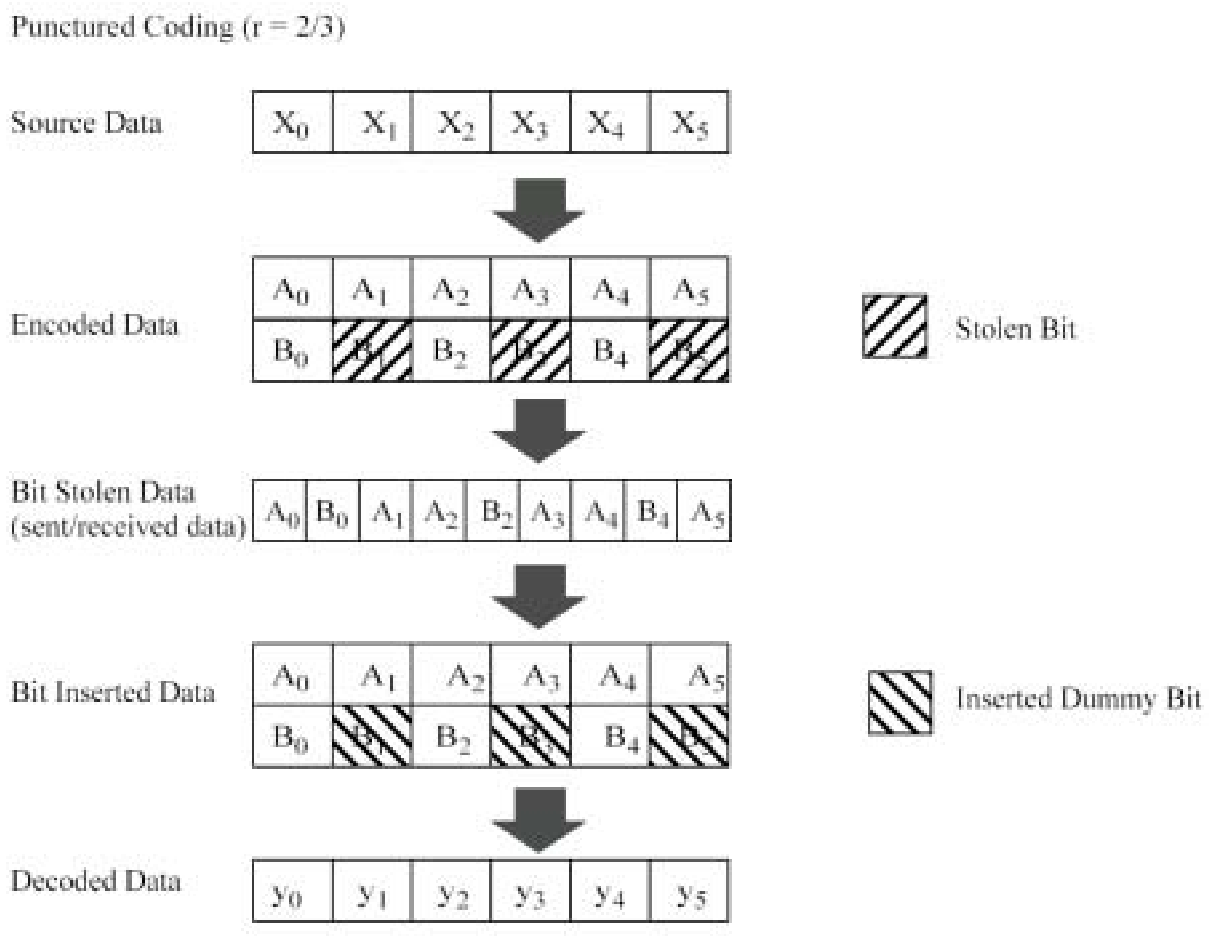
8.3.4 802.11a WLAN Standard

☞ **Puncturing Procedure for rate *3/4* code**



8.3.4 802.11a WLAN Standard

☞ **Puncturing Procedure for rate *2/3* code**



8.3.4 802.11a WLAN Standard

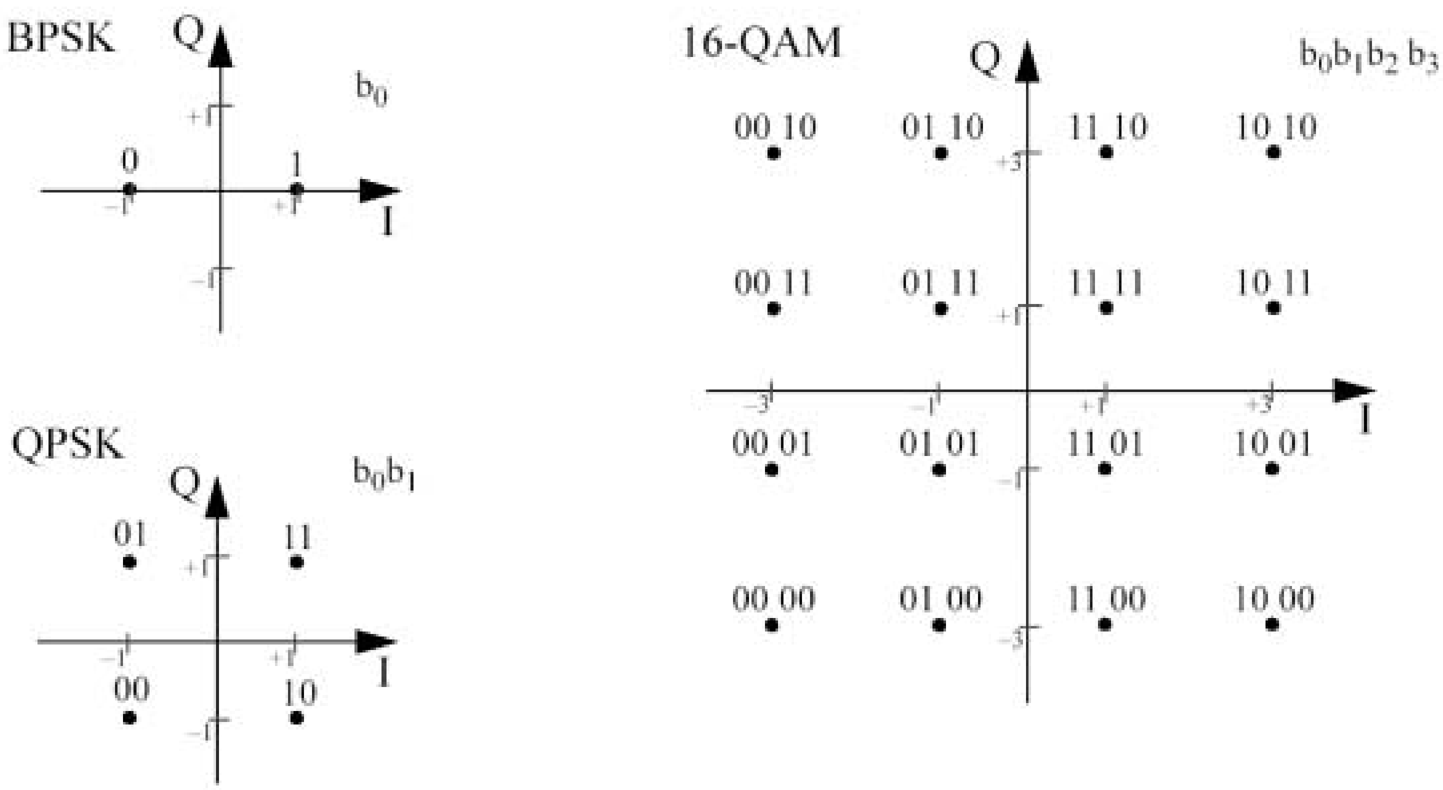
- **Data interleaving**
  - **All encoded data bits shall be interleaved by a block interleaver with block size corresponding to the number of bits in a single OFDM symbol.**
  - **The interleaver is defined by a two-step permutation.**
  - **The coded bits are interleved in the transmitter and deinterleaved in the receiver.**
  - **The purpose of the interleaver is to prevent long burst of errors.**

8.3.4 802.11a WLAN Standard

- **Subcarrier modulation mapping**
  - **BPSK, QPSK, 16-QAM, or 64-QAM is employed depending on the rate required.**
  - **The interleaved date is grouped into 1, 2, 4, or 6 bits and mapped to BPSK, QPSK, 16-QAM, or 64-QAM constellation points.**

8.3.4 802.11a WLAN Standard

☞ **Signal constellations - BPSK, QPSK, and 16-QAM**



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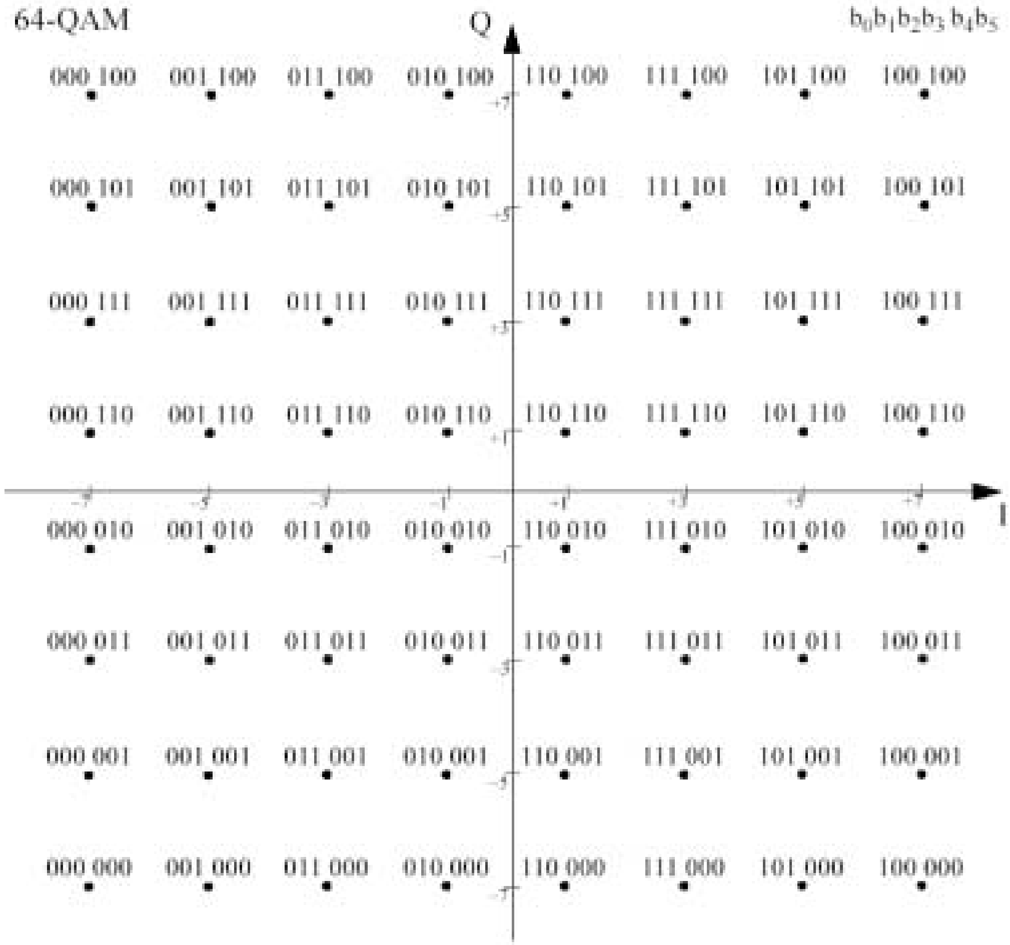
8.3.4 802.11a WLAN Standard

- Signal constellations - 64-QAM



8.3.4 802.11a WLAN Standard

- OFDM modulation
  - The stream of complex number is divided into groups of 48 complex number.
  - We may write the complex number $d_{k,n}$ which corresponds to subcarrier k of OFDM symbol n.

$$d_{k,n} \equiv d_{k+N_{SD}\times n}, \qquad k = 0, \ldots N_{SD}-1,\ n = 0, \ldots N_{SYM}-1$$

  - An OFDM symbol is defined as

Data Carriers

$$r_{DATA,n}(t) = w_{TSYM}(t)\left(\sum_{k=0}^{N_{SD}-1} d_{k,n}\exp\left(j2\pi M(k)\Delta_F(t-T_{GI})\right) + p_{n+1}\sum_{k=-N_{ST}/2}^{N_{ST}/2} p_k \exp\left(j2\pi k\Delta_F(t-T_{GI})\right)\right)$$

Pilot Carriers

8.3.4 802.11a WLAN Standard

- Where *M(k)* maps from subcarrier number 0 to 47 into frequency index

$$M(k) = \begin{cases} k-26 & 0 \le k \le 4 \\ k-25 & 5 \le k \le 17 \\ k-24 & 18 \le k \le 23 \\ k-23 & 24 \le k \le 29 \\ k-22 & 30 \le k \le 42 \\ k-21 & 43 \le k \le 47 \end{cases}$$

- The contribution of the pilot subcarriers for the *n*th OFDM symbol is produced by Fourier transform sequence P, given by

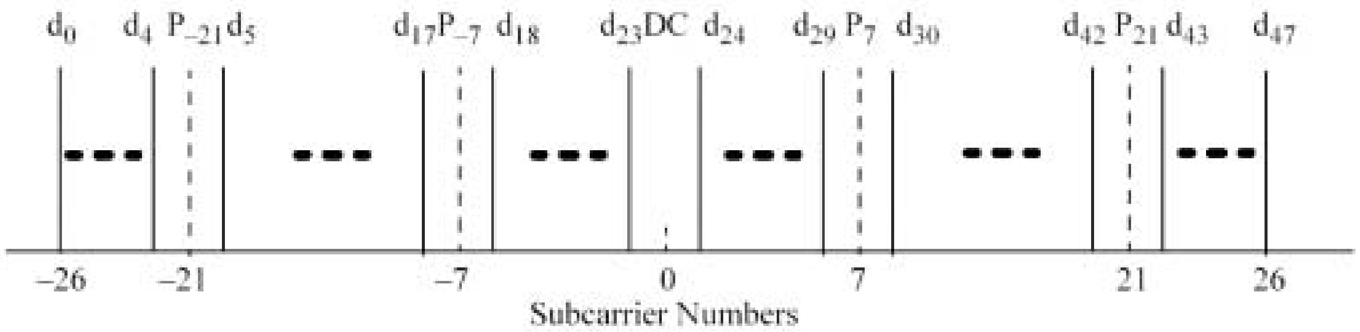
$$P_{-26,26} = \{0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0\}$$

8.3.4 802.11a WLAN Standard

- The polarity of the pilot subcarriers is controlled by the sequence

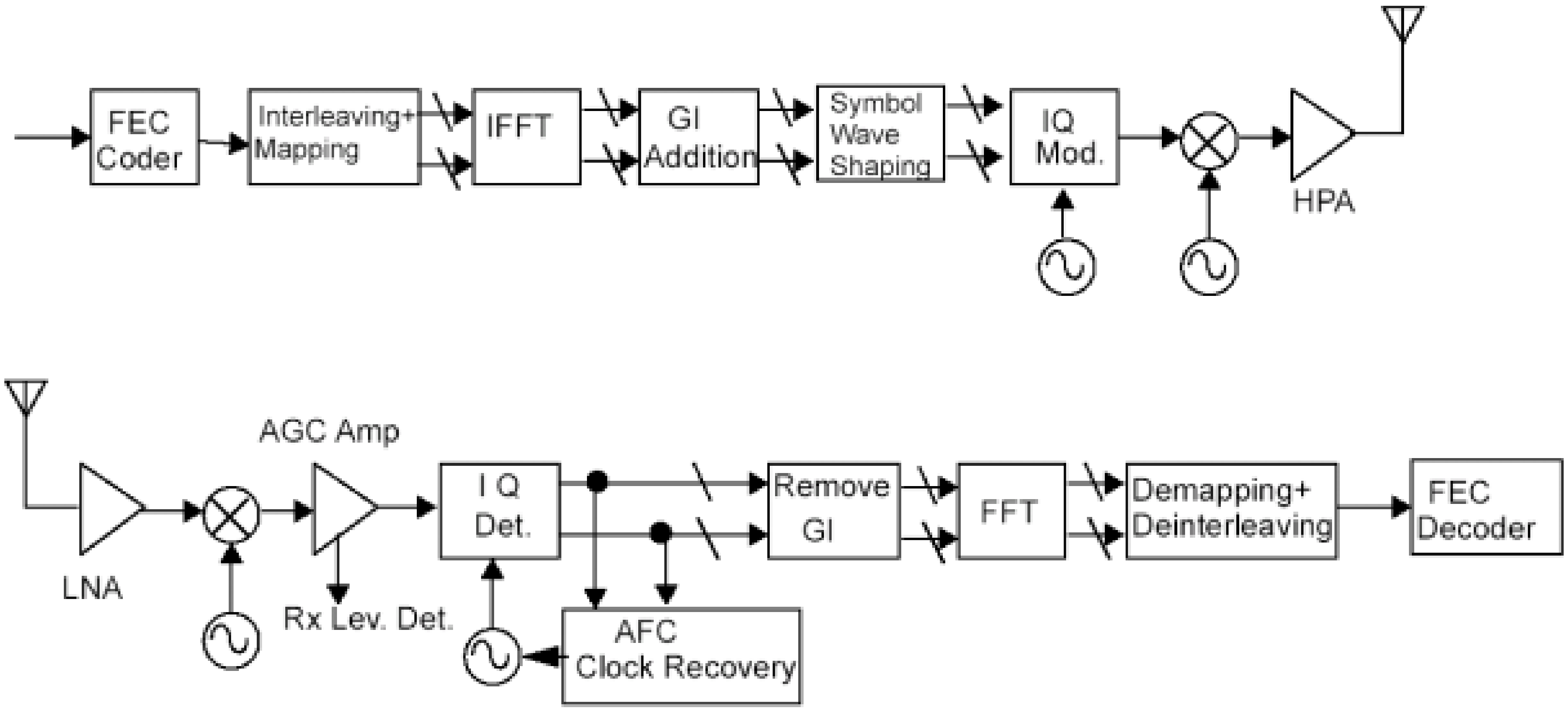
$$
\begin{aligned}
p_{0..126v} = \{&1,1,1,1,\ -1,-1,-1,1,\ -1,-1,-1,-1,\ 1,1,-1,1,\ -1,-1,1,1,\ -1,1,1,-1,\ 1,1,1,1,\ 1,1,-1,1,\\
&1,1,-1,1,\ 1,-1,-1,1,\ 1,1,-1,1,\ -1,-1,-1,1,\ -1,1,-1,-1,\ 1,-1,-1,1,\ 1,1,1,1,\ -1,-1,1,1,\\
&-1,-1,1,-1,\ 1,-1,1,1,\ -1,-1,-1,1,\ 1,-1,-1,-1,\ -1,1,-1,-1,\ 1,-1,1,1,\ 1,1,-1,1,\ -1,1,-1,1,\\
&-1,-1,-1,-1,\ -1,1,-1,1,\ 1,-1,1,-1,\ 1,1,1,-1,\ -1,1,-1,-1,\ -1,1,1,1,\ -1,-1,-1,-1,\ -1,-1,-1\}
\end{aligned}
$$

- Subcarrier frequency allocation



8.3.4 802.11a WLAN Standard

☞ **802.11a Transmitter and Receiver structure**



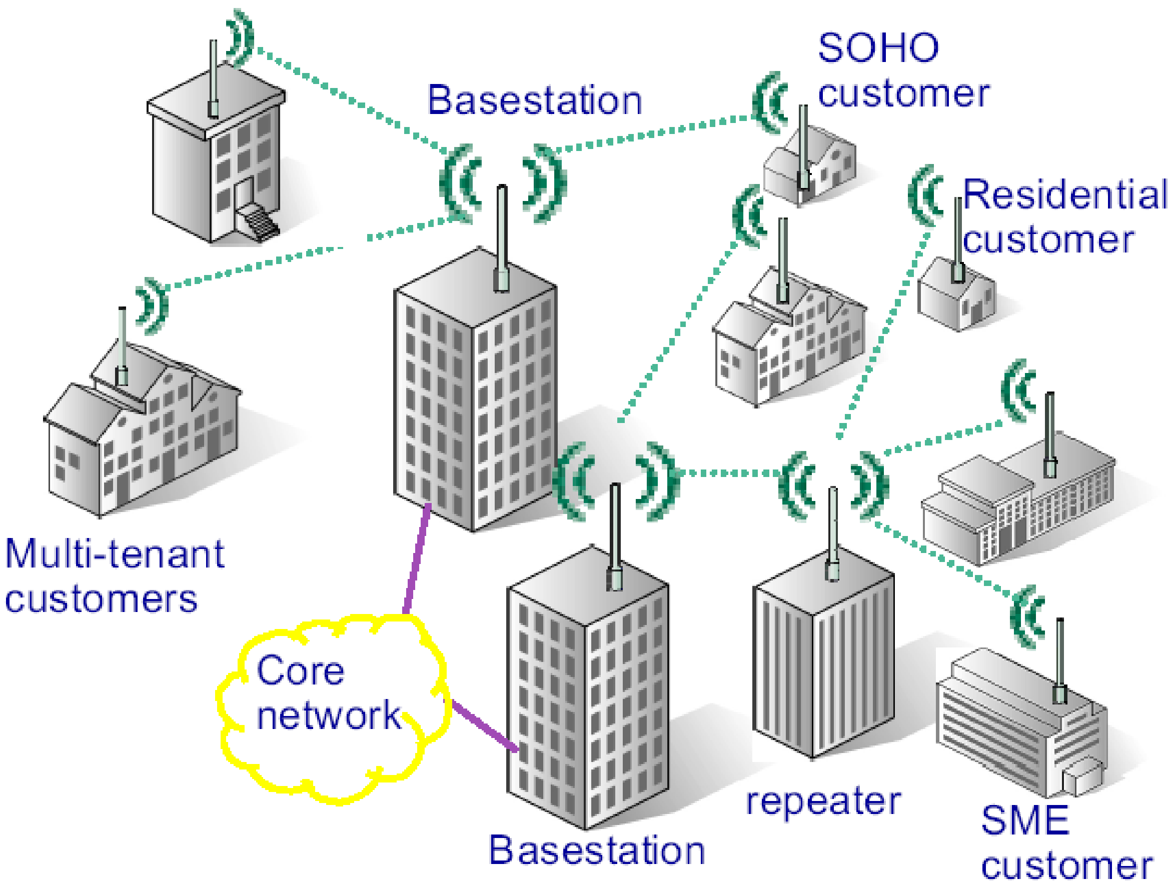
8.4 IEEE 802.16
Broadband Wireless Access System

8.4.1 Introduction to IEEE 802.16

- **BWAS is the broadband wireless technology used to deliver voice, data, Internet, and video service in the 25-GHz and higher spectrum.**

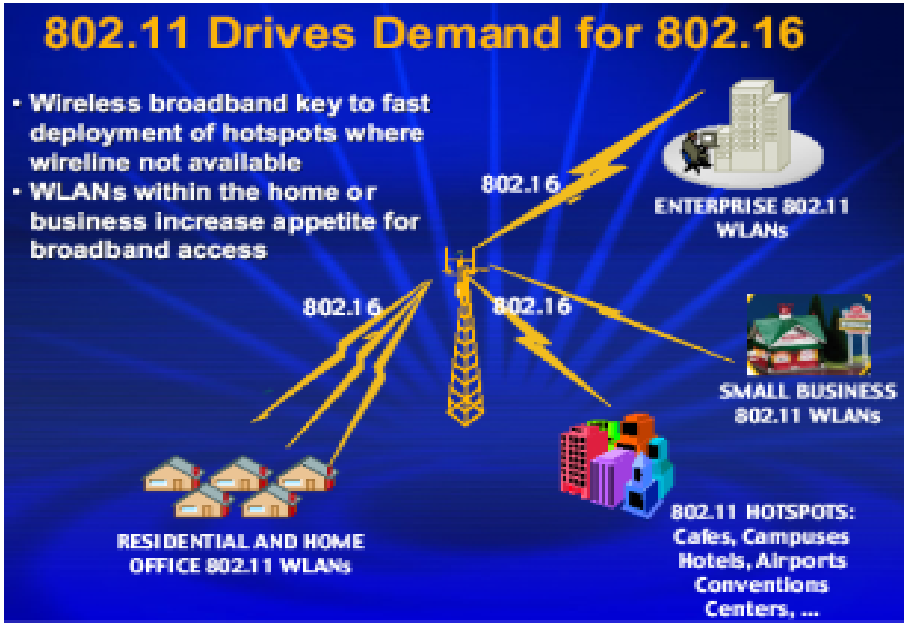
8.4.1 Introduction to IEEE 802.16

☞ BWAS Scenario



8.4.1 Introduction to IEEE 802.16

- **IEEE 802.16 Wireless MAN Background**
  - **Target: FBWA (Fixed Broadband Wireless Access)**
  - **Fast local connection to network**
  - **Project Development since 1998**



8.4.1 Introduction to IEEE 802.16

- **Point-to-Multipoint Wireless MAN: not a LAN**
  - **Base Station (BS) connected to public networks**
  - **BS serves Subscriber Station (SSs)**
    - **SS typically serves a building**
    - **Provide SS with access to public network.**
- **Compared to Wireless LAN**
  - **Multimedia QoS not only contention-based**
  - **Many more users**
  - **Much higher data rates**
  - **Much longer distances**

8.4.1 Introduction to IEEE 802.16

- **Properties of 802.16**
  - **Broad BW: up to 134 Mbps in 28 MHz wide channel (10-66 GHz)**
  - **Support simultaneous multiple services with full QoS**
    - **IPv4, IPv6, ATM, Ethernet, etc.**
  - **BW on demand (per frame)**
  - **MAC designed for efficient spectrum use**
  - **Comprehensive, modern and extensible security**
  - **Support multiple frequency allocation from 2-66 GHz**
    - **OFDM & OFDMA for NLOS applications**

8.4.1 Introduction to IEEE 802.16

- **TDD & FDD**
  - **Link Adaptation: Adaptive modulation & coding**
    - **Per subscriber, per burst, per up-/down- link**
  - **Point-to-multipoint topology, with mesh extensions**
  - **Support for adaptive antennas and space-time coding**
  - **Extensions to mobility**

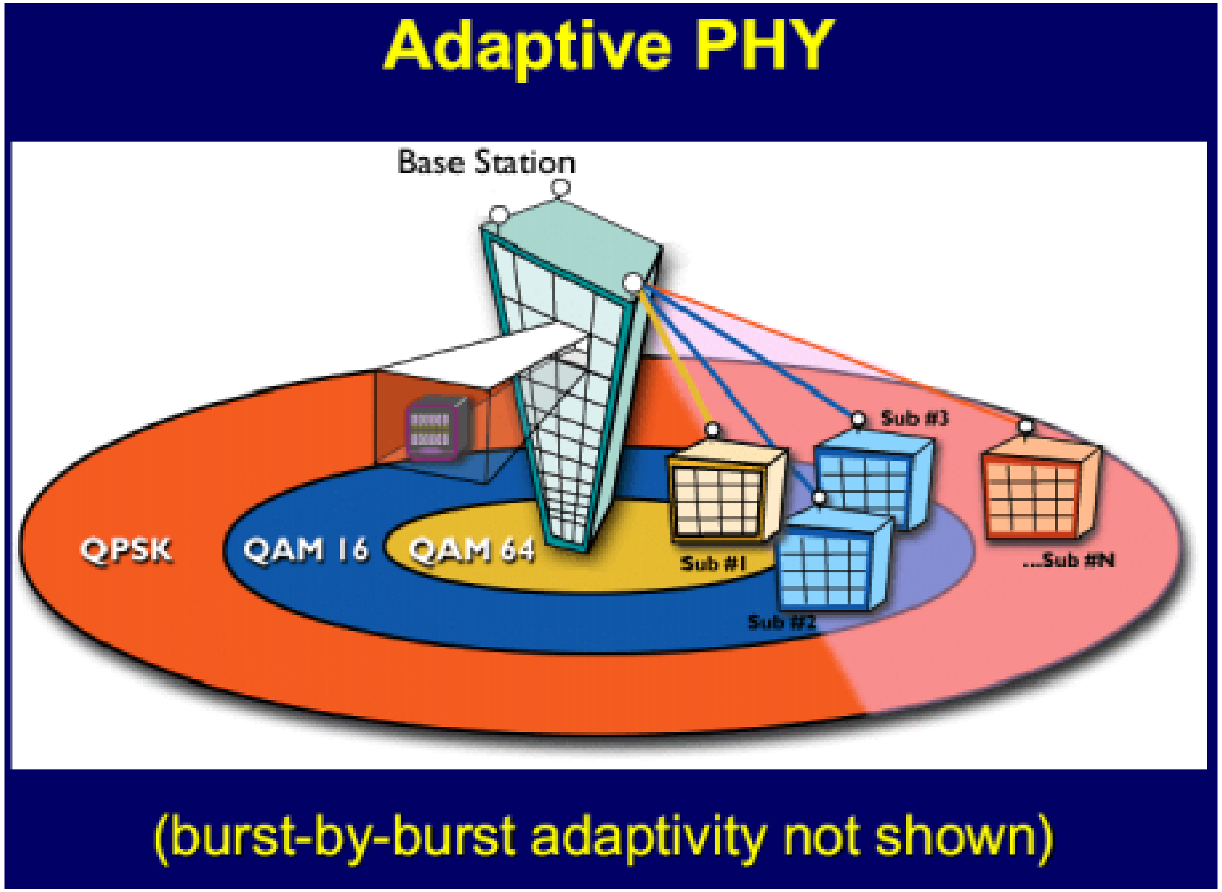
8.4.1 Introduction to IEEE 802.16

☞ **802.16 Bit Rate and Channel Size**

Channel Width (MHz)	Symbol Rate (Msym/s)	QPSK bit rate (Mbps)	16-QAM bit rate (Mbps)	64-QAM bit rate (Mbps)
20	16	32	64	96
25	20	40	80	120
28	22.4	44.8	89.6	134.4

8.4.1 Introduction to IEEE 802.16

☞ 802.16 Link Adaptation Scenario

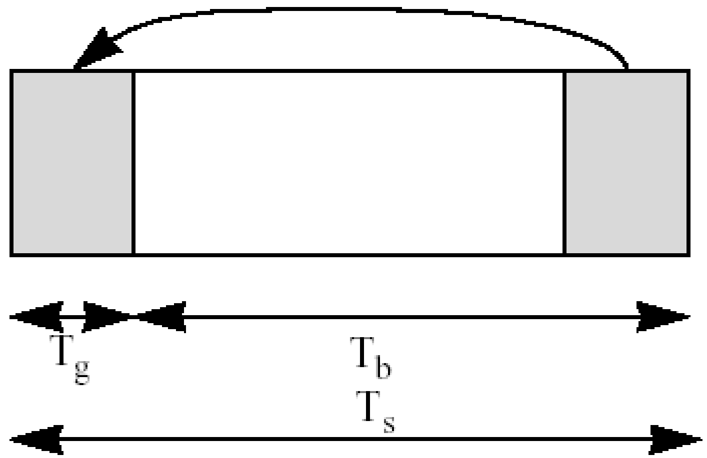


8.4.2 Introduction to Physical Layer of 802.16

- **Physical Layer of 802.16**
  - **OFDM (WMAN-OFDM Air Interface):**
    - **256-FFT w/ TDMA (TDD/FDD)**
  - **OFDMA (WMAN-OFDMA Air Interface) :**
    - **2048-FFT w/ OFDMA (TDD/FDD)**
  - **Single-Carrier (WMAN-SCa Air Interface):**
    - **TDMA (TDD/FDD)**
    - **BPSK, QPSK, 4/16/64/256-QAM**

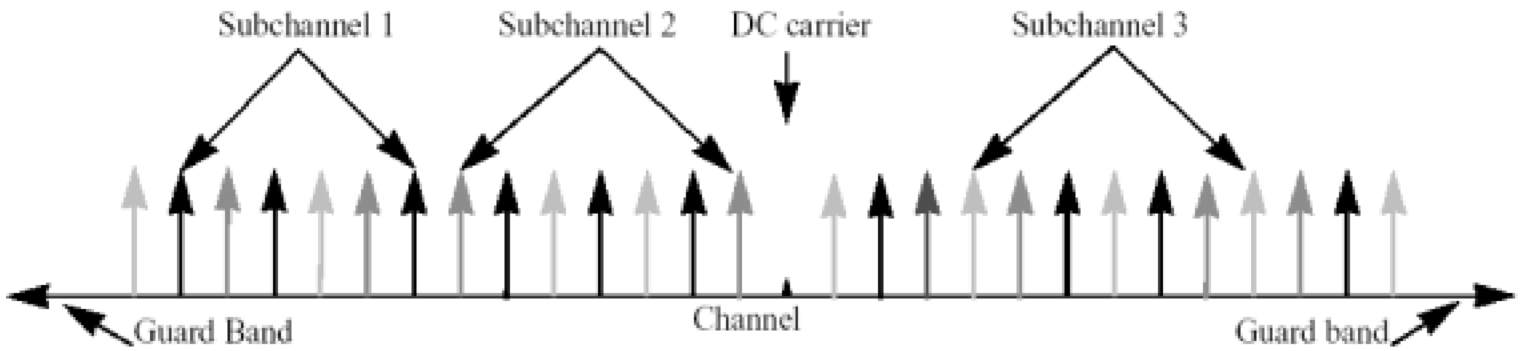
8.4.2 Introduction to Physical Layer of 802.16

- **OFDM time-domain symbol description**
  - **Useful symbol time T_b**
  - **Cyclic Prefix T_g**
  - **Symbol Time $T_s = T_b + T_s$**



8.4.2 Introduction to Physical Layer of 802.16

- **OFDM frequency domain**
  - **Data carriers**
  - **Pilot carriers**
  - **Null carriers**



8.4.2 Introduction to Physical Layer of 802.16

☞The Transmitted signal at the antenna

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{k=-N_{used}/2}^{N_{used}/2} c_k e^{j2\pi k\Delta f (t-T_g)} \right\}$$

t = time, elapsed since the beginning of the subject OFDM symbol, with $0 < t < T_S$.

c_k = a complex number; the data to be transmitted on the carrier whose frequency offset index is *k,* during the subject OFDM symbol. It specifies a point in a QAM constellation.

T_g = guard time

T_S = OFDM symbol duration, including guard time

Δf = carrier frequency spacing

8.4.2 Introduction to Physical Layer of 802.16

- **Four types of forward error correction (FEC)**
  - **Code Type 1: Reed-Solomon Code only**
  - **Code Type 2: Reed-Solomon Code + Block convolutional code**
  - **Code Type 3: Reed-Solomon + Parity check**
  - **Code Type 4: Block Turbo code**

Code Type	Outer Code	Inner Code
1	Reed-Solomon over GF(256)	None
2	Reed-Solomon over GF(256)	(24,16) Block convolutional code
3 (Optional)	Reed-Solomon over GF(256)	(9,8) Parity check code
4 (Optional)	Block Turbo Code	---

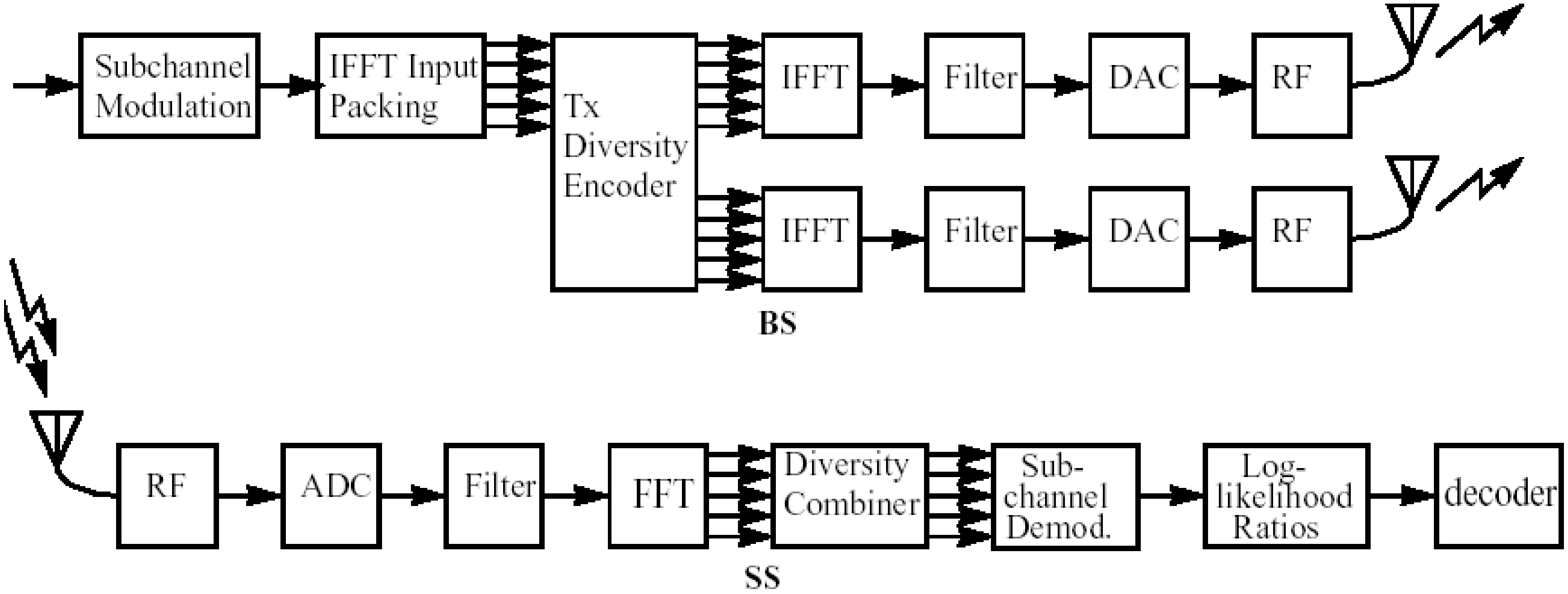
8.4.2 Introduction to Physical Layer of 802.16

☞OFDM Carrier Allocations

Parameter	Value
Number of dc carriers	1
Number of Guard Carriers, Left	176
Number of Guard Carriers, Right	175
N_{used}, Number of Used Carriers	1696
Total Number of Carriers	2048
$N_{varLocPilots}$	0
Number of Fixed-location Pilots	160
Number of Variable-Location Pilots which coincide with Fixed-Location Pilots	0
Total Number of Pilots (*)	160
Number of data carriers	1536
$N_{subchannels}$	32
$N_{subcarriers}$	48
Number of data carriers per subchannel	48
BasicFixedLocationPilots	{5,16,27,38,49} within each subchannel

8.4.2 Introduction to Physical Layer of 802.16

☞ **Transmit diversity – space time coding**



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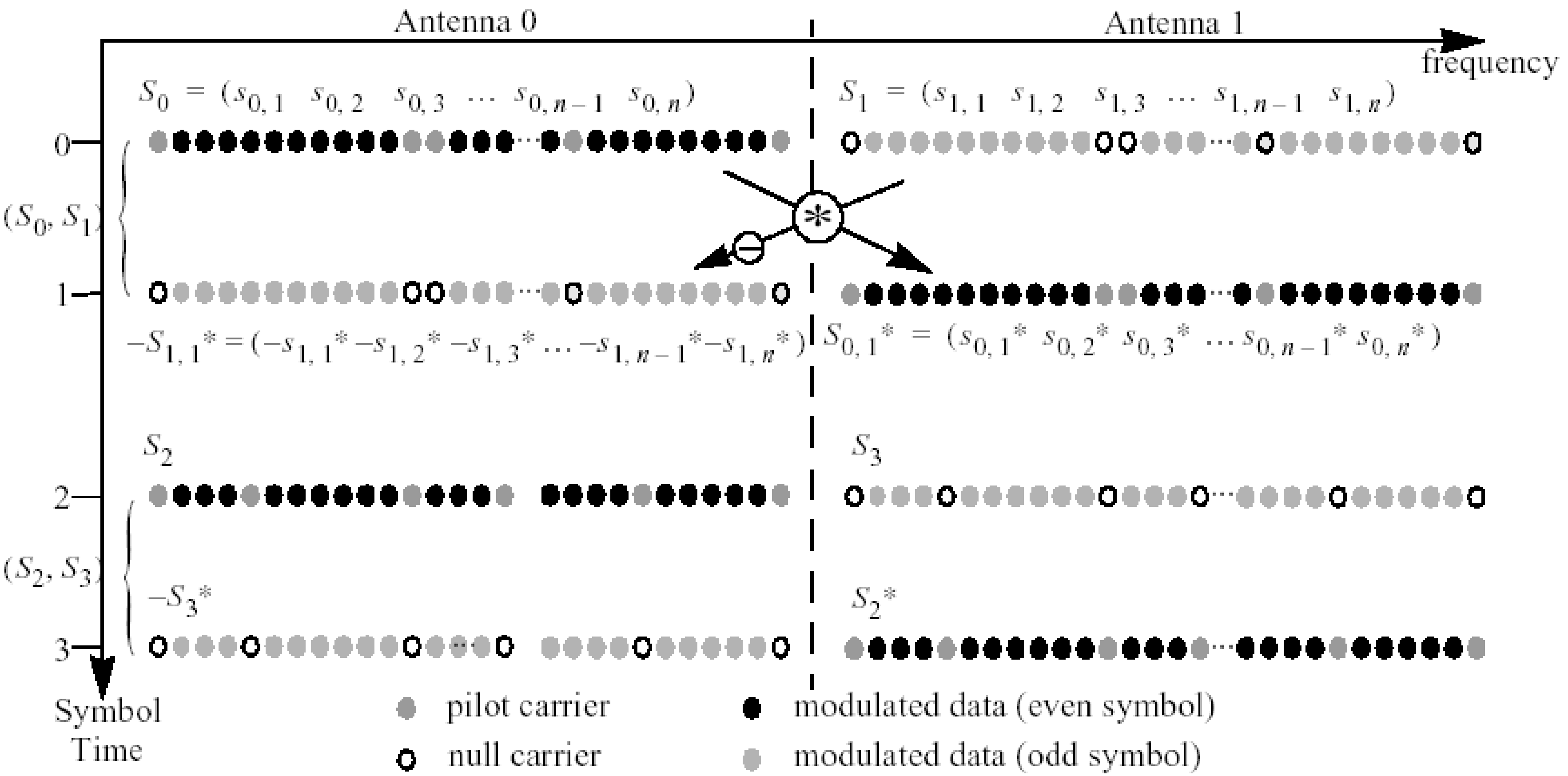
8.4.2 Introduction to Physical Layer of 802.16

- **STC encoding**
  - **Transmits 2 complex symbols s0 and s1, using the MISO channel (2 Tx, one Rx) twice with channel vector values h0 (for antenna 0) and h1 (for antenna 1).**
  - **First channel use : Ant0 transmits s_0, Ant1 transmit s_1**
  - **Second channel use: Ant0 transmit s_0^* , antenna 1 transmit $-s_1^*$**
  - **The receiver get the benefit of the 2nd order diversity**

8.4.2 Introduction to Physical Layer of 802.16

☞STC Usage with OFDM



8.4.2 Introduction to Physical Layer of 802.16

☞Concatenated Reed-Solomon / convolutional code (RS-CC)

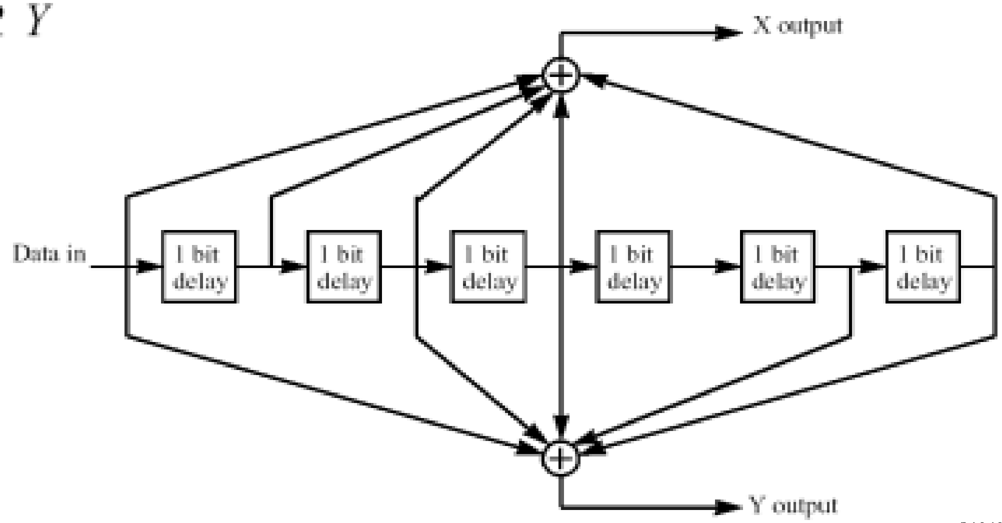
•RS code is derived from (255,239) RS code that can correct up to 8 symbol errors.

•The RS encoded block is then encoded by a convolutional code of rate ½ with generator polynomial

$$G_1 = 171_{OCT} \qquad FOR\ X$$

$$G_2 = 133_{OCT} \qquad FOR\ Y$$

•Convolutional encoder



8.4.2 Introduction to Physical Layer of 802.16

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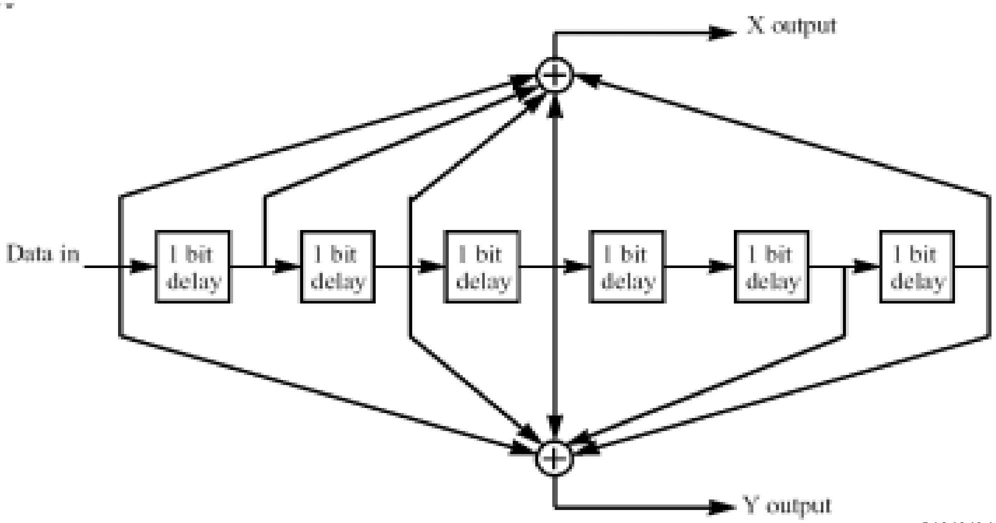


8.4.2 Introduction to Physical Layer of 802.16

☞ **Puncturing Pattern**

	Code Rates		
Rate	2/3	3/4	5/6
d_{free}	6	5	4
X	10	101	10101
Y	11	110	11010
XY	$X_1Y_1Y_2$	$X_1Y_1Y_2X_3$	$X_1Y_1Y_2X_3Y_4X_5$

8.4.2 Introduction to Physical Layer of 802.16

☞ Channel Coding and Modulation

Modulation	Uncoded Block Size (Bytes)	Overall Coding Rate	Coded Block Size (Bytes)	RS Code	CC Code Rate
QPSK	18	1/2	36	(24,18,3)	2/3
QPSK	26	~3/4	36	(30,26,2)	5/6
16 QAM	36	1/2	72	(48,36,6)	2/3
16 QAM	54	3/4	72	(60,54,3)	5/6
64 QAM	72	2/3	108	(81,72,4)	3/4
64 QAM	82	~3/4	108	(90,82,4)	5/6

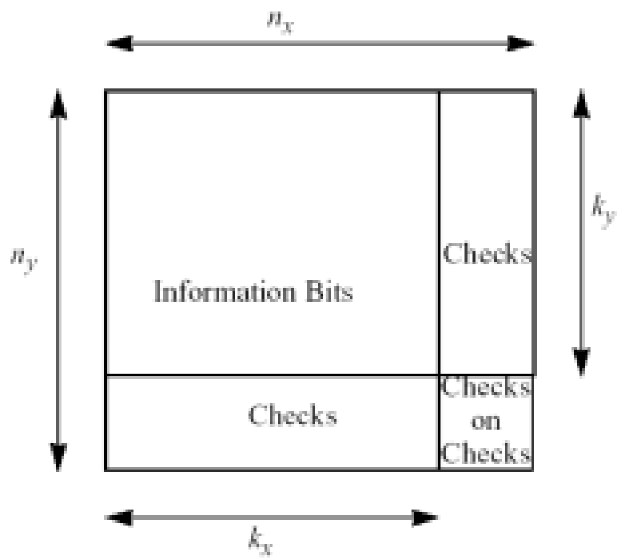
8.4.2 Introduction to Physical Layer of 802.16

- **Block Turbo codes**
  - **Based on the product of two component codes.**
  - **Binary extended Hamming code or parity check code**

Component code (n,k)	Code type
(64,57)	Extended Hamming Code
(32,26)	Extended Hamming Code
(16,11)	Extended Hamming Code
(32,31)	Parity Check Code
(16,15)	Parity Check Code
(8,7)	Parity Check Code

8.4.2 Introduction to Physical Layer of 802.16

- The component codes are used in a two dimensional matrix form
  - k_x information bits are encoded into n_x bits by using (n_x,k_x) block code.
  - After encoding the rows, the columns are encoded using a (n_y,k_y) block code, where the check bits of the first code are also encoded.



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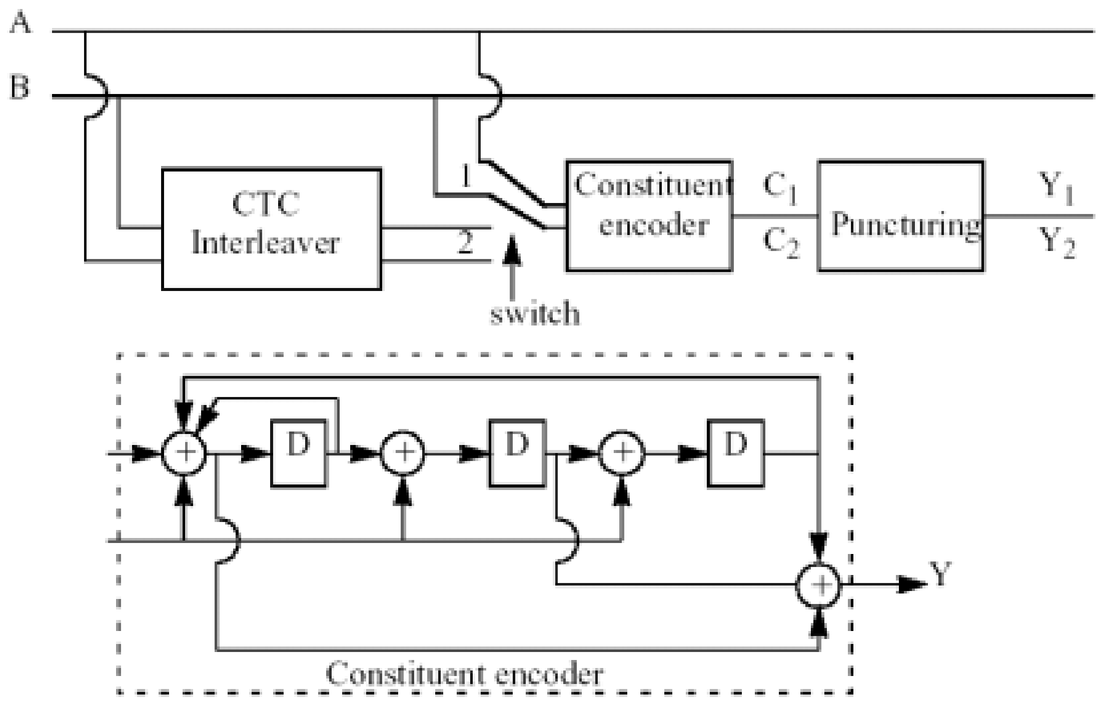
8.4.2 Introduction to Physical Layer of 802.16

- **Convolutional turbo code**
  - **Circular Recursive Systematic Convolutional**
  - **The turbo code encoder**



8.4.2 Introduction to Physical Layer of 802.16

☞ Convolutional turbo code channel coding and modulation

Modulation	Data Block Size (Bytes)	Coded Block Size (Bytes)	Overall Code Rate	N	P_0	P_1	P_2	P_3
QPSK	18	36	1/2	72	11	6	0	6
QPSK	24	36	2/3	96	7	48	24	72
QPSK	27	36	3/4	108	11	54	56	2
16 QAM	36	72	1/2	144	17	74	72	2
16 QAM	54	72	3/4	216	31	2	4	10
64 QAM	72	108	2/3	288	13	144	72	216
64 QAM	81	108	3/4	324	11	172	164	16