Codificación para los sistemas de comunicaciones

(Coding and Modulation for Wireless Networks)

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Outline

- Introduction: A simple two-path wireless channel
  - Flat and frequency selective fading
  - Fast and slow fading
- Diversity techniques for wireless channels
- IEEE 802 wireless network (PHY) standards
  - Bit-interleaved coded modulation
  - Modulations and codes used today

A wireless two-path channel

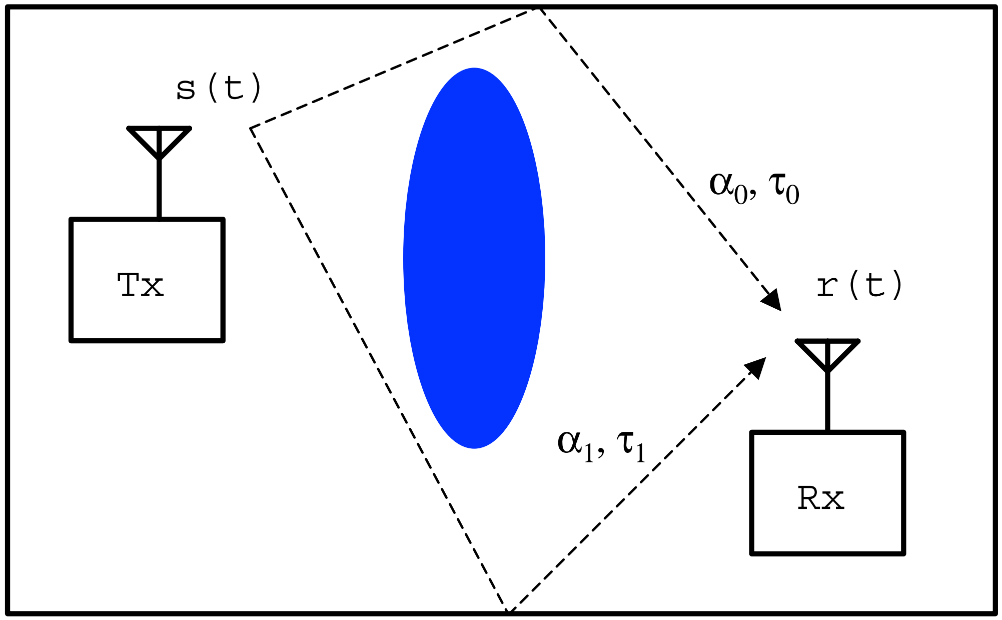
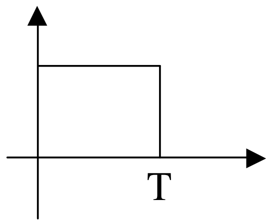


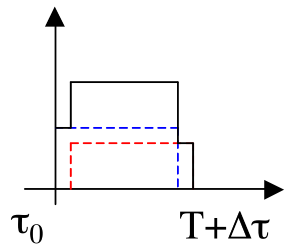
Figure 1: A wireless two-path channel.

Wireless two-path channel response to rectangular pulses

Narrowband pulses, $T > \Delta\tau \quad (\Delta\tau = \tau_1 - \tau_0)$



Input

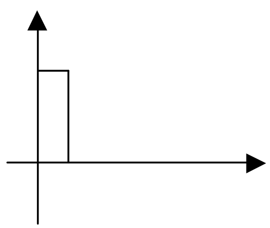


Output

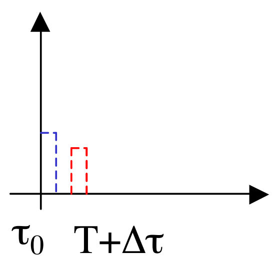
- Amplitude variation:
  Fading
- Distorsion

FLAT FADING

Wideband pulses, $T < \Delta\tau$



Input

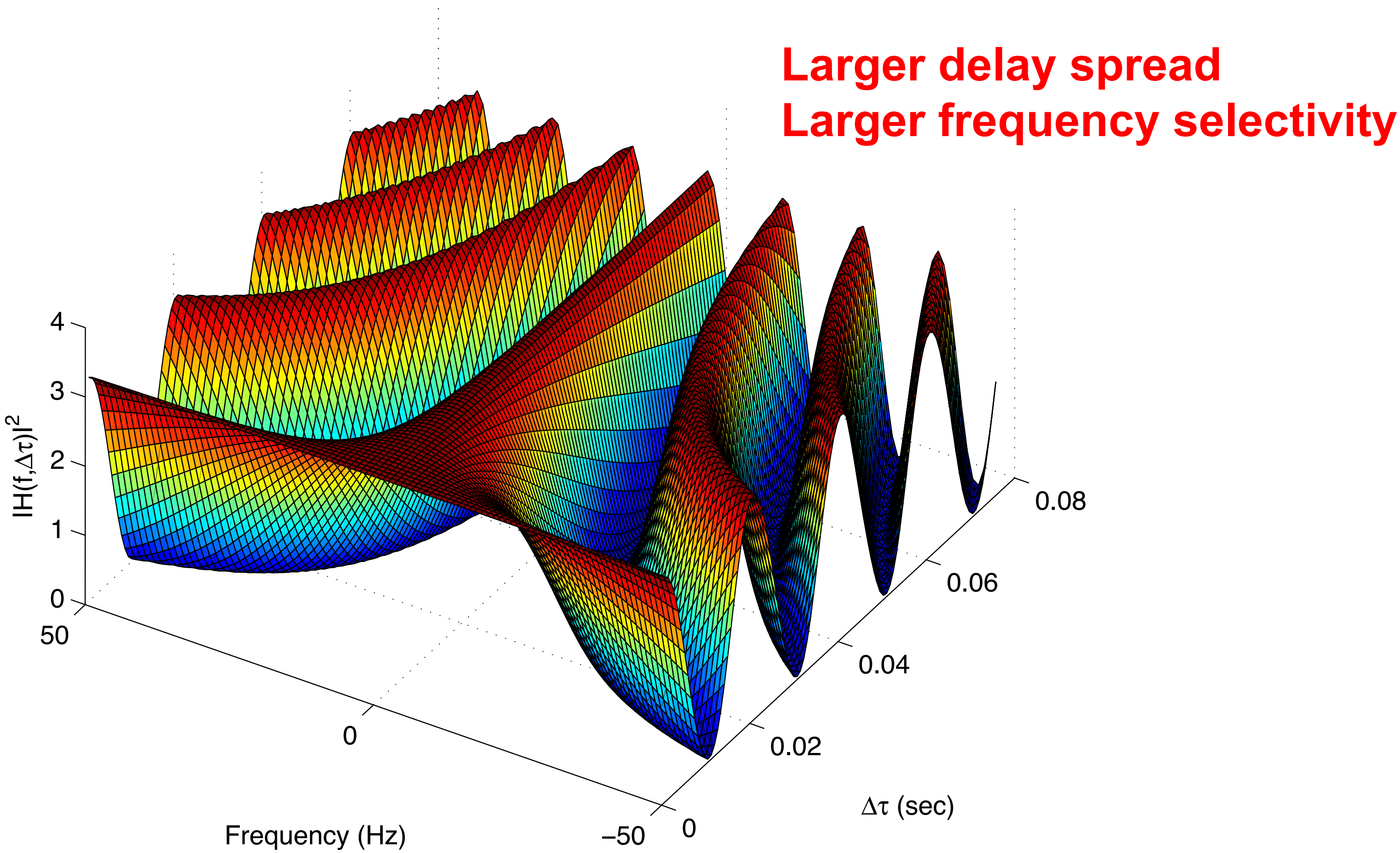


Output

- Amplitude variation:
  Fading (less)
- No distorsion
- Overlap to next pulse:
  Interference

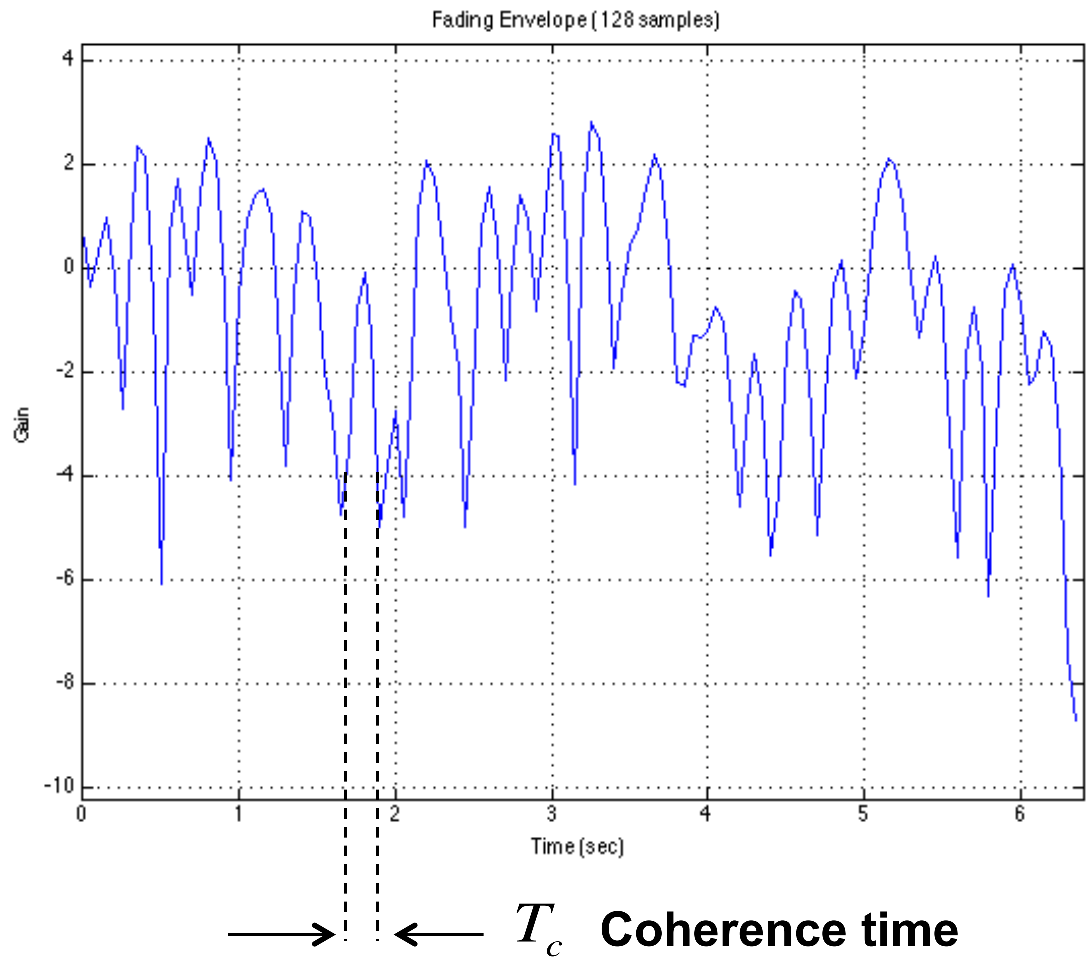
FREQUENCY-SELECTIVE FADING

PSD of a wireless two-path channel



Fading and time variations

- Variations in received power due to movement (Doppler):



$$T_c = \frac{1}{B_D}$$

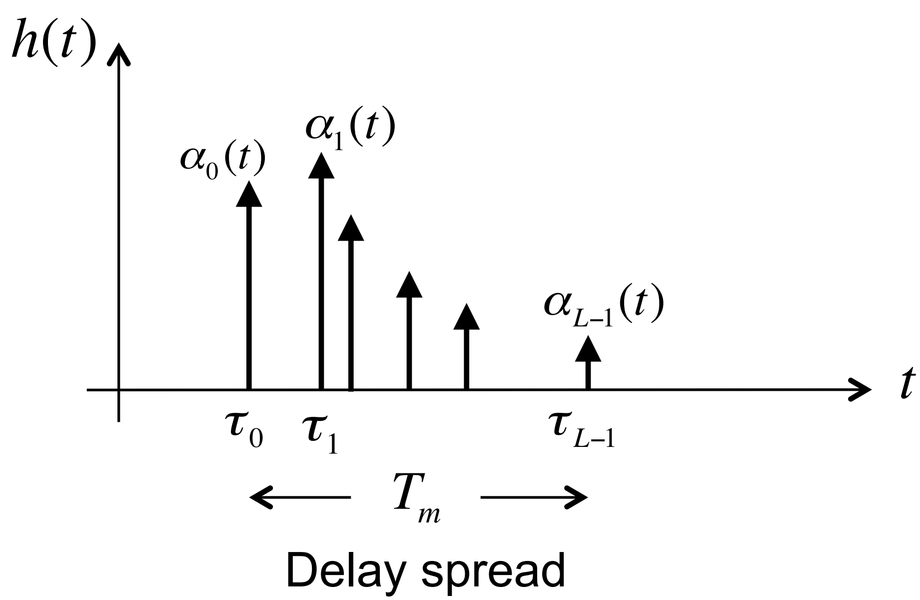
B_D : Doppler bandwidth

$$B_D = 2vf_c / c$$

Slow fading: $T < T_c$
Fast fading: $T > T_c$
T is the symbol duration

Multipath effects

- Reflections (paths) of the transmitted electromagnetic signal on objects
- *L*-path channel impulse response:



Coherence bandwidth:

$$B_c = \frac{1}{T_m}$$

Phase rotation:

$$\phi_i(t) = 2\pi f_c \tau_i(t)$$

Basic types of fading

- Flat fading:

$$B << B_c \quad \text{or} \quad 2\text{W} << \frac{1}{T_m}$$

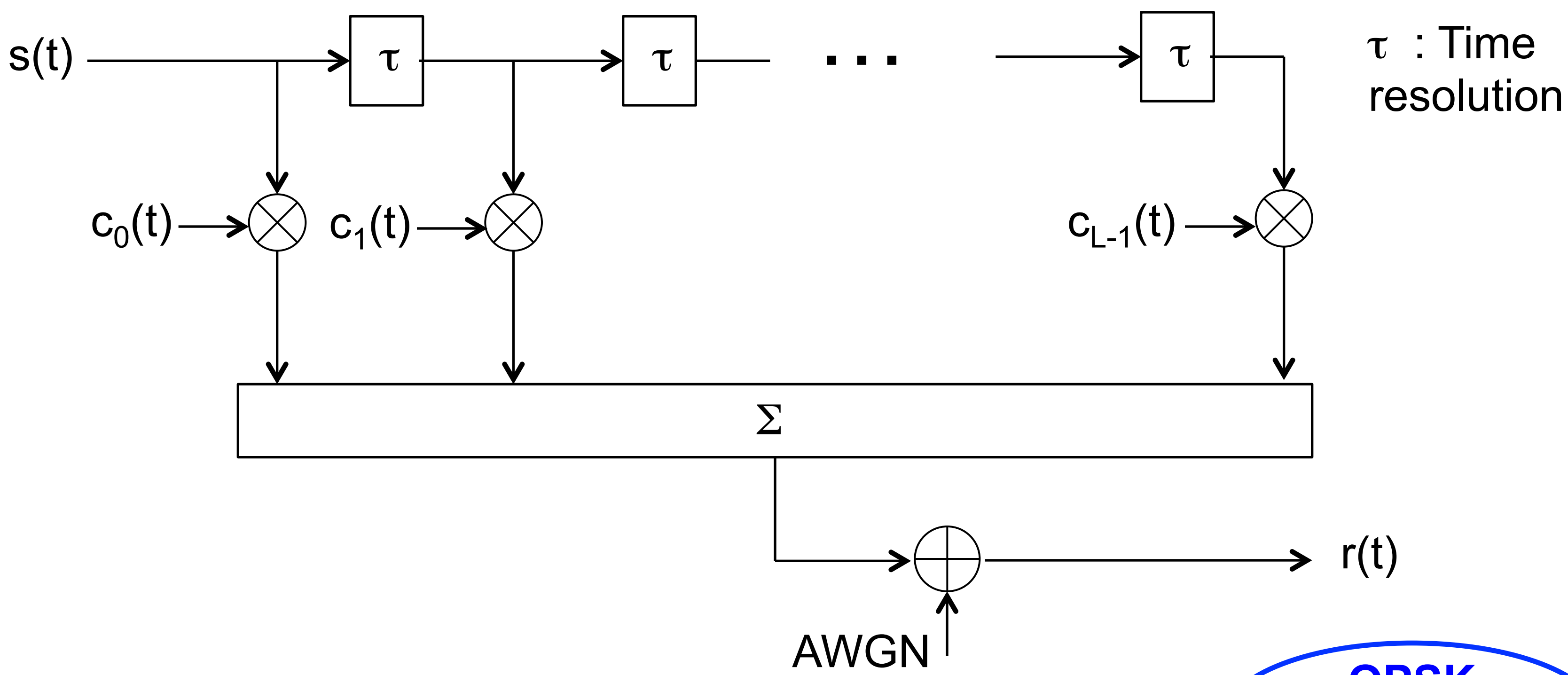
  – **Narrowband** signaling ***B=2W* is the signal bandwidth**

- Frequency-selective fading:

$$B >> B_c \quad \text{or} \quad 2\text{W} >> \frac{1}{T_m}$$

  – **Wideband** signaling

Complex baseband frequency-selective multipath channel model



QPSK Matlab demo

Note: L=1 and $c_0(t)=c_0$ gives flat fading

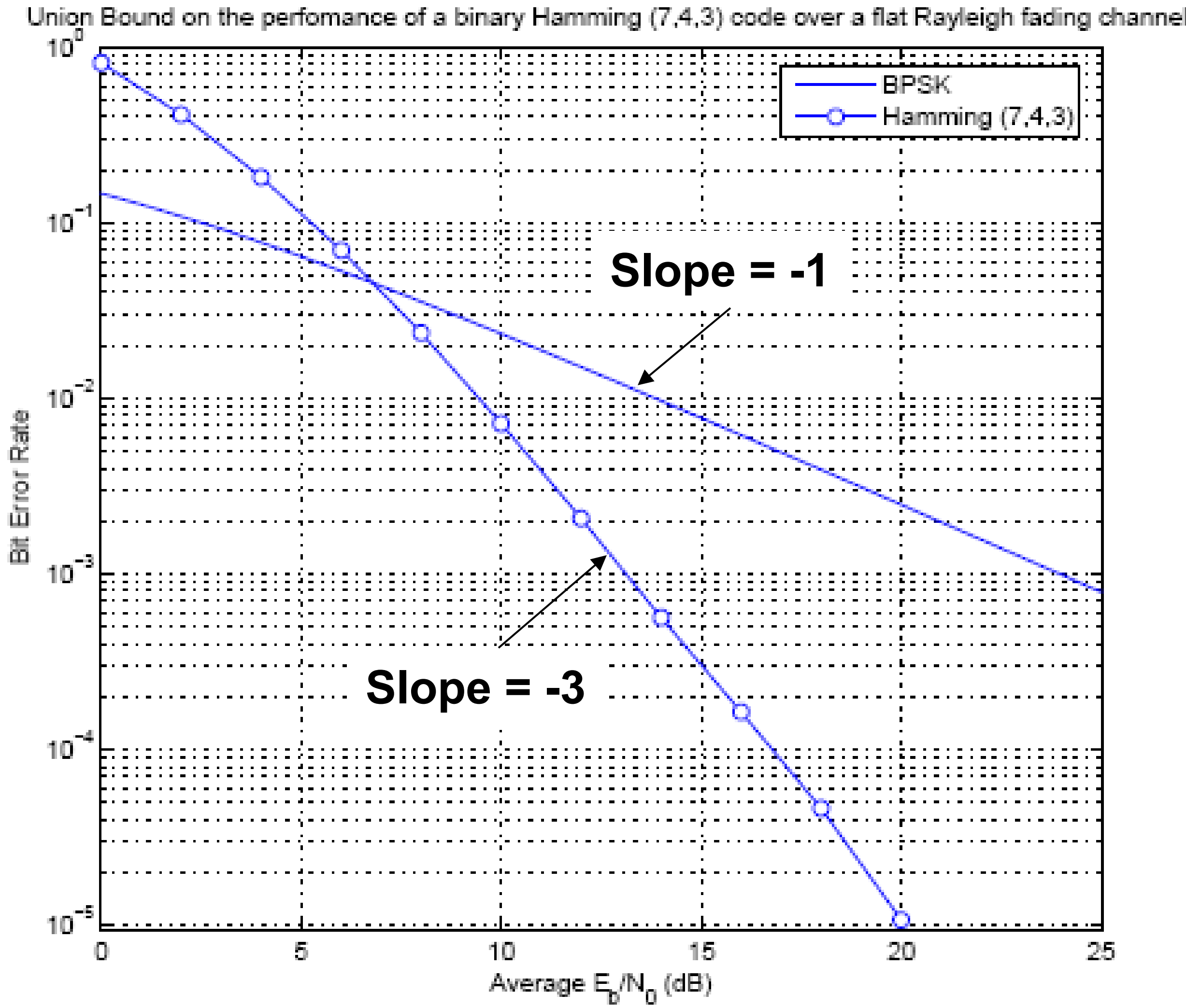
$c_i(t) = \alpha_i(t)\, e^{j\phi i(t)}$: i-th path (complex valued) gain, i=0,2,…,L-1

Time diversity for multipath channels

Time-diversity techniques

- Time-diversity techniques can be classified according to the frequency selectivity of the multipath channel
- Flat fading channels
  - ***Error correcting coding*** & ***interleaving***
  - Diversity order equal to the ***minimum Hamming distance*** of the code
- Frequency-selective channels
  - ***RAKE*** demodulation
  - Linear adaptive ***equalization***

Flat Rayleigh fading: ECC diversity with a Hamming (7,4,3) code



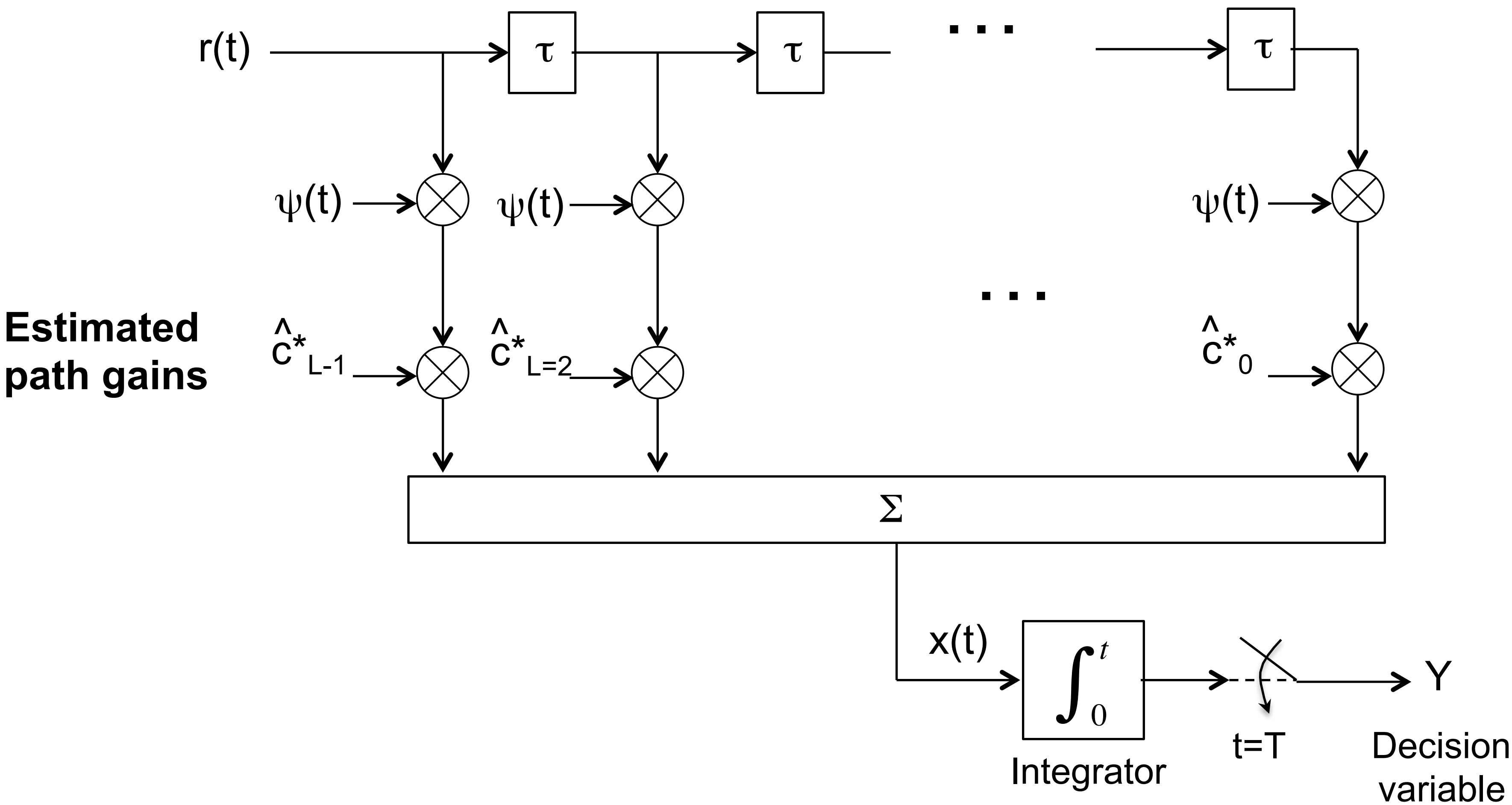
RAKE demodulator: Assumptions

- Slow fading: $T << T_c \quad \Rightarrow \quad c_i(t) = c_i, i = 0, \cdots, L-1$
- Frequency-selective fading: $W >> B_c$ (1)
- No intersymbol interference (ISI_: $T >> T_m$ (2)

- (1) and (2) are satisfied by ***wideband pulses***, such as PPM or spread-spectrum

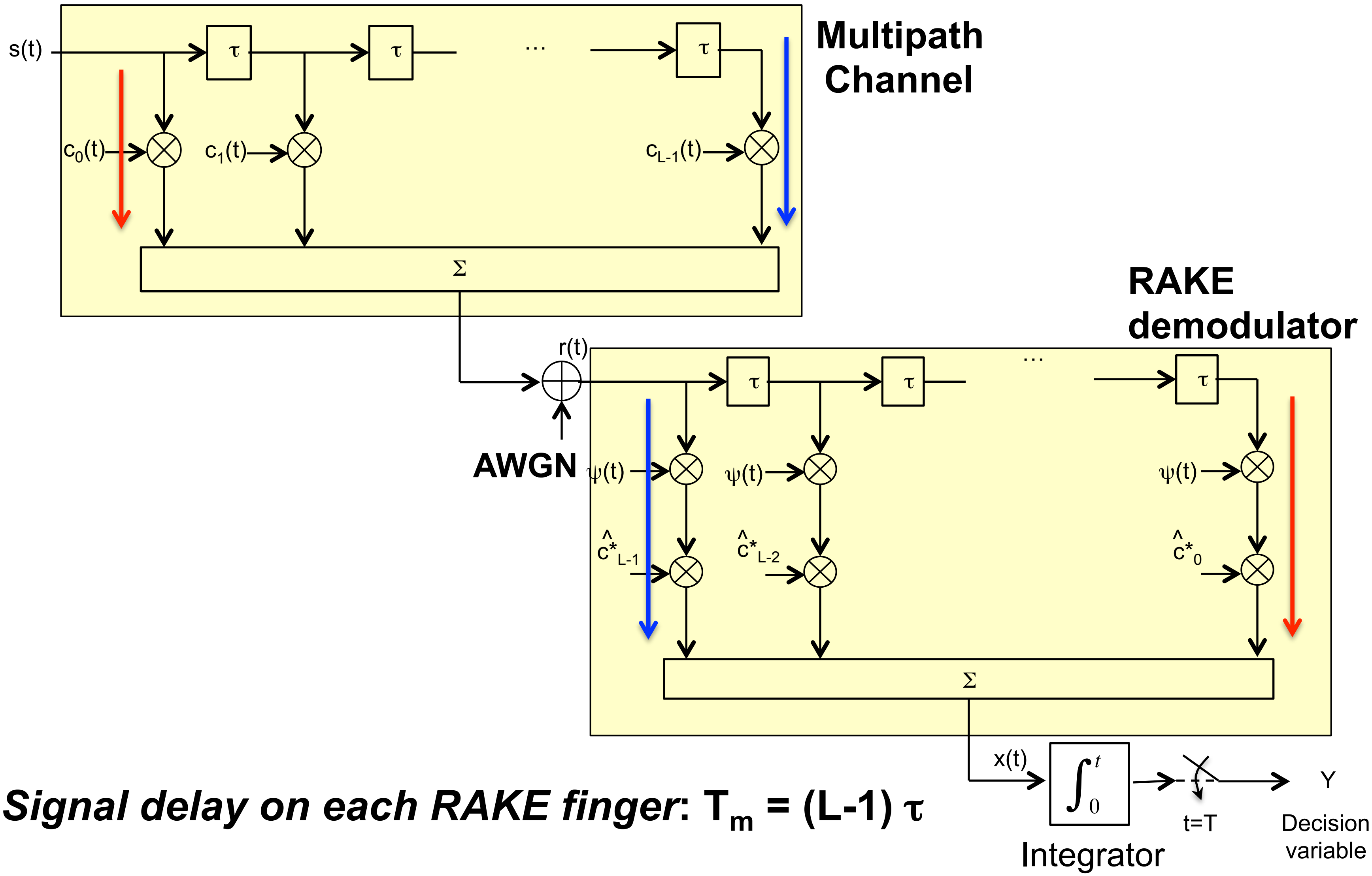
- Path gains and delays need to be known
  - Need ***channel estimation*** techniques (“*finger search*”)

RAKE demodulator: Structure (BPSK)



→ **L fingers (diversity branches)**

Maximal-ratio combining property

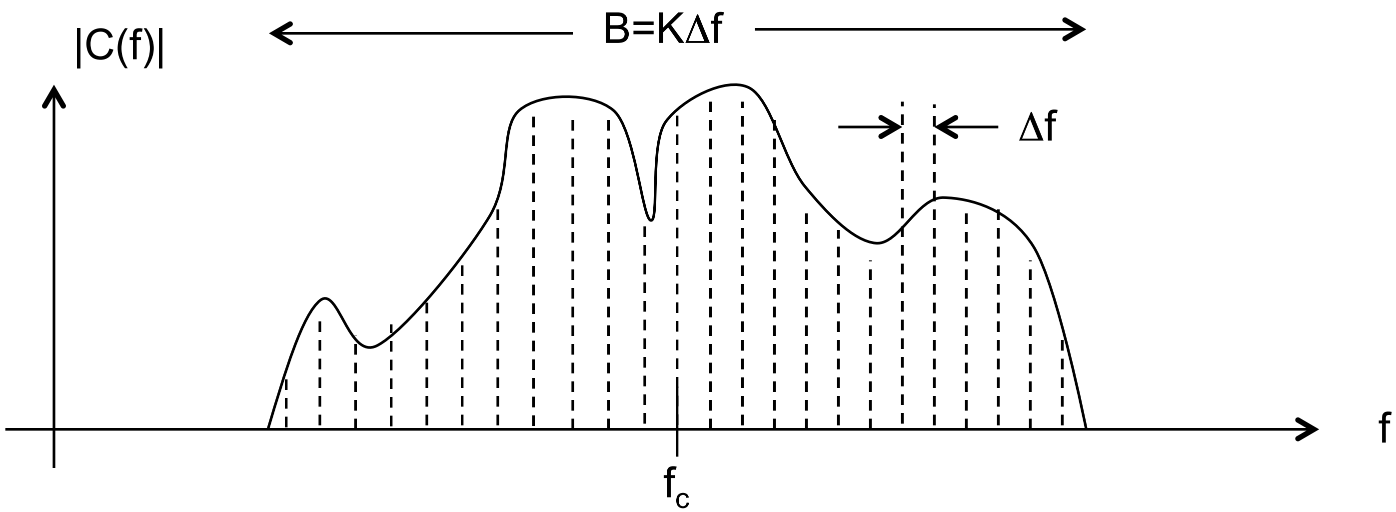


***Signal delay on each RAKE finger*: T_m = (L-1) τ**

Frequency diversity for frequency-selective multipath channels: OFDM

Frequency-domain approach

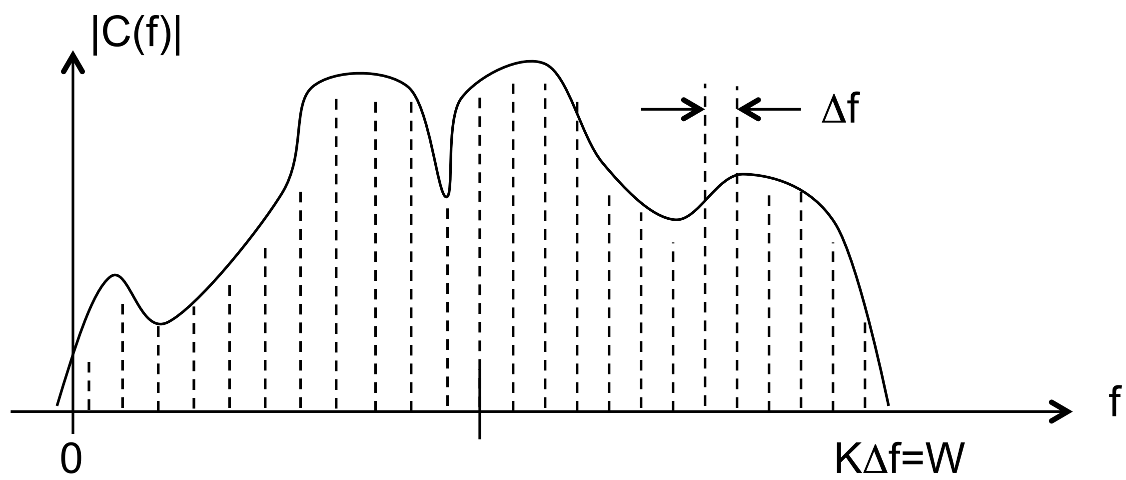
- Divide and conquer: Create K *subchannels* with frequency responses that are relatively constant (flat):



- Subcarrier frequencies:

$$f_k = f_c - \frac{K-1}{2T} + \frac{k}{T}, \quad k = 0, 1, \cdots, K-1.$$

Complex baseband spectrum



- Each baseband channel has an associated basis signal

$$\psi_k(t) = e^{j\left(2\pi \frac{k}{T} t\right)}, \quad k = 0,1,\cdots,K-1.$$

- Frequency separation and symbol duration (sinc pulses):

$$\Delta f = \frac{W}{K}, \quad T = \frac{1}{\Delta f} = \frac{K}{W} \qquad \rightarrow \text{ Symbol duration is proportional to K}$$

OFDM signal

- A large value of K results in T >> T_m and fading becomes ***flat***
  - Constant subchannel gains:

$$C\left(2\pi\frac{k}{T}\right) = C_k = A_k e^{j\phi_k}, \quad k = 0,1,\cdots,K-1.$$

- Each subcarrier is typically M-QAM mapped so that the signal transmitted over each subchannel is:

$$u_k(t) = \sqrt{\frac{2}{T}}S_{Ik}\cos\left(2\pi\frac{k}{T}t\right) + j\sqrt{\frac{2}{T}}S_{Qk}\sin\left(2\pi\frac{k}{T}t\right),\ 0 \le t \le T,$$

where $S_k = S_{Ik} + jS_{Qk}$ represent the modulation symbols.

- Complex baseband OFDM signal: $s(t) = \sum_{k=0}^{K-1} u_k(t)$

OFDM receiver processing

- For each subchannel, k=0,1, …, K-1, the ***received signal*** is

$$r_k(t) = \sqrt{\frac{2}{T}} A_k S_{k1} \cos\left(2\pi \frac{k}{T} t + \phi_k\right) + j\sqrt{\frac{2}{T}} A_k S_{k2} \sin\left(2\pi \frac{k}{T} t + \phi_k\right) + N_k(t), \ \ 0 \le t \le T,$$

AWGN

with A_k the amplitude response and ϕ_k the phase response.

- ***Basis functions***:

$$\psi_{k1}(t) = \sqrt{\frac{2}{T}} \cos\left(2\pi \frac{k}{T} t\right), \quad \psi_{k2}(t) = \sqrt{\frac{2}{T}} \sin\left(2\pi \frac{k}{T} t\right), \ \ 0 \le t \le T.$$

- Corresponding ***matched filter outputs***:

$$Y_{k1} = A_k \cos(\phi_k) \cdot S_{k1} + W_{k1}, \quad Y_{k2} = A_k \sin(\phi_k) \cdot S_{k2} + W_{k2}, \ \ \text{or}$$

$$\boxed{Y_k = C_k S_k + W_k,} \quad \text{as a complex number.}$$

One-tap equalization

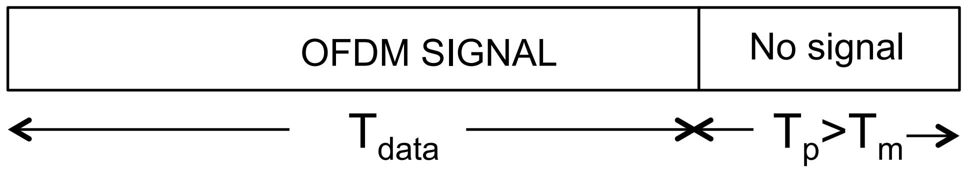
- The receiver estimates the subchannel gains using ***pilot symbols*** known to both transmitter and receiver

- Based on these estimates $\hat{C}_k$, the scaling of the transmitted symbols is removed by a process known in the literature as "***one-tap equalization***":

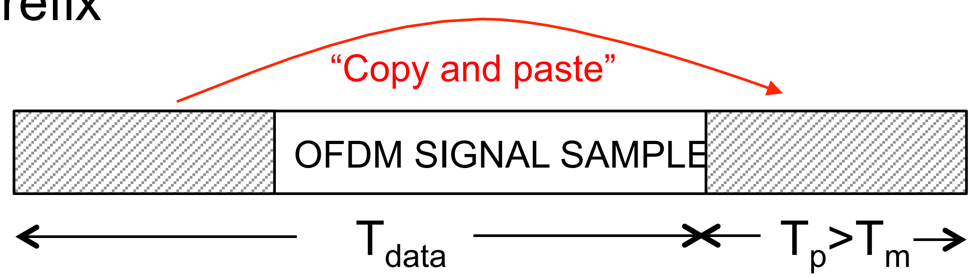
$$\boxed{Y_k' = \frac{\hat{C}_k^*}{\left|\hat{C}_k\right|^2} Y_k = \frac{\hat{C}_k^*}{\left|\hat{C}_k\right|^2}\left(C_k S_k + W_k\right) \approx S_k + W_k'}, \quad k = 0,1,\cdots,K-1$$

ISI removal

- Effects of delay spread T_m can be removed using a ***prefix***
- Two choices
  - Zero prefix (or time guardband)

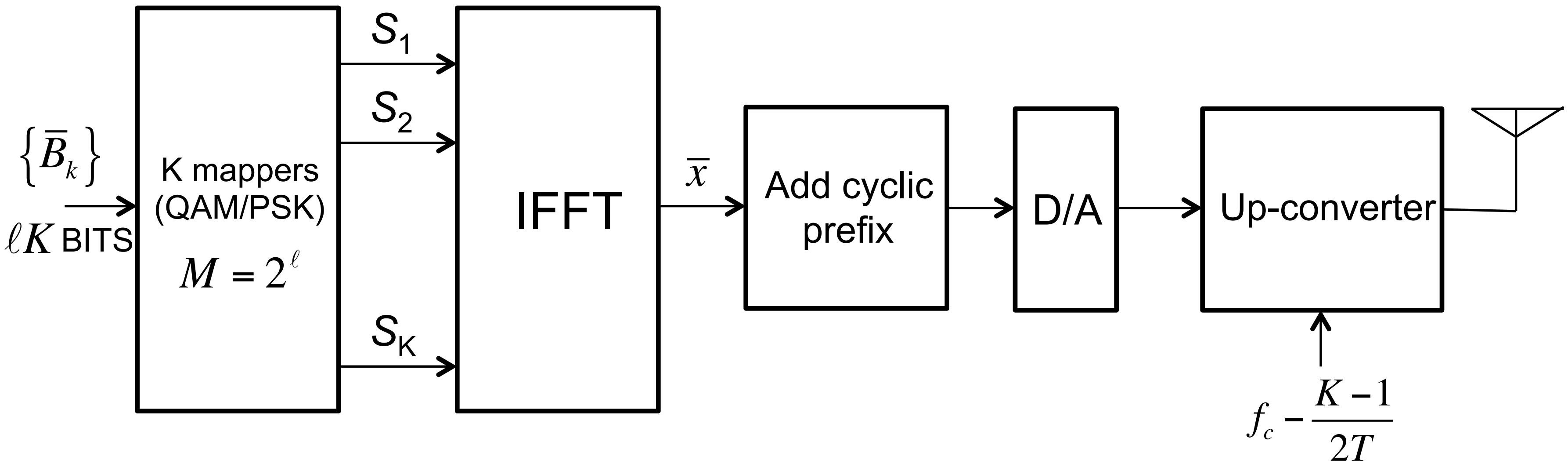


  - Cyclic prefix

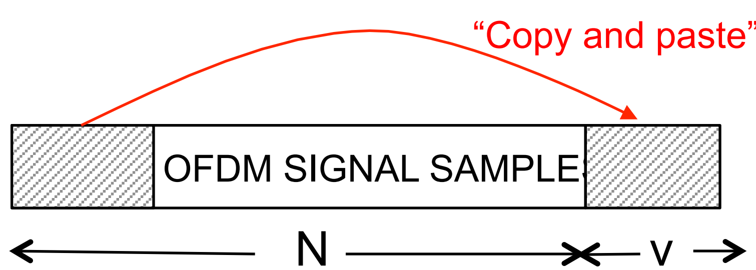


- The choice of a cyclic prefix offers the additional advantage that the ***discrete Fourier transform*** (implemented via the FFT algorithm) can be used

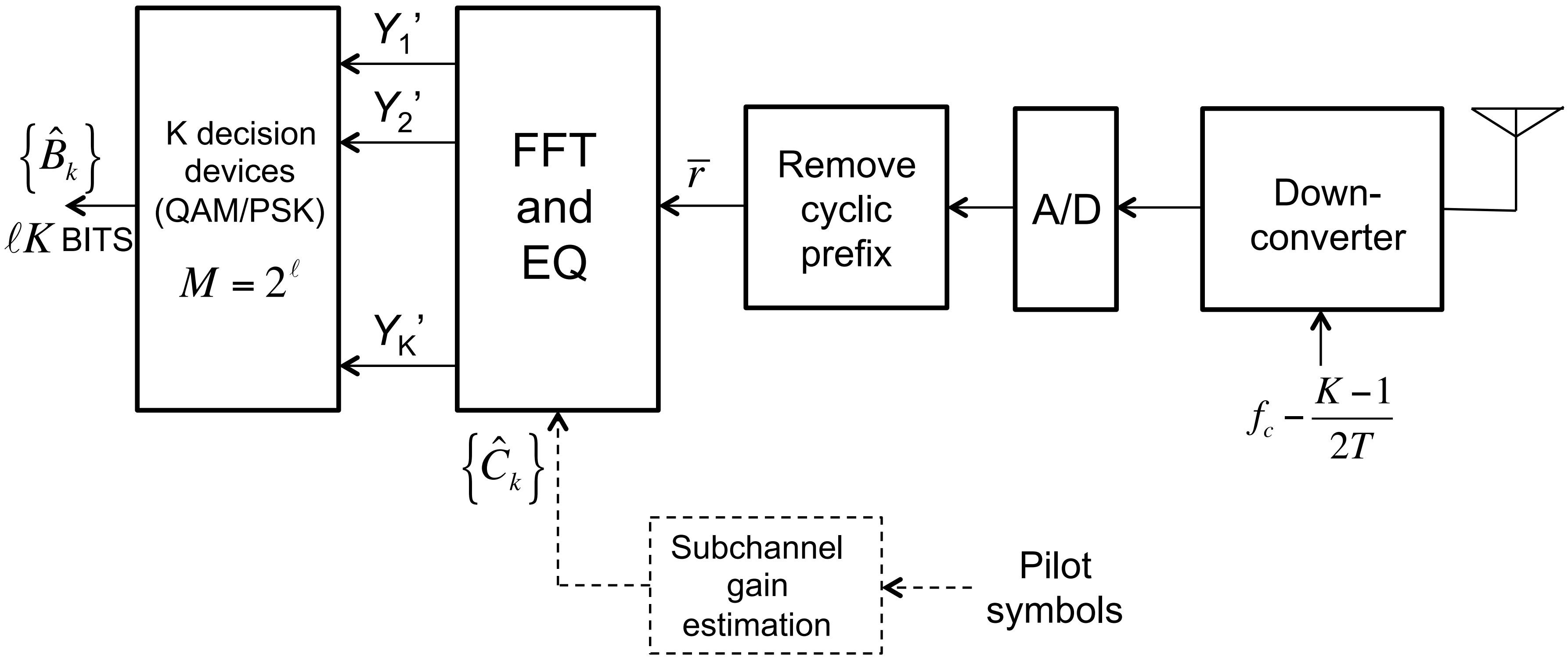
OFDM transmitter



$\overline{x}$: Vector of K signal samples



OFDM receiver

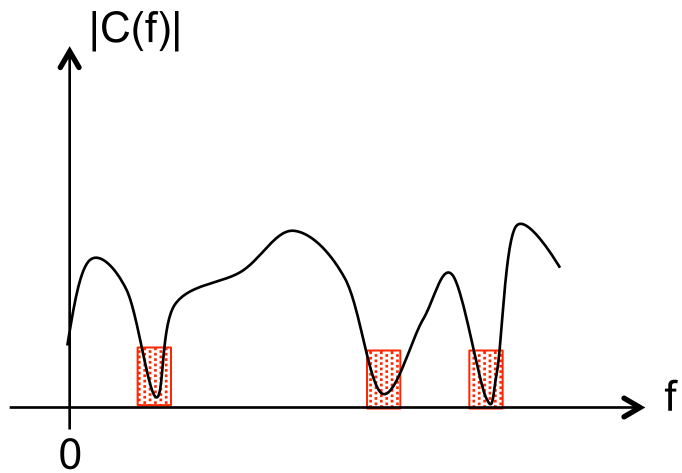


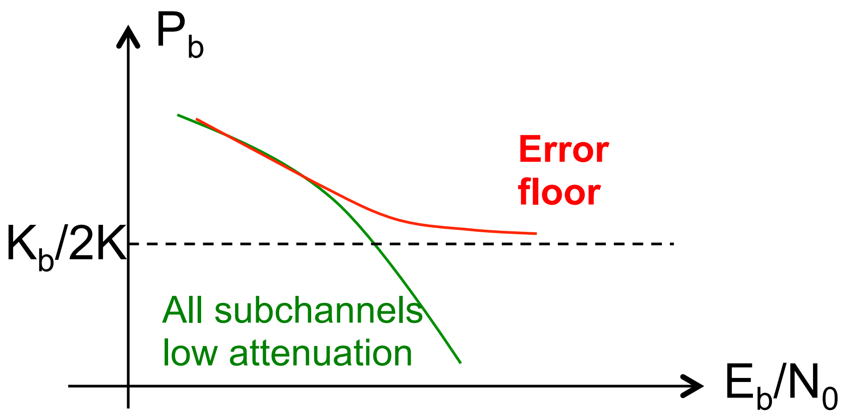
$\bar{r}$: Vector of K received signal samples

EQ : Array of K one-tap equalizers

Error floors in OFDM

- Subchannels (say K_b out of K) with high attenuation (low amplitude A_k) will experience large number of errors $(\approx 1/2)$

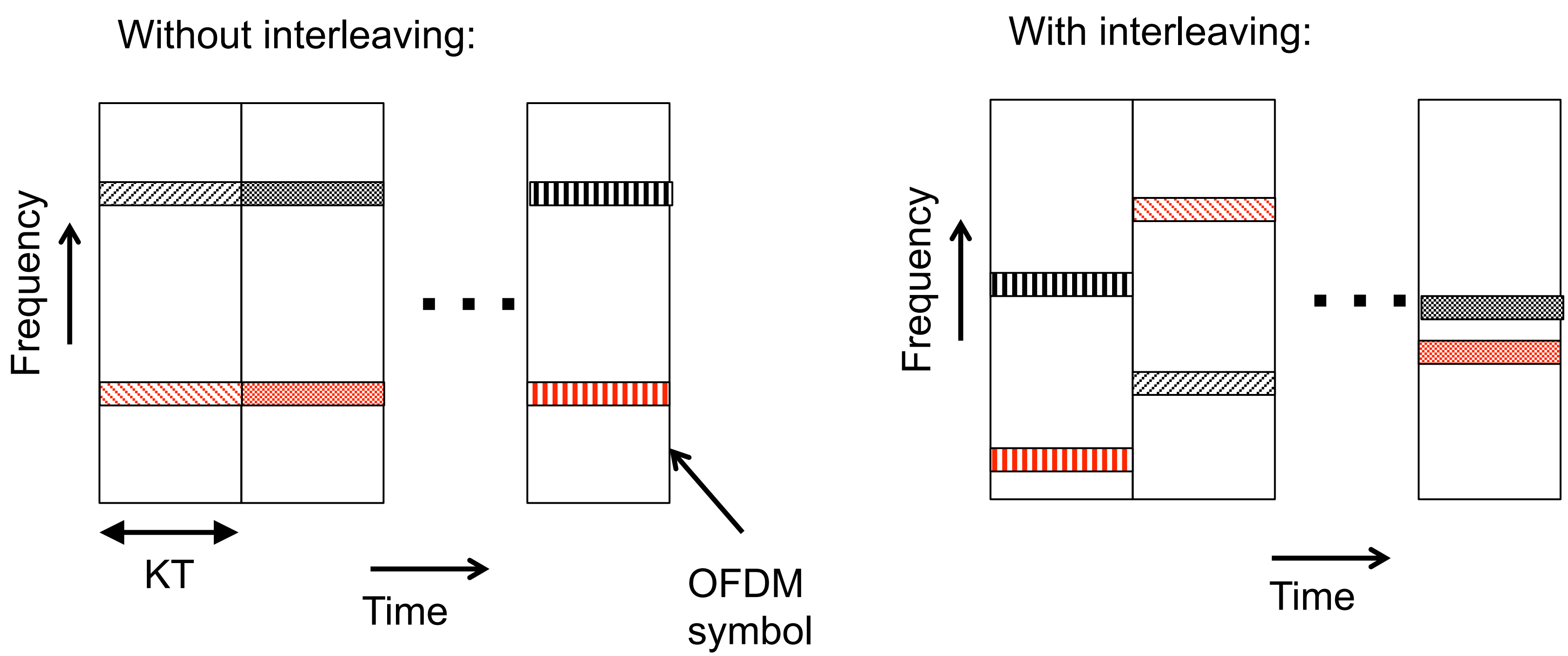




- Solution (e.g., all IEEE 802.11 physical layer specifications):
  - Scramble the symbols: ***Interleaving***
  - Use ***error correcting coding***

Time-Frequency Interleaving

Goal: Spread those subchannel symbols affected by frequency nulls (low energy) in channel response



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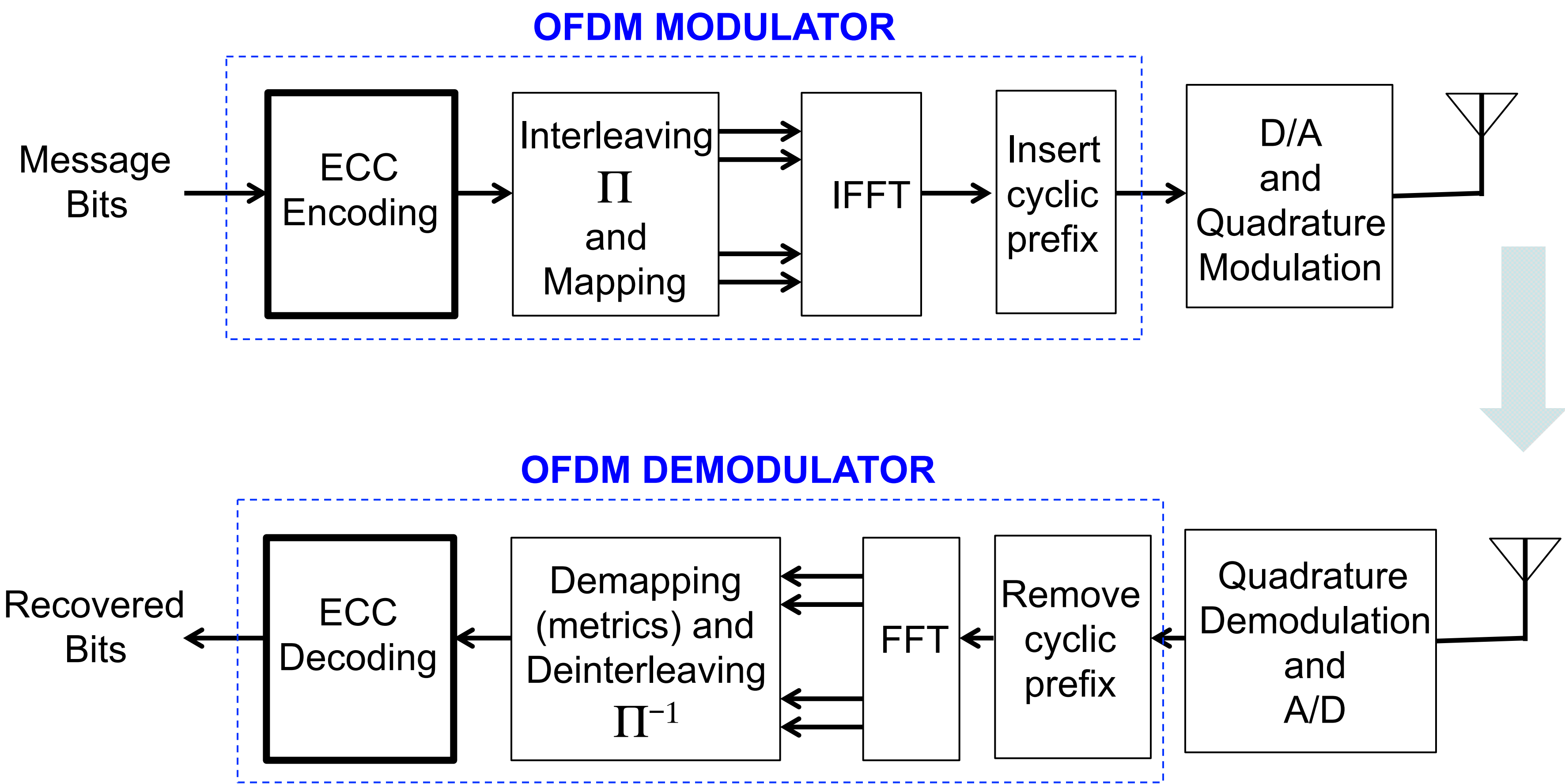
Error Control Coding (ECC)

- Correct errors in symbols with low energy



Coding and Modulation in IEEE 802 Wireless Network Standards

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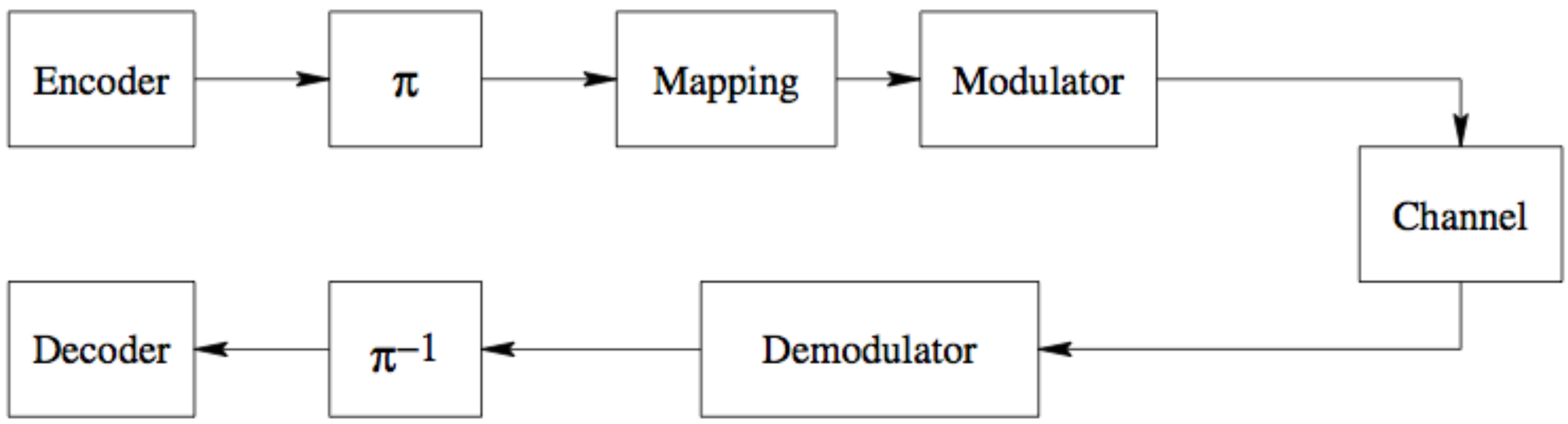
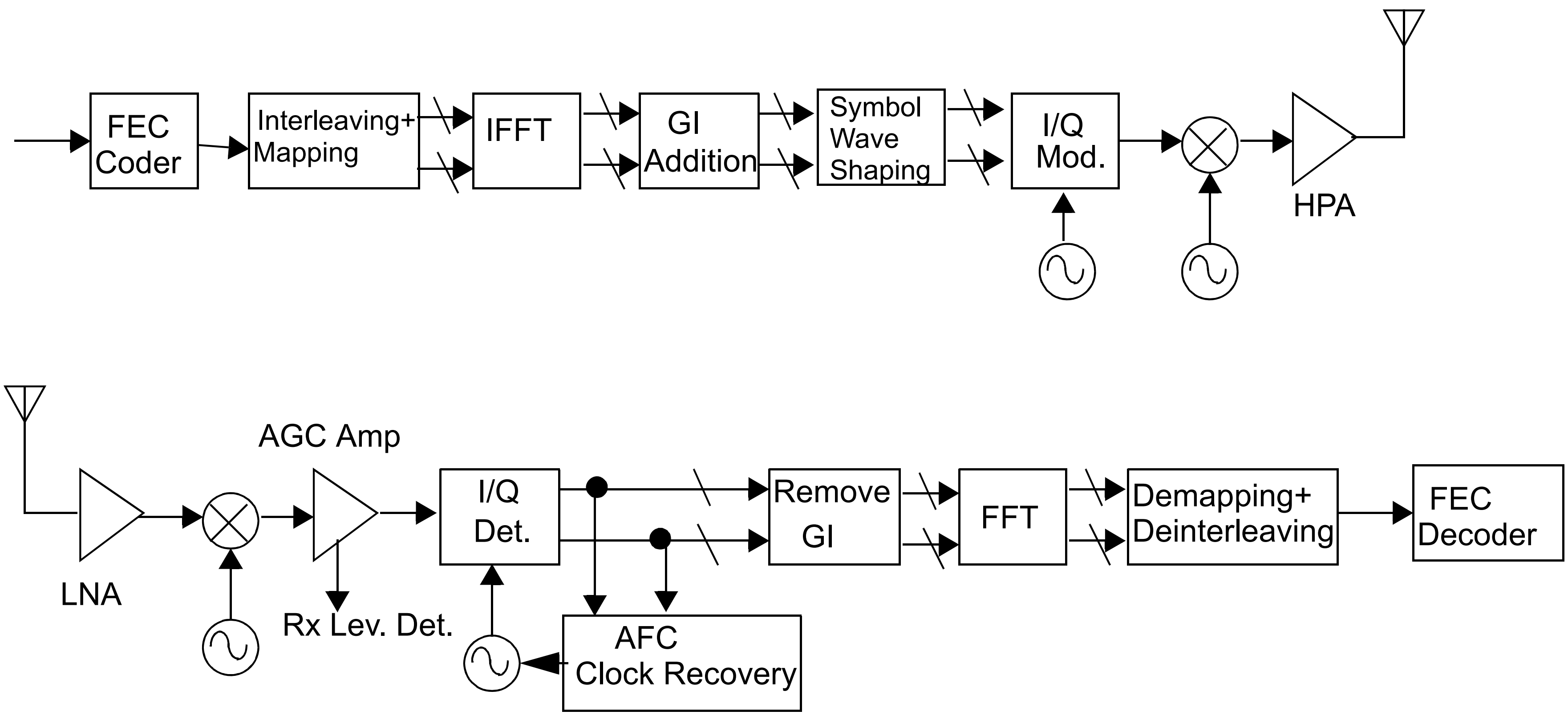
Bit-interleaved coded modulation

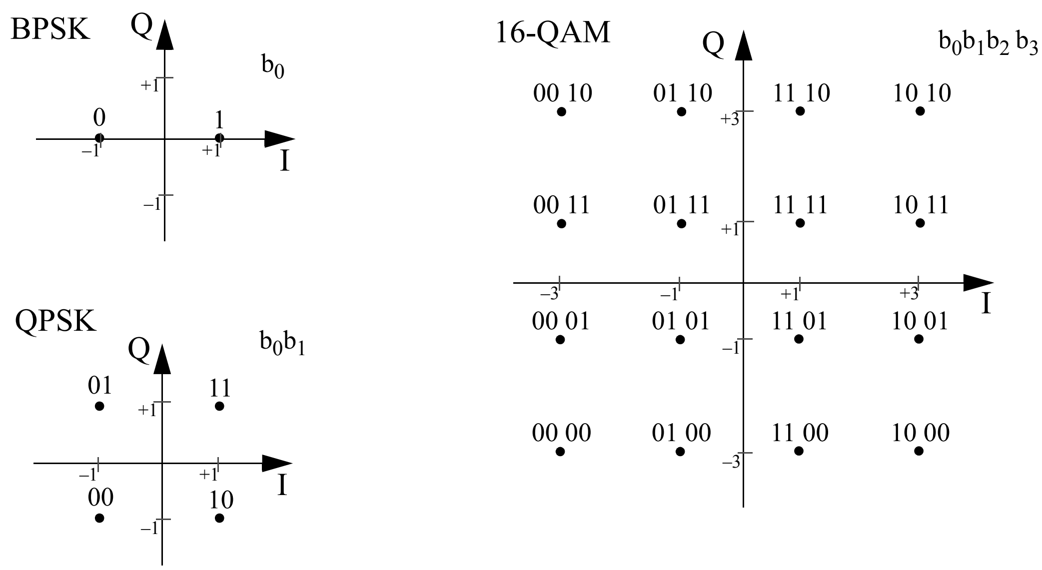


- ***Gray mapping*** of bits to *modulation symbols*
- Demapping to produce *binary metrics (LLR values)*
- Practically all IEEE 802 standards use it

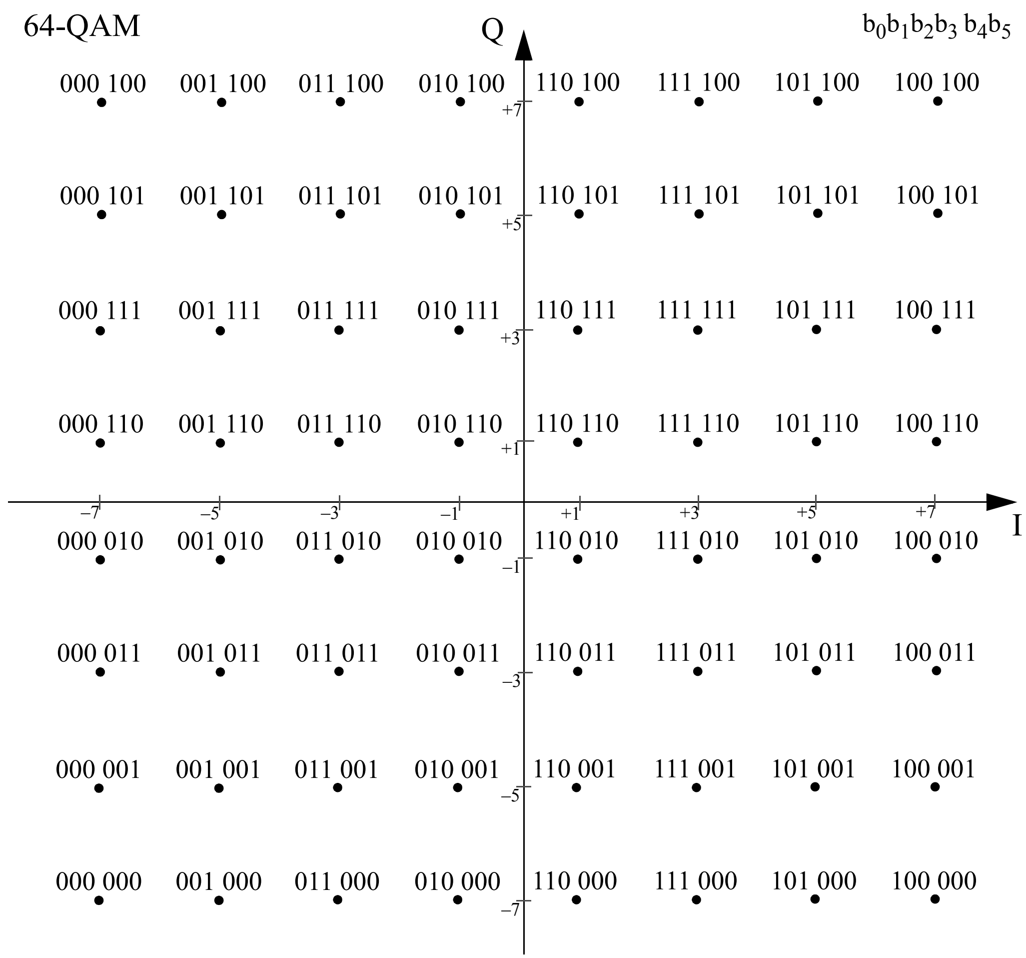
IEEE 802.11-2012



IEEE 802.11-2012: Constellations (1)



IEEE 802.11-2012: Constellations (2)



IEEE 802.11-2012: OFDM and Rates

Table 17-3—Modulation-dependent parameters

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

Permutation matrix

Table F-1—Matrix prototypes for codeword block length *n*=648 bits, subblock size is *Z* = 27 bits

(a) Coding rate R = 1/2.

0	-	-	-	0	0	-	-	0	-	-	0	1	0	-	-	-	-	-	-	-	-	-	-
22	0	-	-	17	-	0	0	12	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-
6	-	0	-	10	-	-	-	24	-	0	-	-	-	0	0	-	-	-	-	-	-	-	-
2	-	-	0	20	-	-	-	25	0	-	-	-	-	-	0	0	-	-	-	-	-	-	-
23	-	-	-	3	-	-	-	0	-	9	11	-	-	-	-	0	0	-	-	-	-	-	-
24	-	23	1	17	-	3	-	10	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-
25	-	-	-	8	-	-	-	7	18	-	-	0	-	-	-	-	-	0	0	-	-	-	-
13	24	-	-	0	-	8	-	6	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-
7	20	-	16	22	10	-	-	23	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-
11	-	-	-	19	-	-	-	13	-	3	17	-	-	-	-	-	-	-	-	-	0	0	-
25	-	8	-	23	18	-	14	9	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
3	-	-	-	16	-	-	2	25	5	-	-	1	-	-	-	-	-	-	-	-	-	-	0

(b) Coding rate R = 2/3.

25	26	14	-	20	-	2	-	4	-	-	8	-	16	-	18	1	0	-	-	-	-	-	-
10	9	15	11	-	0	-	1	-	-	18	-	8	-	10	-	-	0	0	-	-	-	-	-
16	2	20	26	21	-	6	-	1	26	-	7	-	-	-	-	-	-	0	0	-	-	-	-
10	13	5	0	-	3	-	7	-	-	26	-	-	13	-	16	-	-	-	0	0	-	-	-
23	14	24	-	12	-	19	-	17	-	-	-	20	-	21	-	0	-	-	-	0	0	-	-
6	22	9	20	-	25	-	17	-	8	-	14	-	18	-	-	-	-	-	-	-	0	0	-
14	23	21	11	20	-	24	-	18	-	19	-	-	-	-	22	-	-	-	-	-	-	0	0
17	11	11	20	-	21	-	26	-	3	-	-	18	-	26	-	1	-	-	-	-	-	-	0

(c) Coding rate R = 3/4.

16	17	22	24	9	3	14	-	4	2	7	-	26	-	2	-	21	-	1	0	-	-	-	-
25	12	12	3	3	26	6	21	-	15	22	-	15	-	4	-	-	16	-	0	0	-	-	-
25	18	26	16	22	23	9	-	0	-	4	-	4	-	8	23	11	-	-	-	0	0	-	-
9	7	0	1	17	-	-	7	3	-	3	23	-	16	-	-	21	-	0	-	-	0	0	-
24	5	26	7	1	-	-	15	24	15	-	8	-	13	-	13	-	11	-	-	-	-	0	0
2	2	19	14	24	1	15	19	-	21	-	2	-	24	-	3	-	2	1	-	-	-	-	0

(d) Coding rate R = 5/6.

17	13	8	21	9	3	18	12	10	0	4	15	19	2	5	10	26	19	13	13	1	0	-	-
3	12	11	14	11	25	5	18	0	9	2	26	26	10	24	7	14	20	4	2	-	0	0	-
22	16	4	3	10	21	12	5	21	14	19	5	-	8	5	18	11	5	5	15	0	-	0	0
7	7	14	14	4	16	16	24	24	10	1	7	15	6	10	26	8	18	21	14	1	-	-	0

Matrices de paridad

Permutation matrix example

- Z=27, p=22

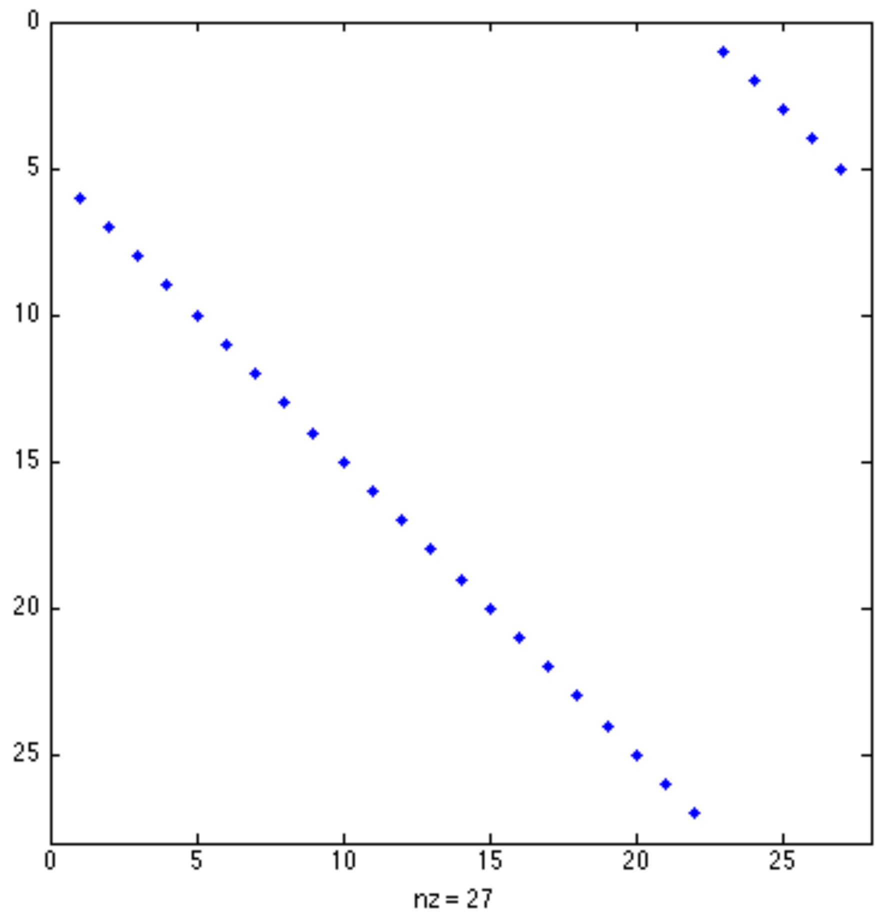


Table F-2—Matrix prototypes for codeword block length *n*=1296 bits, subblock size is *Z*= 54 bits

(a) Coding rate R = 1/2.

40	-	-	-	22	-	49	23	43	-	-	-	1	0	-	-	-	-	-	-	-	-	-	-
50	1	-	-	48	35	-	-	13	-	30	-	-	0	0	-	-	-	-	-	-	-	-	-
39	50	-	-	4	-	2	-	-	-	-	49	-	-	0	0	-	-	-	-	-	-	-	-
33	-	-	38	37	-	-	4	1	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-
45	-	-	-	0	22	-	-	20	42	-	-	-	-	-	-	0	0	-	-	-	-	-	-
51	-	-	48	35	-	-	-	44	-	18	-	-	-	-	-	-	0	0	-	-	-	-	-
47	11	-	-	-	17	-	-	51	-	-	-	0	-	-	-	-	-	0	0	-	-	-	-
5	-	25	-	6	-	45	-	13	40	-	-	-	-	-	-	-	-	-	0	0	-	-	-
33	-	-	34	24	-	-	-	23	-	-	46	-	-	-	-	-	-	-	-	0	0	-	-
1	-	27	-	1	-	-	-	38	-	44	-	-	-	-	-	-	-	-	-	-	0	0	-
-	18	-	-	23	-	-	8	0	35	-	-	-	-	-	-	-	-	-	-	-	-	0	0
49	-	17	-	30	-	-	-	34	-	-	19	1	-	-	-	-	-	-	-	-	-	-	0

(b) Coding rate R = 2/3.

39	31	22	43	-	40	4	-	11	-	-	50	-	-	-	6	1	0	-	-	-	-	-	-
25	52	41	2	6	-	14	-	34	-	-	-	24	-	37	-	-	0	0	-	-	-	-	-
43	31	29	0	21	-	28	-	-	2	-	-	7	-	17	-	-	-	0	0	-	-	-	-
20	33	48	-	4	13	-	26	-	-	22	-	-	46	42	-	-	-	-	0	0	-	-	-
45	7	18	51	12	25	-	-	-	50	-	-	5	-	-	-	0	-	-	-	0	0	-	-
35	40	32	16	5	-	-	18	-	-	43	51	-	32	-	-	-	-	-	-	-	0	0	-
9	24	13	22	28	-	-	37	-	-	25	-	-	52	-	13	-	-	-	-	-	-	0	0
32	22	4	21	16	-	-	-	27	28	-	38	-	-	-	8	1	-	-	-	-	-	-	0

(c) Coding rate R = 3/4.

39	40	51	41	3	29	8	36	-	14	-	6	-	33	-	11	-	4	1	0	-	-	-	-
48	21	47	9	48	35	51	-	38	-	28	-	34	-	50	-	50	-	-	0	0	-	-	-
30	39	28	42	50	39	5	17	-	6	-	18	-	20	-	15	-	40	-	-	0	0	-	-
29	0	1	43	36	30	47	-	49	-	47	-	3	-	35	-	34	-	0	-	-	0	0	-
1	32	11	23	10	44	12	7	-	48	-	4	-	9	-	17	-	16	-	-	-	-	0	0
13	7	15	47	23	16	47	-	43	-	29	-	52	-	2	-	53	-	1	-	-	-	-	0

(d) Coding rate R = 5/6.

48	29	37	52	2	16	6	14	53	31	34	5	18	42	53	31	45	-	46	52	1	0	-	-
17	4	30	7	43	11	24	6	14	21	6	39	17	40	47	7	15	41	19	-	-	0	0	-
7	2	51	31	46	23	16	11	53	40	10	7	46	53	33	35	-	25	35	38	0	-	0	0
19	48	41	1	10	7	36	47	5	29	52	52	31	10	26	6	3	2	-	51	1	-	-	0

Table F-3—Matrix prototypes for codeword block length *n*=1944 bits, subblock size is *Z* = 81 bits

(a) Coding rate R = 1/2.

57	-	-	-	50	-	11	-	50	-	79	-	1	0	-	-	-	-	-	-	-	-	-	-
3	-	28	-	0	-	-	-	55	7	-	-	-	0	0	-	-	-	-	-	-	-	-	-
30	-	-	-	24	37	-	-	56	14	-	-	-	-	0	0	-	-	-	-	-	-	-	-
62	53	-	-	53	-	-	3	35	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-
40	-	-	20	66	-	-	22	28	-	-	-	-	-	-	-	0	0	-	-	-	-	-	-
0	-	-	-	8	-	42	-	50	-	-	8	-	-	-	-	-	0	0	-	-	-	-	-
69	79	79	-	-	-	56	-	52	-	-	-	0	-	-	-	-	-	0	0	-	-	-	-
65	-	-	-	38	57	-	-	72	-	27	-	-	-	-	-	-	-	-	0	0	-	-	-
64	-	-	-	14	52	-	-	30	-	-	32	-	-	-	-	-	-	-	-	0	0	-	-
-	45	-	70	0	-	-	-	77	9	-	-	-	-	-	-	-	-	-	-	-	0	0	-
2	56	-	57	35	-	-	-	-	-	12	-	-	-	-	-	-	-	-	-	-	-	0	0
24	-	61	-	60	-	-	27	51	-	-	16	1	-	-	-	-	-	-	-	-	-	-	0

(b) Coding rate R = 2/3.

61	75	4	63	56	-	-	-	-	-	-	8	-	2	17	25	1	0	-	-	-	-	-	-
56	74	77	20	-	-	-	64	24	4	67	-	7	-	-	-	-	0	0	-	-	-	-	-
28	21	68	10	7	14	65	-	-	-	23	-	-	-	75	-	-	-	0	0	-	-	-	-
48	38	43	78	76	-	-	-	-	5	36	-	15	72	-	-	-	-	-	0	0	-	-	-
40	2	53	25	-	52	62	-	20	-	-	44	-	-	-	-	0	-	-	-	0	0	-	-
69	23	64	10	22	-	21	-	-	-	-	-	68	23	29	-	-	-	-	-	-	0	0	-
12	0	68	20	55	61	-	40	-	-	-	52	-	-	-	44	-	-	-	-	-	-	0	0
58	8	34	64	78	-	-	11	78	24	-	-	-	-	-	58	1	-	-	-	-	-	-	0

(c) Coding rate R = 3/4.

48	29	28	39	9	61	-	-	-	63	45	80	-	-	-	37	32	22	1	0	-	-	-	-
4	49	42	48	11	30	-	-	-	49	17	41	37	15	-	54	-	-	-	0	0	-	-	-
35	76	78	51	37	35	21	-	17	64	-	-	-	59	7	-	-	32	-	-	0	0	-	-
9	65	44	9	54	56	73	34	42	-	-	-	35	-	-	-	46	39	0	-	-	0	0	-
3	62	7	80	68	26	-	80	55	-	36	-	26	-	9	-	72	-	-	-	-	-	0	0
26	75	33	21	69	59	3	38	-	-	-	35	-	62	36	26	-	-	1	-	-	-	-	0

(d) Coding rate R = 5/6.

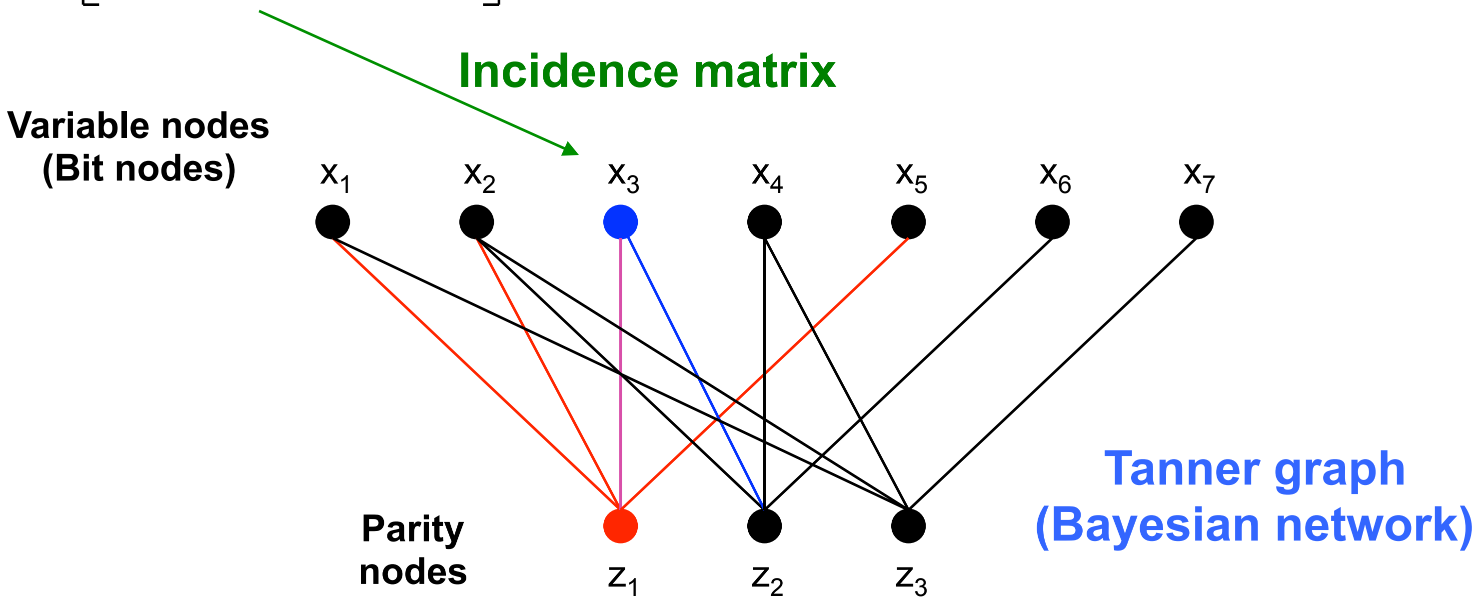
13	48	80	66	4	74	7	30	76	52	37	60	-	49	73	31	74	73	23	-	1	0	-	-
69	63	74	56	64	77	57	65	6	16	51	-	64	-	68	9	48	62	54	27	-	0	0	-
51	15	0	80	24	25	42	54	44	71	71	9	67	35	-	58	-	29	-	53	0	-	0	0
16	29	36	41	44	56	59	37	50	24	-	65	4	65	52	-	4	-	73	52	1	-	-	0

The parity-check matrix interpreted as the incidence matrix of a graph

<u>Example</u>: Hamming (7,4,3) code

Parity-check matrix | **Parity-check equations (syndromes)**

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \Longrightarrow \begin{array}{l} z_1 = x_1 + x_2 + x_3 + x_5 \\ z_2 = x_2 + x_3 + x_4 + x_6 \\ z_3 = x_1 + x_2 + x_4 + x_7 \end{array}$$



Iterative decoding of LDPC codes using Tanner graph

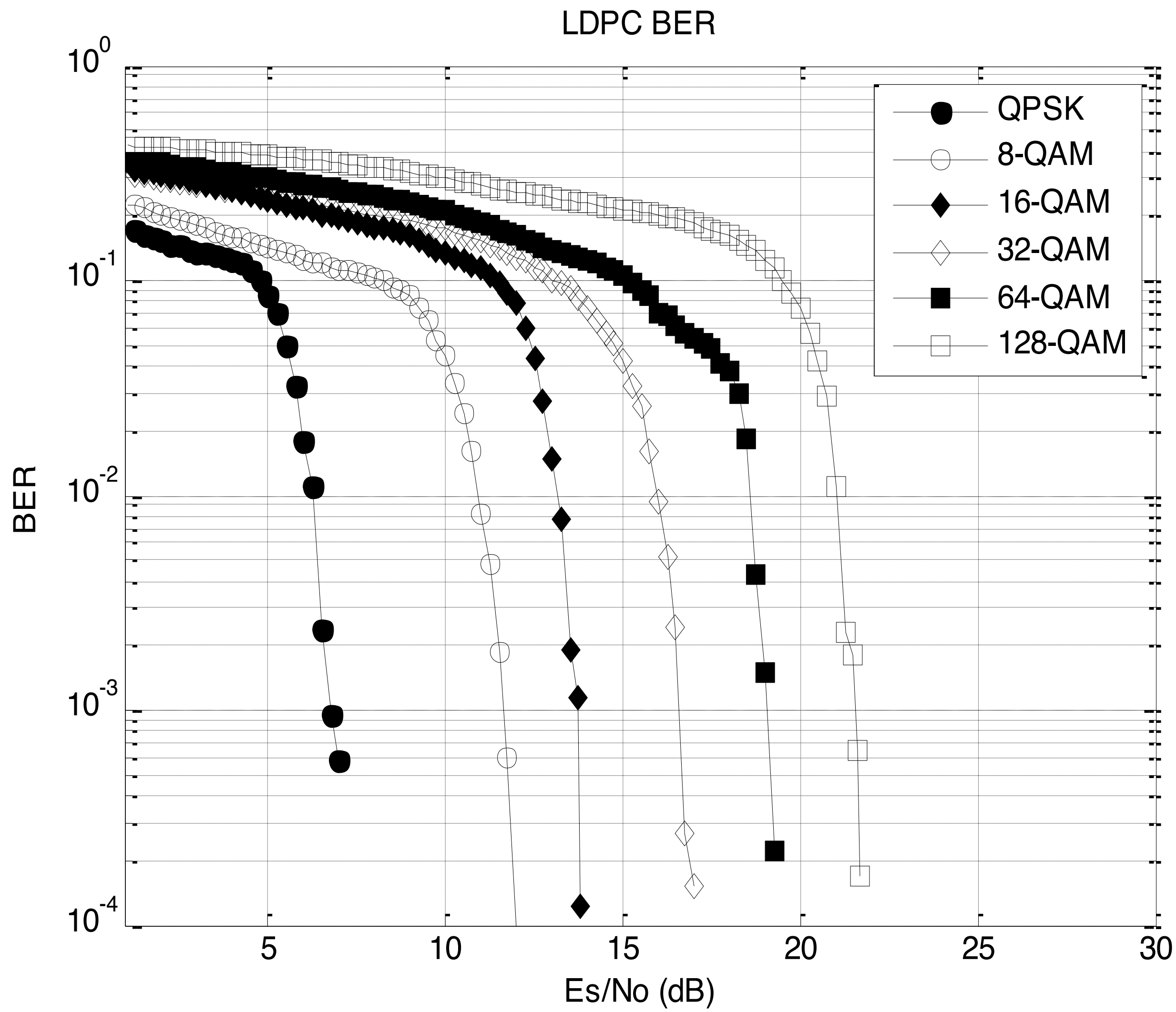
- Hard-decision

  Preliminary ("hard") decisions: ***bit-flip***

- Soft-decision

  Channel outputs (matched filter): ***belief propagation***

More constellations: Illustration using binary (273,191,17) EG code



Add 8-, 32- and 128-QAM to the mix !!

IEEE 802.11n-2009: Code rates

Table 20-21—Allowed relative constellation error versus constellation size and coding rate

Modulation	Coding rate	Relative constellation error (dB)
BPSK	1/2	–5
QPSK	1/2	–10
QPSK	3/4	–13
16-QAM	1/2	–16
16-QAM	3/4	–19
64-QAM	2/3	–22
64-QAM	3/4	–25
64-QAM	5/6	–28

IEEE 802.11n: Space-Time Block Coding

Table 20-17—Constellation mapper output to spatial mapper input for STBC

N_{STS}	HT-SIG MCS field (bits 0–6 in HT-SIG$_1$)	N_{SS}	HT-SIG STBC field (bits 4–5 in HT-SIG$_2$)	i_{STS}	$\tilde{d}_{k,i,2m}$	$\tilde{d}_{k,i,2m+1}$
2	0–7	1	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
3	8–15, 33–38	2	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$
4	8–15	2	2	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$
				4	$-d^*_{k,2,2m+1}$	$d^*_{k,2,2m}$
4	16–23, 39, 41, 43, 46, 48, 50	3	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$
				4	$d_{k,3,2m}$	$d_{k,3,2m+1}$

802.11ad-2012: OFDM

Table 21-14—Modulation and coding scheme for OFDM

MCS index	Modulation	Code rate	N_{BPSC}	N_{CBPS}	N_{DBPS}	Data rate (Mbps)
13	SQPSK	1/2	1	336	168	693.00
14	SQPSK	5/8	1	336	210	866.25
15	QPSK	1/2	2	672	336	1386.00
16	QPSK	5/8	2	672	420	1732.50
17	QPSK	3/4	2	672	504	2079.00
18	16-QAM	1/2	4	1344	672	2772.00
19	16-QAM	5/8	4	1344	840	3465.00
20	16-QAM	3/4	4	1344	1008	4158.00
21	16-QAM	13/16	4	1344	1092	4504.50
22	64-QAM	5/8	6	2016	1260	5197.50
23	64-QAM	3/4	6	2016	1512	6237.00
24	64-QAM	13/16	6	2016	1638	6756.75

802.11ad-2012: LDPC codes (1)

- **Rate 1/2:**

N = 16x42 = 672
N-K = 8x42 = 336

K = 336

21.3.8.2 Rate-1/2 LDPC code matrix H = 336 rows x 672 columns, Z = 42

Table 21-6—Rate 1/2 LDPC code matrix
(Each nonblank element i in the table is the cyclic permutation matrix P_i of size $Z \times Z$; blank entries represent the zero matrix of size $Z \times Z$)

40		38		13		5		18							
34		35		27			30	2	1						
	36		31		7		34		10	41					
	27		18		12	20				15	6				
35		41		40		39		28			3	28			
29		0			22		4		28		27		23		
	31		23		21		20			12			0	13	
	22		34	31		14		4				13		22	24

802.11ad-2012: LDPC codes (2)

- **Rate 5/8:**

N = 16x42 = 672
N-K = 6x42 = 252

K = 420

21.3.8.3 Rate-5/8 LDPC code matrix H = 252 rows x 672 columns, Z = 42

Table 21-7—Rate 5/8 LDPC code matrix
(Each nonblank element i in the table is the cyclic permutation matrix P_i of size $Z \times Z$; blank entries represent the zero matrix of size $Z \times Z$)

20	36	34	31	20	7	41	34		10	41					
30	27		18		12	20	14	2	25	15	6				
35		41		40		39		28			3	28			
29		0			22		4		28		27	24	23		
	31		23		21		20		9	12			0	13	
	22		34	31		14		4						22	24

802.11ad-2012: LDPC codes (3)

- **Rate 3/4:**

N = 16x42 = 672
N-K = 4x42 = 168
K = 504

21.3.8.4 Rate-3/4 LDPC code matrix H = 168 rows x 672 columns, Z = 42

Table 21-8—Rate 3/4 LPDC code matrix
(Each nonblank element i in the table is the cyclic permutation matrix P_i of size $Z \times Z$; blank entries represent the zero matrix of size $Z \times Z$)

35	19	41	22	40	41	39	6	28	18	17	3	28			
29	30	0	8	33	22	17	4	27	28	20	27	24	23		
37	31	18	23	11	21	6	20	32	9	12	29		0	13	
25	22	4	34	31	3	14	15	4		14	18	13	13	22	24

802.11ad-2012: LDPC codes (4)

- **Rate 13/16:**

N = 16x42 = 672
N-K = 3x42 = 126
K = 546

21.3.8.5 Rate-13/16 LDPC code matrix H = 126 rows x 672 columns, Z = 42

Table 21-9—Rate 13/16 LDPC code matrix
(Each nonblank element i in the table is the cyclic permutation matrix P_i of size $Z \times Z$; blank entries represent the zero matrix of size $Z \times Z$)

29	30	0	8	33	22	17	4	27	28	20	27	24	23		
37	31	18	23	11	21	6	20	32	9	12	29	10	0	13	
25	22	4	34	31	3	14	15	4	2	14	18	13	13	22	24

802.11ad-2012: Single-Carrier (1)

Table 21-18—Modulation and coding scheme for SC

MCS index	Modulation	N_{CBPS}	Repetition	Code rate	Data rate (Mbps)
1	π/2-BPSK	1	2	1/2	385
2	π/2-BPSK	1	1	1/2	770
3	π/2-BPSK	1	1	5/8	962.5
4	π/2-BPSK	1	1	3/4	1155
5	π/2-BPSK	1	1	13/16	1251.25
6	π/2-QPSK	2	1	1/2	1540
7	π/2-QPSK	2	1	5/8	1925
8	π/2-QPSK	2	1	3/4	2310
9	π/2-QPSK	2	1	13/16	2502.5
10	π/2-16QAM	4	1	1/2	3080
11	π/2-16QAM	4	1	5/8	3850
12	π/2-16QAM	4	1	3/4	4620

802.11ad-2012: Single-Carrier (2)

Table 21-19—LDPC code rates

Code rate	Codeword size	Number of data bits
1/2	672	336
5/8	672	420
3/4	672	504
13/16	672	546

Table 21-22—Low-power SC modulation and coding schemes

MCS	Modulation	Effective code rate	Coding scheme	N_{CPB}	Rate (Mbps)
25	π/2-BPSK	13/28	RS(224,208)+Block-Code(16,8)	392	626
26	π/2-BPSK	13/21	RS(224,208)+Block-Code(12,8)	392	834
27	π/2-BPSK	52/63	RS(224,208)+SPC(9,8)	392	1112
28	π/2-QPSK	13/28	RS(224,208)+Block-Code(16,8)	392	1251
29	π/2-QPSK	13/21	RS(224,208)+Block-Code(12,8)	392	1668
30	π/2-QPSK	52/63	RS(224,208)+SPC(9,8)	392	2224
31	π/2-QPSK	13/14	RS(224,208)+Block-Code(8,8)	392	2503

IEEE 802.15.3c-2009: Code Rates

Table 103—MCS dependent parameters

MCS class	MCS identifier	Data rate (Mb/s) with pilot word length = 0	Data rate (Mb/s) with pilot word length = 64	Modulation	Spreading factor, L_{SF}	FEC type
Class1	0	25.8 (CMS)	—	π/2 BPSK/(G)MSK[a]	64	RS(255,239)
	1	412	361		4	
	2	825	722		2	
	3	1650 (MPR)	1440		1	
	4	1320	1160	π/2 BPSK/(G)MSK	1	LDPC(672,504)
	5	440	385	π/2 BPSK/(G)MSK	2	LDPC(672,336)
	6	880	770		1	
Class2	7	1760	1540	π/2 QPSK	1	LDPC(672,336)
	8	2640	2310	π/2 QPSK	1	LDPC(672,504)
	9	3080	2700	π/2 QPSK	1	LDPC(672,588)
	10	3290	2870	π/2 QPSK	1	LDPC(1440,1344)
	11	3300	2890	π/2 QPSK	1	RS(255,239)
Class3	12	3960	3470	π/2 8-PSK	1	LDPC(672,504)
	13	5280	4620	π/2 16-QAM	1	LDPC(672,504)

IEEE 802.15.3c-2009: Unequal Error Protection !!

12.4 Audio/Visual mode of mmWave PHY

The Audio/Visual (AV) PHY is implemented with two PHY modes, the high-rate PHY (HRP) and low-rate PHY (LRP), both of which use orthogonal frequency domain multiplexing (OFDM). The data rates supported by the HRP are defined in Table 134.

Table 134—HRP data rates and coding

HRP mode index	Coding mode	Modulation	Inner code rate		Data rate (Gb/s)
			MSB [7] [6] [5] [4]	LSB [3] [2] [1] [0]	
0	EEP	QPSK	1/3		0.952
1		QPSK	2/3		1.904
2		16-QAM	2/3		3.807
3	UEP	QPSK	4/7	4/5	1.904
4		16-QAM	4/7	4/5	3.807
5	MSB-only retransmission	QPSK	1/3	N/A	0.952
6		QPSK	2/3	N/A	1.904

IEEE 802.15.7-2011: OOK and PPM (1)

Table 73—PHY I operating modes

Modulation	RLL code	Optical clock rate	FEC		Data rate
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67 kb/s
			(15,11)	1/3	24.44 kb/s
			(15,11)	2/3	48.89 kb/s
			(15,11)	none	73.3 kb/s
			none	none	100 kb/s
VPPM	4B6B	400 kHz	(15,2)	none	35.56 kb/s
			(15,4)	none	71.11 kb/s
			(15,7)	none	124.4 kb/s
			none	none	266.6 kb/s

IEEE 802.15.7-2011: OOK and PPM (2)

Table 74—PHY II operating modes

Modulation	RLL code	Optical clock rate	FEC	Data rate
VPPM	4B6B	3.75 MHz	RS(64,32)	1.25 Mb/s
			RS(160,128)	2 Mb/s
		7.5 MHz	RS(64,32)	2.5 Mb/s
			RS(160,128)	4 Mb/s
			none	5 Mb/s
OOK	8B10B	15 MHz	RS(64,32)	6 Mb/s
			RS(160,128)	9.6 Mb/s
		30 MHz	RS(64,32)	12 Mb/s
			RS(160,128)	19.2 Mb/s
		60 MHz	RS(64,32)	24 Mb/s
			RS(160,128)	38.4 Mb/s
		120 MHz	RS(64,32)	48 Mb/s
			RS(160,128)	76.8 Mb/s
			none	96 Mb/s

IEEE 802.15.7-2011: CSK (Color-Shift Keying)

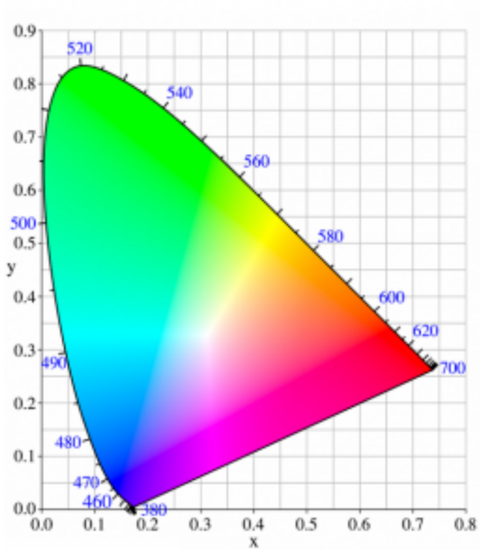
Table 75—PHY III operating modes

Modulation	Optical clock rate	FEC	Data rate
4-CSK	12 MHz	RS(64,32)	12 Mb/s
8-CSK		RS(64,32)	18 Mb/s
4-CSK	24 MHz	RS(64,32)	24 Mb/s
8-CSK		RS(64,32)	36 Mb/s
16-CSK		RS(64,32)	48 Mb/s
8-CSK		none	72 Mb/s
16-CSK		none	96 Mb/s

IEEE 802.15.7-2011: Colors

Table 106—*xy* color coordinates

Band (nm)	Code	Center (nm)	(*x*, *y*)
380–478	000	429	(0.169, 0.007)
478–540	001	509	(0.011, 0.733)
540–588	010	564	(0.402, 0.597)
588–633	011	611	(0.669, 0.331)
633–679	100	656	(0.729, 0.271)
679–726	101	703	(0.734, 0.265)
726–780	110	753	(0.734, 0.265)



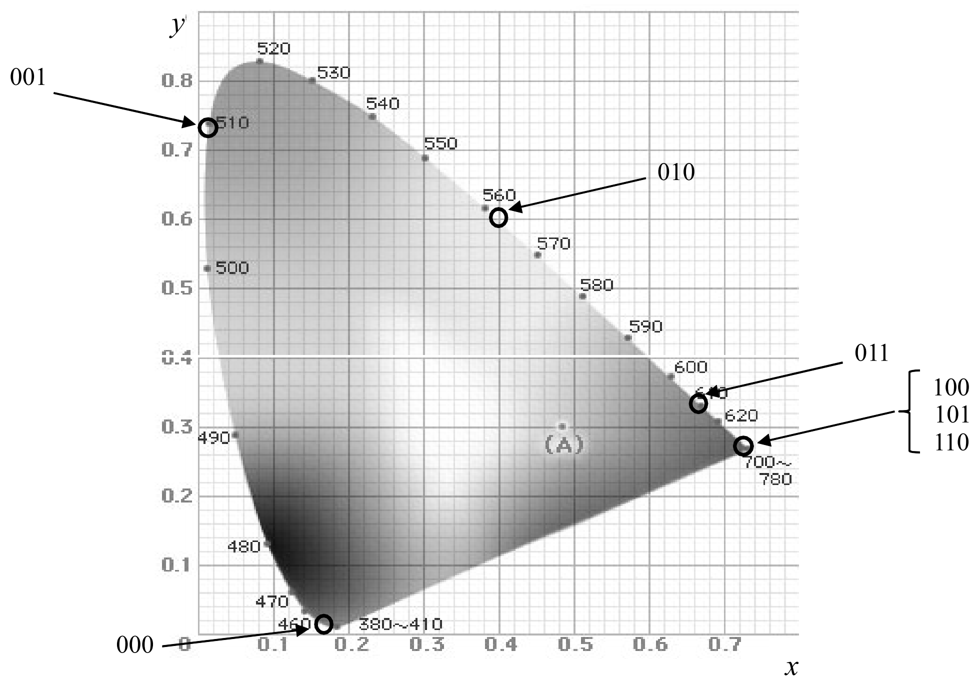


Figure 137—Center of color bands on *xy* color coordinates

IEEE 802.16-2009: Alamouti (STBC)

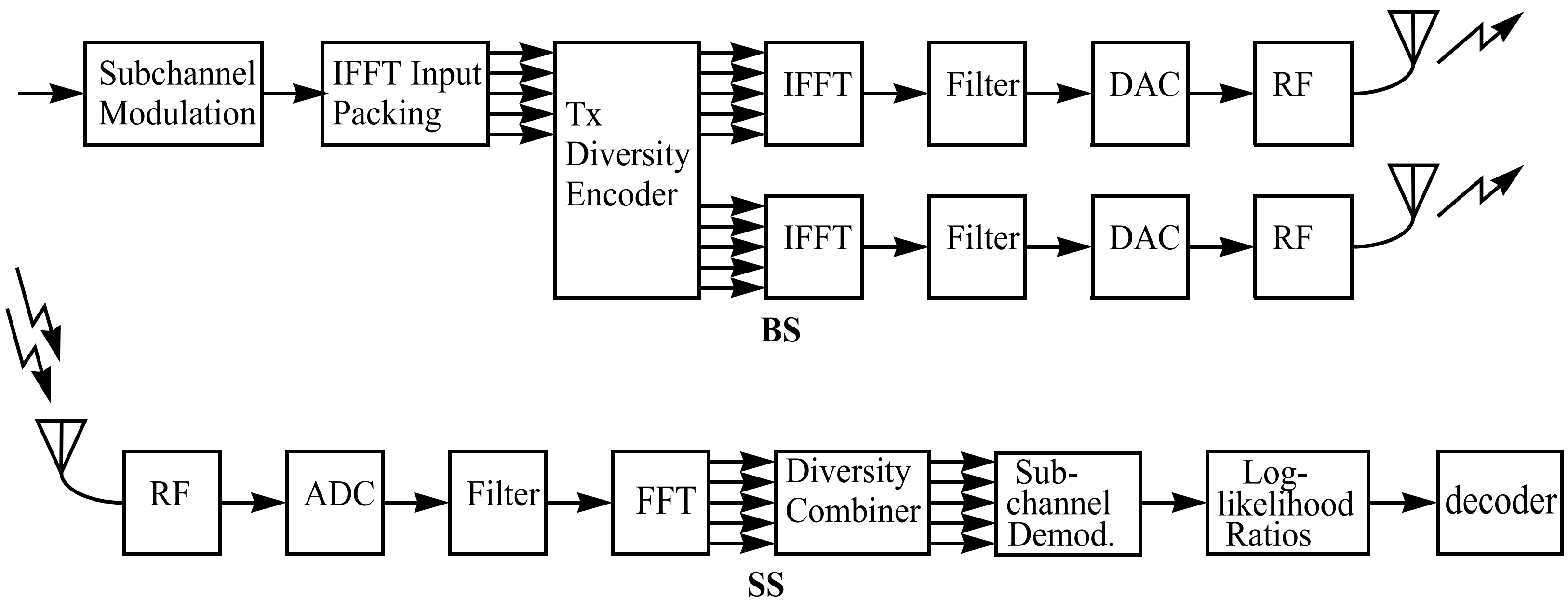


Figure 259—Illustration of STC

IEEE 802.20-2008: Modulations

Table 434—Modulation and coding rates

ModClass	Bits/Sym	Signal Set	Puncture	Shaper	Block Code
0	0.5	π/2 BPSK	Repeat	—	—
1	0.67	π/2 BPSK	1 of 4	—	—
2	1	QPSK	—	—	—
3	1.5	QPSK	2 of 6	—	—
4	2	8-PSK	—	—	(64,57)
5	2.5	8-PSK	—	—	(64,57)
6	3	12-QAM	2 of 6	3/4	(48,47)
7	3.5	16-QAM	2 of 6	4/4	(64,63)
8	4	24-QAM	2 of 6	5/4	(80,79)
9	4.5	32-QAM	2 of 6	5/5	(80,79)
10	5.5	64-QAM	2 of 5	6/6	(80,79)
11–15	RESERVED				

References

[1] IEEE 802 Part 3: Carrier sense multiple access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications, IEEE Computer Society, 2008.

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[4] IEEE 802 Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) – Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension, 2009

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[8] IEEE 802 Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands, IEEE Computer Society, 2011.

GRACIAS!

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