Short introduction to OFDM

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Abstract

We provide hereafter some notions on OFDM wireless transmissions. Any comments should be sent to: Mérouane Debbah, Alcatel-Lucent Chair on Flexible Radio, Supelec, 3 rue Joliot-Curie 91192 GIF SUR YVETTE CEDEX, France, merouane.debbah@supelec.fr.

I. INTRODUCTION

Recently, a worldwide convergence has occurred for the use of *Orthogonal Frequency Division Multiplexing* (OFDM) as an emerging technology for high data rates. In particular, many wireless standards (Wi-Max, IEEE802.11a, LTE, DVB) have adopted the OFDM technology as a mean to increase dramatically future wireless communications. OFDM is a particular form of Multi-carrier transmission and is suited for frequency selective channels and high data rates. This technique transforms a frequency-selective wide-band channel into a group of non-selective narrowband channels, which makes it robust against large delay spreads by preserving orthogonality in the frequency domain. Moreover, the ingenious introduction of cyclic redundancy at the transmitter reduces the complexity to only FFT processing and one tap scalar equalization at the receiver[1]

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II. OFDM PRINCIPLE

In this section, we will focus on the baseband discrete-time representation of OFDM. For a more general presentation based on orthogonal transmultiplexers or block precoding issues, the reader can refer to [**?**], [1], [2].
The history of multi-carrier modulation began more then 30 years ago. At the beginning, only analog design based on the use of orthogonal waveforms was proposed [3]. The use of discrete Fourier Transform (DFT) for modulation and demodulation was first proposed in [4]. Only recently has it been finding its way into commercial use, as the recent developments in technology have lowered the cost of the signal processing that is needed to implement OFDM systems [5], [6], [7].

In this section, we first give a brief overview of frequency selective channels [8], [9]
Let $r(t)$ be the low-pass received signal:

$$r(t) = \int_{-\infty}^{\infty} c(\tau)x(t-\tau)d\tau + n(t). \tag{1}$$

Frequency selectivity occurs whenever the transmitted signal $x(t)$ occupies an interval bandwidth $[-\frac{W}{2}, \frac{W}{2}]$ greater then the coherence bandwidth B_{coh} of the channel $c(t)$ (defined as the inverse of the delay spread T_d [8]). In this case, the frequency components of $x(t)$ with frequency separation exceeding B_{coh} are subject to different gains.

Fig II presents a typical time impulse response $c(t)$ of a channel. For usual high data rates schemes, the symbol rate T is small compared to T_d (they are also called broadband signals) and the signals are therefore subject to frequency selectivity.

The multipath-channel can be modeled by an impulse response given by $c(t) = \sum_{l=0}^{M-1} \lambda_l g(t-\tau_l)$ where $g(t)$ is transmitting filter and T_d is the duration of the multipath or delay spread. Here, the complex gains $(\lambda_l)_{l=0,\ldots,M-1}$ are the multi-path gains and the $(\tau_l)_{l=0,\ldots,(M-1)}$ are the corresponding time delays. The variance of each gain as well as the time delays are usually determined form propagation measurements. As a typical example, we give in table I and table II provide the delay profile of indoor channels A and E. Let W denote the signal bandwidth and $T = \frac{1}{W}$ the sampling rate. We will assume hereafter that the transmitting filter is supposed to be ideal ($G(f) = 1$ for $f \in [-\frac{W}{2}, \frac{W}{2}]$ and 0 outside, $G(f)$ being the Fourier transform of the transmitting filter $g(t)$).

[1]The invention of OFDM in its present form is still not clear. To the author's knowledge, the first patent is due to Tristan de Couasnon with the patent W09004893 in 1989 which introduces the guard interval.

Tap Number	Delay (ns)	Average Relative Power (dB)
1	0	0
2	10	-0.9
3	20	-1.7
4	30	-2.6
5	40	-3.5
6	50	-4.3
7	60	-5.2
8	70	-6.1
9	80	-6.9
10	90	-7.8
11	110	-4.7
12	140	-7.3
13	170	-9.9
14	200	-12.5
15	240	-13.7
16	290	-18.0
17	340	-22.4
18	390	-26.7

TABLE I

MODEL A, CORRESPONDING TO A TYPICAL OFFICE ENVIRONMENT FOR NLOS CONDITIONS.

Tap Number	Delay (ns)	Average Relative Power (dB)
1	0	-4.9
2	10	-5.1
3	20	-5.2
4	40	-0.8
5	70	-1.3
6	100	-1.9
7	140	-0.3
8	190	-1.2
9	240	-2.1
10	320	-0.0
11	430	-1.9
12	560	-2.8
13	710	-5.4
14	880	-7.3
15	1070	-10.6
16	1280	-13.4
17	1510	-17.4
18	1760	-20.9

TABLE II

MODEL E, CORRESPONDING TO A TYPICAL LARGE OPEN SPACE ENVIRONMENT FOR NLOS CONDITIONS.

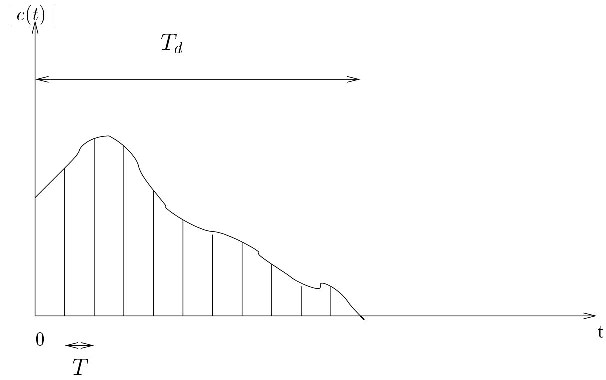

Fig. 1. Multi-path channel.

One of the main concerns in transmissions schemes is to retrieve $x(t)$ from eq (1). This operation is called equalization and the difficulty of extracting $x(t)$ is mostly due to the frequency selectivity behavior of the channel (with $c(t) = \delta(t)$ where $\delta(t)$ is the Dirac distribution, no equalization is required!). Moreover, the equalization task is all the more difficult to implement that the complexity of an equalizer grows with the channel memory. Therefore, the cost (in terms of complexity and power consumption) of such an equalizer could be prohibitively too high, especially in the case of high data rates communications. The main idea of OFDM transmissions is to turn the channel convolutional effect of equation (1) into a multiplicative one in order to simplify the equalization task. To this end, OFDM schemes add redundancy known as cyclic prefix in a clever manner in order to circularize the channel effect. Based on the fact that circular convolution can be diagonalized in an FFT basis [10], the multi-path time domain channel is transformed into a set of parallel frequency flat fading channels. Moreover, OFDM systems take benefit from the low cost implementation structure of digital FFT modulators[2]. All these advantages make OFDM particularly suited for frequency selective channels.

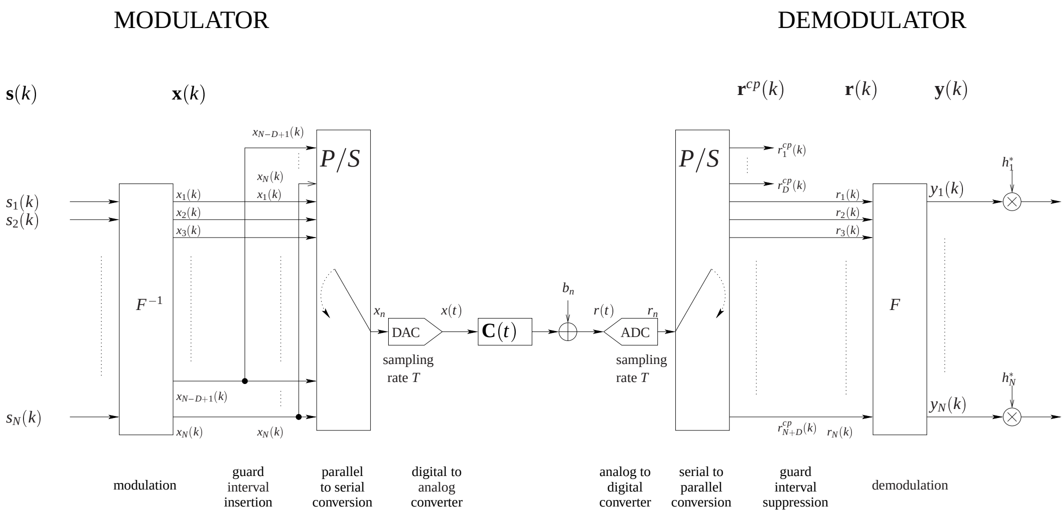

Fig. 2. OFDM model.

Let us now focus on the conventional OFDM transceiver depicted in fig.II. As a starting point, we will consider the noiseless transmission case. The incoming high rate information is split onto N rate sub-carriers . The data is therefore transmitted by blocks of size N: $\mathbf{s(k)} = [s_1(k), \ldots, s_i(k), \ldots, s_N(k)]$ where the index k is the block OFDM symbol number and the subscript i is for the carrier index. The block OFDM symbol

[2]The reader should note that other schemes based on block redundant precoding are also able to circularize the linear convolution (zero-padded OFDM [11], pseudo-random cyclic prefix [**?**])

is precoded by an inverse FFT matrix $\mathbf{F}_N^H = \mathbf{F}_N^{-1}$ to yield the so-called time domain block vector $\mathbf{x}(\mathbf{k}) = [x_1(k), \ldots, x_i(k), \ldots, x_N(k)]$. At the output of the IFFT, a guard interval of D samples is inserted at the beginning of each block $[x_{N-D+1}(k), \ldots, x_N(k), x_1(k), \ldots, x_i(k), \ldots, x_N(k)]$. It consists of a cyclic extension of the time domain OFDM symbol of size larger than the channel impulse response ($D > L-1$). The cyclic prefix (CP) is appended between each block in order to transform the multipath linear convolution into a circular one. After Parallel to Serial (P/S) and Digital to Analog Conversion (ADC), the signal is sent through a frequency-selective channel.

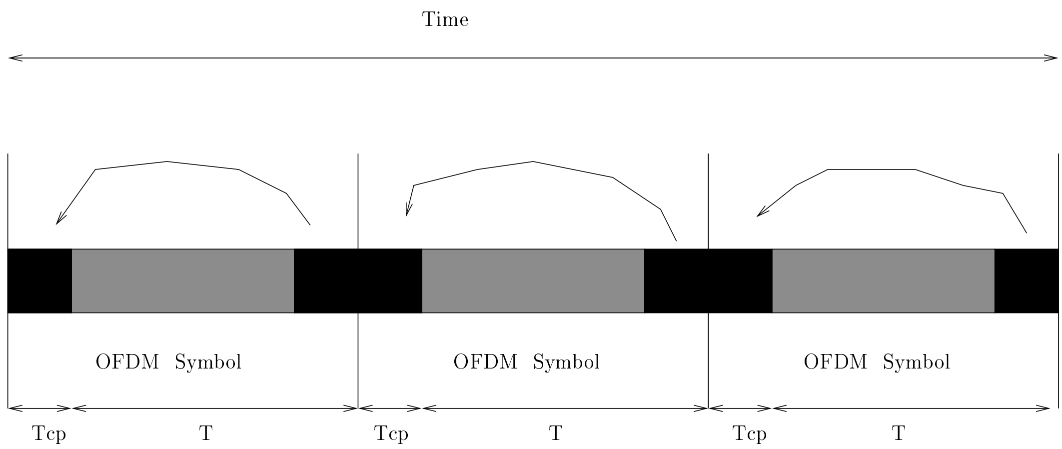

Fig. 3. time representation of OFDM.

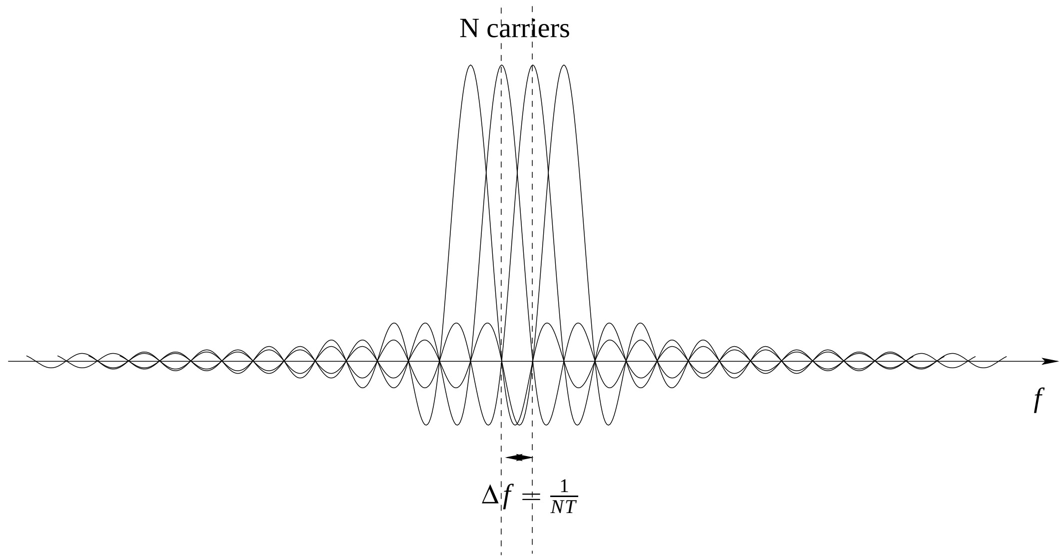

Fig. 4. Frequency representation of OFDM.

The channel can be represented by an equivalent discrete time model and its effects can be modeled by a linear Finite Impulse Response (FIR) filtering with Channel Impulse Response $\mathbf{c}_N = [c_1, \ldots, c_{L-1}, 0, \ldots, 0]$. Usually, the system is designed so that D is smaller than N (D=$\frac{N}{4}$) and greater than $(L-1)$. One can notice that the redundancy factor is equal to $\frac{N}{N+D}$. On the one hand, in order to avoid spectrally inefficient transmissions, N has to be chosen far greater than D ($\lim_{N\to\infty} \frac{N}{N+D} = 1$: for a fixed D, the redundancy factor tends to 1 as the the number of carriers increases). On the other hand, the FFT complexity per carrier grows with the size of N. Moreover, the channel should not change inside one OFDM symbol to be able to circularize the convolution. Finally, the carrier spacing is related to the factor $\frac{1}{NT}$ and reduces as N increases: there is no gain in terms of diversity for a fixed channel by increasing N. The choice of N depends therefore on the type of channel (slow

varying, fast fading, high diversity channel, impulse response length...) and the complexity cost one is able to accept.
At the receiver, symmetrical operations are performed: down conversion, Analog to Digital Conversion (ADC). The discrete time received signal with guard interval $\mathbf{r^{CP}}$ has therefore the following expression:

$$\mathbf{r^{CP}} = \begin{bmatrix} {r^{CP}}_1(k) \\ {r^{CP}}_2(k) \\ \vdots \\ \vdots \\ \vdots \\ {r^{CP}}_{N+D}(k) \end{bmatrix}_{(N+D)\times 1} = \mathbf{H}_{\text{ISI}} \begin{bmatrix} x_{N-D+1}(k) \\ \vdots \\ x_N(k) \\ x_1(k) \\ \vdots \\ x_N(k) \end{bmatrix}_{(N+D)\times 1} + \mathbf{H}_{\text{IBI}} \begin{bmatrix} x_{N-D+1}(k-1) \\ \vdots \\ x_N(k-1) \\ x_1(k-1) \\ \vdots \\ x_N(k-1) \end{bmatrix}_{(N+D)\times 1}$$

with

$$\mathbf{H}_{\text{ISI}} = \begin{bmatrix} c_0 & 0 & \cdots & \cdots & \cdots & 0 \\ \vdots & \ddots & \ddots & & & \vdots \\ c_{L-1} & & \ddots & \ddots & & \vdots \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & c_{L-1} & \cdots & c_0 \end{bmatrix}_{(N+D)\times(N+D)} \qquad \mathbf{H}_{\text{IBI}} = \begin{bmatrix} 0 & \cdots & 0 & c_{L-1} & \cdots & c_1 \\ \vdots & \ddots & & \ddots & \ddots & \vdots \\ \vdots & & \ddots & & \ddots & c_{L-1} \\ \vdots & & & \ddots & & 0 \\ \vdots & & & & \ddots & \vdots \\ 0 & \cdots & \cdots & \cdots & \cdots & 0 \end{bmatrix}_{(N+D)\times(N+D)}$$

and

$$\begin{bmatrix} x_1(k) \\ \cdots \\ x_N(k) \end{bmatrix}_{N\times 1} = \mathbf{F}_N^H \begin{bmatrix} \mathbf{s}_1(k) \\ \vdots \\ \vdots \\ \vdots \\ \mathbf{s}_N(k) \end{bmatrix}_{N\times 1}$$

$\mathbf{H}_{\text{ISI}}$ represents inter-symbol interference generated by the frequency selective behavior of the channel inside an OFDM block at time k
$[x_{N-D+1}(k), \ldots, x_N(k), x_1(k), \ldots, x_i(k), \ldots, x_N(k)]$ while $\mathbf{H}_{\text{IBI}}$ corresponds to inter-block interference between two consecutive OFDM block transmissions at time k $[x_{N-D+1}(k), \ldots, x_N(k), x_1(k), \ldots, x_i(k), \ldots, x_N(k)]$ and at time $(k-1)$ $[x_{N-D+1}(k-1), \ldots, x_N(k-1), x_1(k-1), \ldots, x_i(k-1), \ldots, x_N(k-1)]$.
Denote $H(z) = \sum_{k=0}^{L-1} c_k z^{-k}$ be the channel transfer function and let

$$\begin{aligned} \mathbf{H} = \mathbf{F_N}^{-1}\mathbf{c}_N &= [H(0), H(e^{j2\pi/N}), \ldots, H(e^{j2\pi N-1)/N})]^T \\ &= [h_1, \ldots, h_N]^T \end{aligned}$$

be its Fourier transform. At the receiver, in order to suppress the inter-block interference, the first D samples of the received signal $\mathbf{r^{CP}}$ are discarded.

$$\begin{bmatrix} {r^{CP}}_{D+1}(k) \\ \vdots \\ \vdots \\ {r^{CP}}_{N+D}(k) \end{bmatrix}_{N\times 1} = \begin{bmatrix} r_1(k) \\ \vdots \\ \vdots \\ r_N(k) \end{bmatrix} = \begin{bmatrix} & c_{L-1} & \cdots & c_0 & & & 0 \\ \mathbf{0}_{D-(L-1)} & & \ddots & & \ddots & & \\ \vdots & & & \ddots & & \ddots & \\ & 0 & & & c_{L-1} & \cdots & c_0 \end{bmatrix} \begin{bmatrix} x_{N-D+1}(k) \\ \vdots \\ x_N(k) \\ x_1(k) \\ \vdots \\ x_N(k) \end{bmatrix}_{(N+D)\times 1}$$

which can be rewritten:

$$\begin{bmatrix} r_1(k) \\ \\ \vdots \\ \vdots \\ r_N(k) \end{bmatrix}_{N\times 1} = \begin{bmatrix} c_0 & 0 & \cdots & c_{L-1} & \cdots & c_1 \\ \vdots & \ddots & \ddots & & \ddots & \vdots \\ c_{L-1} & & \ddots & \ddots & & c_{L-1} \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & c_{L-1} & \cdots & c_0 \end{bmatrix}_{N\times N} \mathbf{F}_N^H \begin{bmatrix} s_1(k) \\ \vdots \\ \vdots \\ \vdots \\ s_N(k) \end{bmatrix}_{N\times 1}$$

The use of cyclic redundancy has thus enabled us to turn the linear convolution into a circular convolution. Since any circulant matrix is diagonal in the Fourier basis [12], [13], [14], [15], [16], it is very easy to diagonalize the channel effect by FFT processing at the receiver:

$$\begin{bmatrix} y_1(k) \\ \\ \vdots \\ \vdots \\ y_N(k) \end{bmatrix}_{N\times 1} = \mathbf{F}_N \begin{bmatrix} r_1(k) \\ \\ \vdots \\ \vdots \\ r_N(k) \end{bmatrix}_{N\times 1} \tag{2}$$

$$\begin{bmatrix} y_1(k) \\ \\ \vdots \\ \vdots \\ y_N(k) \end{bmatrix}_{N\times 1} = \mathbf{F}_N \begin{bmatrix} c_0 & 0 & \cdots & c_{L-1} & \cdots & c_1 \\ \vdots & \ddots & \ddots & & \ddots & \vdots \\ c_{L-1} & & \ddots & \ddots & & c_{L-1} \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & c_{L-1} & \cdots & c_0 \end{bmatrix}_{N\times N} \mathbf{F}_N^H \begin{bmatrix} s_1(k) \\ \vdots \\ \vdots \\ \vdots \\ s_N(k) \end{bmatrix}_{N\times 1} \tag{3}$$

Since the circular convolution yields a multiplication in the frequency domain, the signal $[s_1(k), ..., s_N(k)]$ is transmitted over N parallel flat fading channels, subject each to a complex frequency attenuation h_i

$$\begin{bmatrix} y_1(k) \\ \\ \vdots \\ \vdots \\ y_N(k) \end{bmatrix}_{N\times 1} = \begin{bmatrix} h_1 & 0 & \dots & \dots & \dots & 0 \\ 0 & h_2 & 0 & \dots & \dots & \dots \\ \vdots & 0 & \ddots & 0 & \dots & \dots \\ \vdots & \dots & \dots & \ddots & \dots & \dots \\ \vdots & \dots & & \dots & \ddots & \dots \\ \vdots & \dots & \dots & \dots & \dots & h_N \end{bmatrix}_{N\times N} \begin{bmatrix} s_1(k) \\ \vdots \\ \vdots \\ \vdots \\ s_N(k) \end{bmatrix}_{N\times 1} \tag{4}$$

In the case of noisy transmission, the time Gaussian noise vector $[b_1(k), \dots, b_N(k)]^T$ added is multiplied at the receiver by the FFT demodulator:

$$\begin{bmatrix} n_1(k) \\ \\ \vdots \\ \vdots \\ n_N(k) \end{bmatrix}_{N\times 1} = F_N \begin{bmatrix} b_1(k) \\ \\ \vdots \\ \vdots \\ b_N(k) \end{bmatrix}_{N\times 1}$$

Since the statistics of a Gaussian vector does not change by orthogonal transform, $[n_1(k), \dots, n_N(k)]^T$ is a white gaussian vector with the same variance. We give hereafter the frequency equivalent model representation of OFDM.

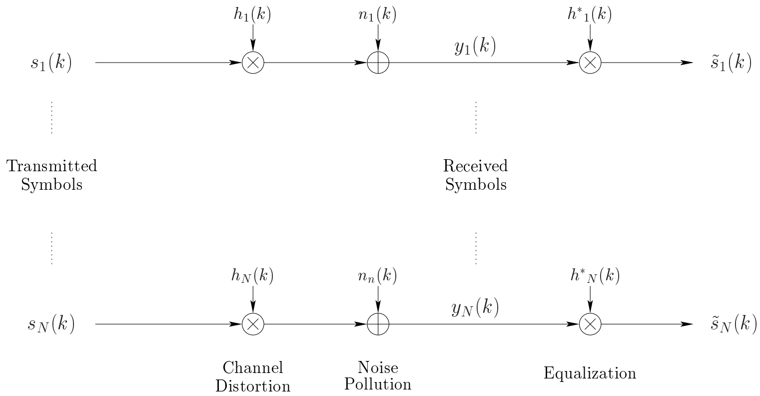

Fig. 5. OFDM frequency model.

Hereafter, a short description of a standardized OFDM scheme known as IEEE802.11a is provided in order to give the reader some basic knowledge of the common parameters used in a wireless network (number of carriers, constellations,...). IEEE802.11a [17] is a 5 Ghz European Standard developed by IEEE with a physical layer based on OFDM. IEEE802.11a is intended to provide wireless connectivity between PCs, laptops... either in an indoor or outdoor environment for pedestrian mobility. The cell radius extends to 30 m in indoor environments or up to 150m outdoors. The lower frequency band, from 5.15 to 5.35 Ghz contains 8 channels spaced by 20 MHz while the upper band consists of 11 channels, from 5.470 to 5.725 Ghz. A typical centralized network consists of different Mobile terminals (MT) that communicate with their respective Access Points (AP) over the air interface. The important general characteristics are summarized below and in the table III:

- sampling frequency : F_e =20MHz;
- adjacent channels spacing : 20MHz;
- FFT size : $N = 64$;
- $K = 48$ useful carriers and 4 pilots (on carriers : ± 7, ± 21; used for phase tracking);
- modulation of sub-carriers :
  - BPSK, QPSK, 8PSK,
  - 16QAM, 64QAM;
- guard interval of 16 samples (800 ns).
- Wireless LAN for indoor/campus/home environment
- OFDM modulation with a TDMA/TDD access scheme
- 19 channels (8 in the lower band, 11 in the upper one) with a bandwidth of 20 Mhz
- High bit rate on top of the PHY layer (6-54 Mbit/s)
- Quality of service support
- Automatic frequency allocation
- Convolutive code constraint length 7 punctured

III. THE PROS AND CONS OF OFDM

In the previous section, we showed how OFDM converts a frequency selective channel into a collection of flat fading channels thanks to the use of cyclic prefix. Such a strategy has immediate advantages.

- As previously stated, one of the attractive features of OFDM is that, for a certain delay spread, the complexity of an OFDM modem vs. sampling rate does not grow as fast as the complexity of a single carrier system with an equalizer (thanks to the use of redundancy). The reason is that when the sampling rate is reduced by a factor of two, an equalizer has to be made twice as long at twice the speed, so its complexity grows quadratically with the inverse of the sampling rate, whereas the complexity of OFDM grows only slightly faster than linear. This makes easier to

Modulation	Code Rate	Net rate on top of PHY	Byte per Symbol
BPSK	1/2	6 Mbit/s	3
BPSK	3/4	9 Mbit/s	4.5
QPSK	1/2	12 Mbit/s	6
QPSK	3/4	18 Mbit/s	9
16-QAM	9/16	27 Mbit/s	13.5
16-QAM	3/4	36 Mbit/s	18
optional			
64-QAM	3/4	54 Mbit/s	27

TABLE III
PHY MODES OF IEEE802.11A.

implement modems, which have to handle data rates exceeding 20 Mb/s. In OFDM systems, only simple (scalar) equalization is performed at the receiver (whereas in the context of single carrier transmission, a matrix inversion is required). Indeed, provided that the impulse response of the channel is shorter then the Guard interval, each constellation is multiplied by the channel frequency coefficient and there is no Inter-Symbol Interference (ISI). However, the channel still has to be compensated by a multiplication of each FFT output by a single coefficient:

$$\hat{s}_i(k) = g_i h_i s_i(k) + g_i(k) n_i(k)$$

The matrix equivalent equation is: $\hat{\mathbf{s}}(k) = \mathbf{G}\mathbf{y}(k)$
with

$$\mathbf{G} = \begin{bmatrix} g_1 & 0 & \dots & \dots & \dots & 0 \\ 0 & g_2 & 0 & \dots & \dots & \dots \\ \vdots & 0 & \ddots & 0 & \dots & \dots \\ \vdots & \dots & \dots & \ddots & \dots & \dots \\ \vdots & \dots & & \dots & \ddots & \dots \\ \vdots & \dots & \dots & \dots & \dots & g_N \end{bmatrix} \tag{5}$$

Among other schemes equalization schemes, zero forcing or MMSE equalization (which takes into account the noise enhancement) is performed at the receiver.

– ZF equalization: $g_i = \frac{h_i^*}{|h_i|^2} = \frac{1}{h_i}$

– MMSE equalization: $g_i = \frac{h_i^*}{|h_i|^2 + {\sigma_i}^2}$

${\sigma_i}^2$ is the noise variance on the carrier i. Of course, the coefficients $(h_i(k))_{i=1,\dots,N}$ can either be known or estimated.

• The channel attenuations can easily be determined in the frequency domain thanks to a learning sequence [18], [19] or by blind estimation methods [20], [21]. Some useful estimation (also called denoising estimation) methods exploit also the time structure of the channel (limited number of coefficients..). It is also possible to take into account the time and frequency autocorrelation function of the channel for turbo estimation [22]. In classical standardized systems such as IEEE802.11a, two OFDM consecutive blocks are transmitted at the beginning of each frame to estimate the channel after synchronization and before the useful transmitted data. Note that after equalization, the noise variance changes from carrier to carrier depending on the channel frequency response. The decoder has to be fed with these modified metrics.

• Finally, the spectral efficiency is increased by allowing frequency overlapping of the different carriers (compared to FDMA systems).

However, the OFDM system also exhibits several weaknesses relative to its single-carrier counterparts.

- OFDM does not capitalize on channel diversity, which prohibits the use of plain OFDM schemes in fading environments. The diversity achieved by the OFDM system can be less than a single-carrier system employing the same error control code in a signaling environment rich in diversity. Indeed, due to frequency flat fading, the transmitted information on one OFDM subchannel can be irremediably lost if a deep fade occurs [6]. Moreover, the Rayleigh behavior of such fading can have a dramatic impact on the performance of uncoded OFDM schemes. Methods based on coding (convolutional codes, block codes, multidimensional constellations, turbo-codes [23], [24], [25], [26], [27], [28], [29]) are usually employed with the use of interleaving to combat fading. When no channel knowledge is available at the transmitter, interleaving is intended to send the information on different carriers. If the receiver can be provided with different replicas of the information, which have been subjected to independent fadings, an appropriate combination of the replicas can restore the information.
  - In the case of time interleaving, the coded bits are sent at different times with interval distances greater than the coherence time of the channel. This method is particularly useful in fast fading environment. Otherwise, it incurs a non-tolerable delay in the transmission.
  - Frequency interleaving is particularly suited for rich scattering environments. The coded bits are sent on different frequency bands separated by the coherence bandwidth.
  - Finally, in the case of space interleaving, the coded information is sent on different antennas. A particular simple space-time coding schemes which benefits from the space diversity is the well-known Alamouti scheme [30].

As a special case of coded diversity used in OFDM, **COFDM** schemes [31] is usually used in standards.
In classical COFDM standardized systems [32], [33], [34], the input bit stream is first scrambled to generate random equal distribution bits at the input of the encoder. The bits are then processed by a convolutional encoder of rate R and constraint length L. The bits are then frequency interleaved in one OFDM block (time interleaving across OFDM blocks is not performed in IEEE802.11a) and mapped into symbols that are sent to the OFDM modulator. The memory size of the encoder is of critical importance. Indeed, the encoder performs a kind of redundant spreading of the information on the channel by linking the various bits through the memory of the encoder. This "spreading" of the information can achieve, in some cases, full diversity. At the receiver, symmetrical operation are performed. Metrics are derived with frequency de-interleaving. These metrics are then fed into the Viterbi decoder in order to retrieve the coded bits before de-scrambling.

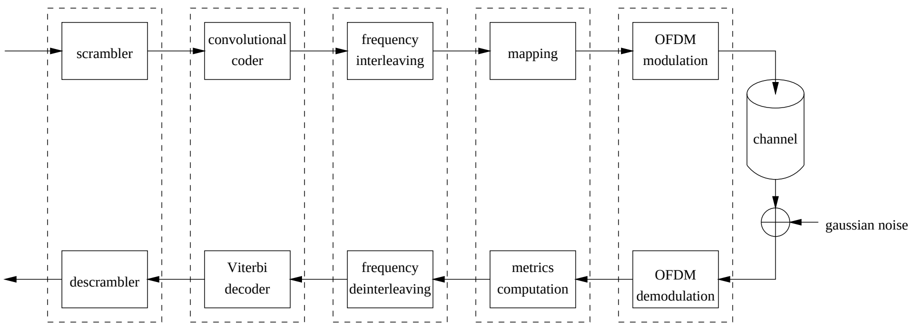

Fig. 6. COFDM scheme.

- The baseband transmitted signal can also exhibit significant amplitude fluctuations over time, generating a high input backoff ratio at the amplifier of the transmitter. Usually, the power amplifier introduces non-linear distortions which destroy the orthogonality between the carriers. This peak to average power ratio (PAPR) [35], [36] increase has drawn intense research lately in order to decrease the power consumption of the amplifiers [35], [37]. Most of PAPR methods are based on a modification of the transmitted signal by a correction vector. It introduces some non-negligible complexity at the transmitter. The vector correction is added to the frequency domain symbols yielding a new constellation with better peak to average power ratio properties (Tone Insertion method of Tellado [37]. In [**?**], an overview as well as implementations structures are given.

• The OFDM model only applies when the channel length is effectively smaller than the cyclic prefix. If this is not the case, the orthogonality between subcarriers is only approximative and some Inter-Carrier Interference appear (ICI): a symbol transmitted on a given subcarrier is polluted by those of adjacent subcarriers. This problem occurs in particular in ADSL context and is solved by using a shortening filter at the receiver [38] whose aim is to reduce the channel length (or more rigorously to concentrate most of the energy in the first L taps) so as to minimize ICI.
• OFDM is also more vulnerable to frequency off-set as well as synchronization problems [39], [40], [41]. In the first case, a frequency off-set yields inter-carrier interference and destroys the orthogonality between subcarriers. In the second case, synchronization errors incurs a phase shift on the estimated symbols. In [40], sensitivity of OFDM systems to Carrier Frequency Offset and phase noise is analytically analyzed. It is shown in particular that OFDM is orders of magnitude more sensitive to frequency offset and phase noise than single carrier modulations. Sensitivity increases with the constellation size. The higher sensitivity of OFDM with respect to single carrier is mostly affected by the N times longer duration of an OFDM block symbol and by the intercarrier interference due to loss of the carrier orthogonality.

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