Multiple Access and Power-Efficiency in Wireless Communications

Prof. Hikmet Sari

SUPELEC

Plateau de Moulon, 3 rue Joliot-Curie

F-91192 Gif sur Yvette, France

Supélec

Presentation Outline

- A historical review of transmission and multiple access technologies: OFDM, SC-FDE, OFDMA
- Multiple access in the WiMAX, LTE, and LTE Advanced standards
- Performance comparison of OFDMA and SC-FDMA on a linear channel
- Power amplifier issues
- Conclusions

Back in the 1980s

- Power being a major issue, there was a strong interest in constant-envelope modulations. The *Groupe Spéciale Mobile* (GSM) selected Gaussian MSK (GMSK) for the first Pan-European digital mobile radio standard, which was soon going to be a major world standard.
- Satellite communications were restricted to phase-shift keying (PSK), because the cost of launch of satellites is directly related to the transponder power.
- In contrast, digital microwave radio systems started using quadrature amplitude modulation (QAM), and 16-QAM and 64-QAM became a de-facto standard in high-capacity digital microwave radio links.
- The channel bandwidth in these systems was on the order of 30 to 40 MHz, and adaptive equalizers were developed to compensate for frequency-selective fading.

OFDM vs. Single-Carrier

- In the 1980s, Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) were hot topics, particularly in Europe, and OFDM was selected for DAB and digital terrestrial TV.
- By many, OFDM was actually perceived as the only technology that is able to cope with difficult multipath conditions, particularly for mobile reception.
- As an "outsider" with no direct interest in digital terrestrial TV, the present author was intrigued by the vague statements about OFDM and its superiority to single-carrier transmission and decided to take a close look at the problem.
- The first paper which proposed single-carrier transmission with frequency-domain equalization (SC-FDE) as an alternative to OFDM was presented at the 1993 International Tirrenia Workshop on Digital Communications, September 1993, Pisa, Italy:

  H. Sari, G. Karam, and I. Jeanclaude, "Channel Equalization and Synchronization in OFDM Systems"

Supélec

OFDM vs. Single-Carrier

- This paper reviewed OFDM and highlighted its attractive features, but also pointed out its drawbacks. It showed that many statements about OFDM were unfounded.
- The reaction from the audience was extremely strong. It was like attacking a religion!
- The Tirrenia paper explained that OFDM does not solve the channel equalization problem, but only shifts it to the frequency domain. It also explained OFDM breaks frequency diversity and that channel coding is required to restore it.
- But most important of all, it made an analogy with a single-carrier system that uses frequency-domain equalization and pointed out that such a system could give similar results to OFDM while avoiding its PAPR and synchronization problems.
- The most well-known paper from the same authors on the subject: *H. Sari, G. Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting" , IEEE Comm. Magazine, vol. 33, pp. 100 – 109, February 1995.*

The Road to OFDMA

- In the early 1990s, the DVB project in Europe adopted OFDM for digital terrestrial TV broadcasting and single-carrier transmission for satellite and cable TV.
- After adoption of the transmission technique for these applications, the group started to work on the return channel. The present author was following the discussions for the return channel of cable networks.
- Proposals were mostly concentrated on TDMA and its variants like DECT. Since the cable return channel is subject to narrowband interference, a basic OFDMA scheme which allocates one carrier to each user seemed to be an interesting choice.
- An OFDMA with a single carrier per user requires a single-carrier transmitter and an OFDM receiver. Therefore, it avoids the PAPR problem of OFDM systems.

The Road to OFDMA

- The carriers subject to narrowband interference can be discarded. This makes OFDMA much more robust to narrowband interference than TDMA and CDMA.
- The proposal (made by the present author) to the DVB Project was not accepted at that time. But OFDMA was later included in the DVB-RC specifications.

FIRST PAPERS:

- H. Sari, Y. Levy, and G. Karam, “Orthogonal Frequency-Division Multiple Access for the Return Channel on CATV Networks”, ICT 1996 Conf. Rec., April 1996, Istanbul.
- H. Sari, “Orthogonal Frequency-Division Multiple Access with Frequency Hopping and Diversity”, in Multi-Carrier Spread Spectrum, Kluwer Academic Publishers, pp.57 – 68, 1997.
- H. Sari and G. Karam, “Orthogonal Frequency-Division Multiple Access and its Application to CATV Networks”, European Transactions on Telecommunications (ETT), November – December 1998.

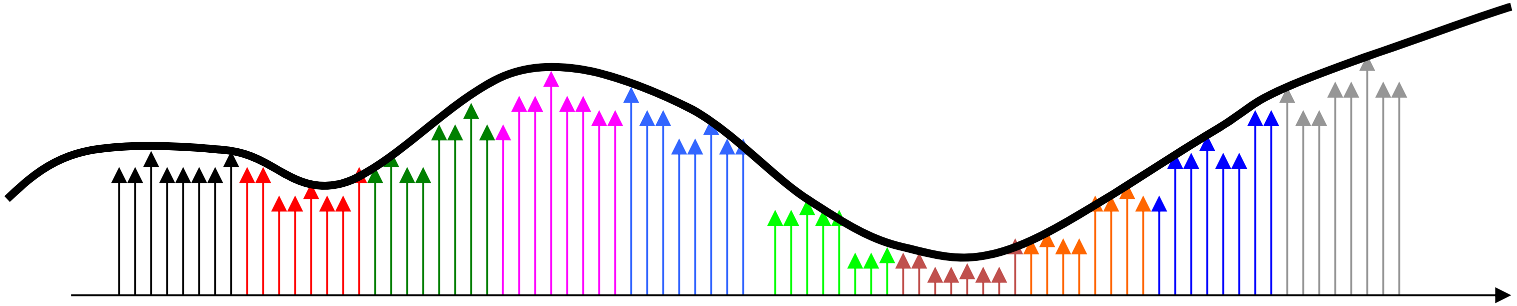
OFDMA Today

- In the IEEE 802.16e specifications, on which mobile WiMAX is based, OFDMA is used on both the downlink and the uplink. In contrast, OFDMA is only used on the downlink in the 3GPP LTE specifications. The uplink in LTE uses Single-Carrier FDMA (SC-FDMA), based on the concept of SC-FDE.
- In modern OFDMA, the base station assigns a group of carriers to each user, and the physical carriers can be clustered (localized) or distributed across the channel.
- Furthermore, the groups of carriers assigned to different users are not fixed, but rather they frequency hop according to a permutation sequence, in order to reduce interference between adjacent cells.

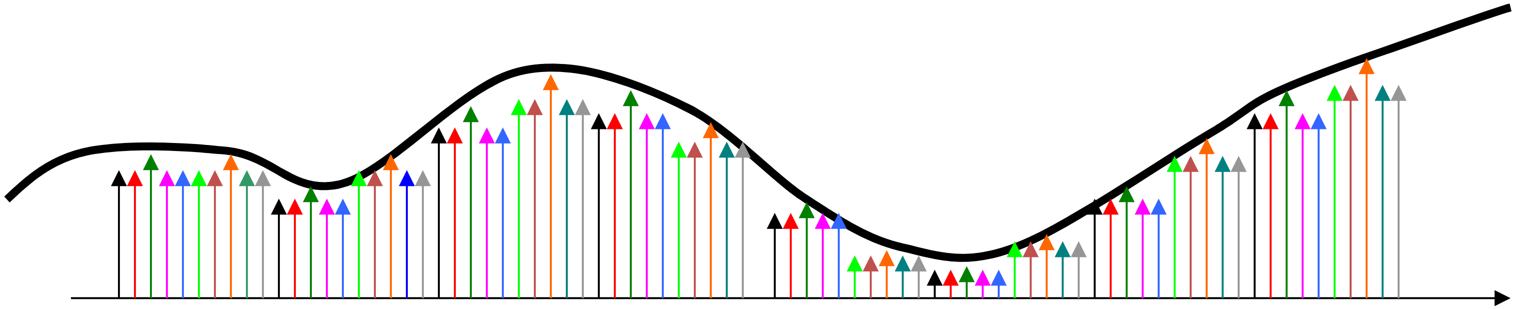
Supélec

Basic Variants of OFDMA

- Clustered (Localized) OFDMA



- Distributed OFDMA



Supélec

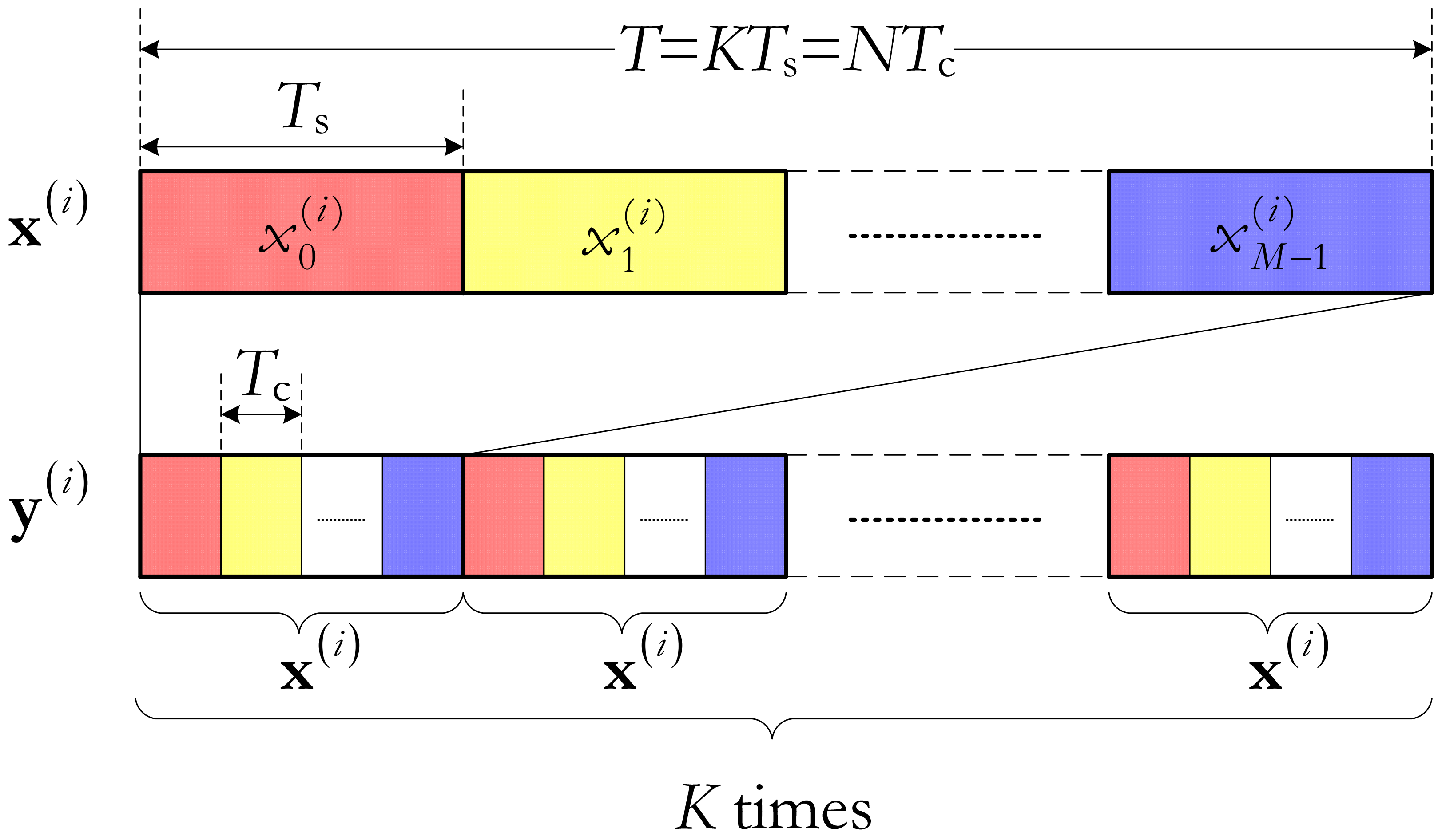
Advantages of OFDMA over TDMA

- Compared to TDMA, OFDMA leads to a significant range extension on the uplink for a given transmit power.
- Indeed, suppose that the transmit output power is P. In TDMA, power P is transmitted over the entire channel bandwidth W, and the receive SNR is $\Gamma = P/N_0W$.
- In an N-carrier OFDMA system allocating M carriers to each user, power P is transmitted over the bandwidth W.M/N, and the SNR is $\Gamma' = \Gamma.N/M$. Consequently, the SNR is increased by 10.log(N/M) dB.
- The same type of range extension is achievable on the downlink by allocating more power to carrier groups assigned to distant users.

The Principle of SC-OFDMA

- SC-FDMA has the same characteristics (cell range extension) as OFDMA, but being a single-carrier technique, it avoids the high PAPR of OFDMA.
- This technique can be generated in the time domain or in the frequency domain. Frequency-domain-generated SC-FDMA is simply a precoded OFDMA scheme where precoding is carried out by the DFT matrix.
- In the 3GPP LTE specifications, SC-FDMA is generated in the frequency domain and it is sometimes referred to as DFT-Spread OFDM(A).
- Time-domain generation of SC-FDMA is illustrated on the following slide.

Time-Domain Generation of SC-OFDMA

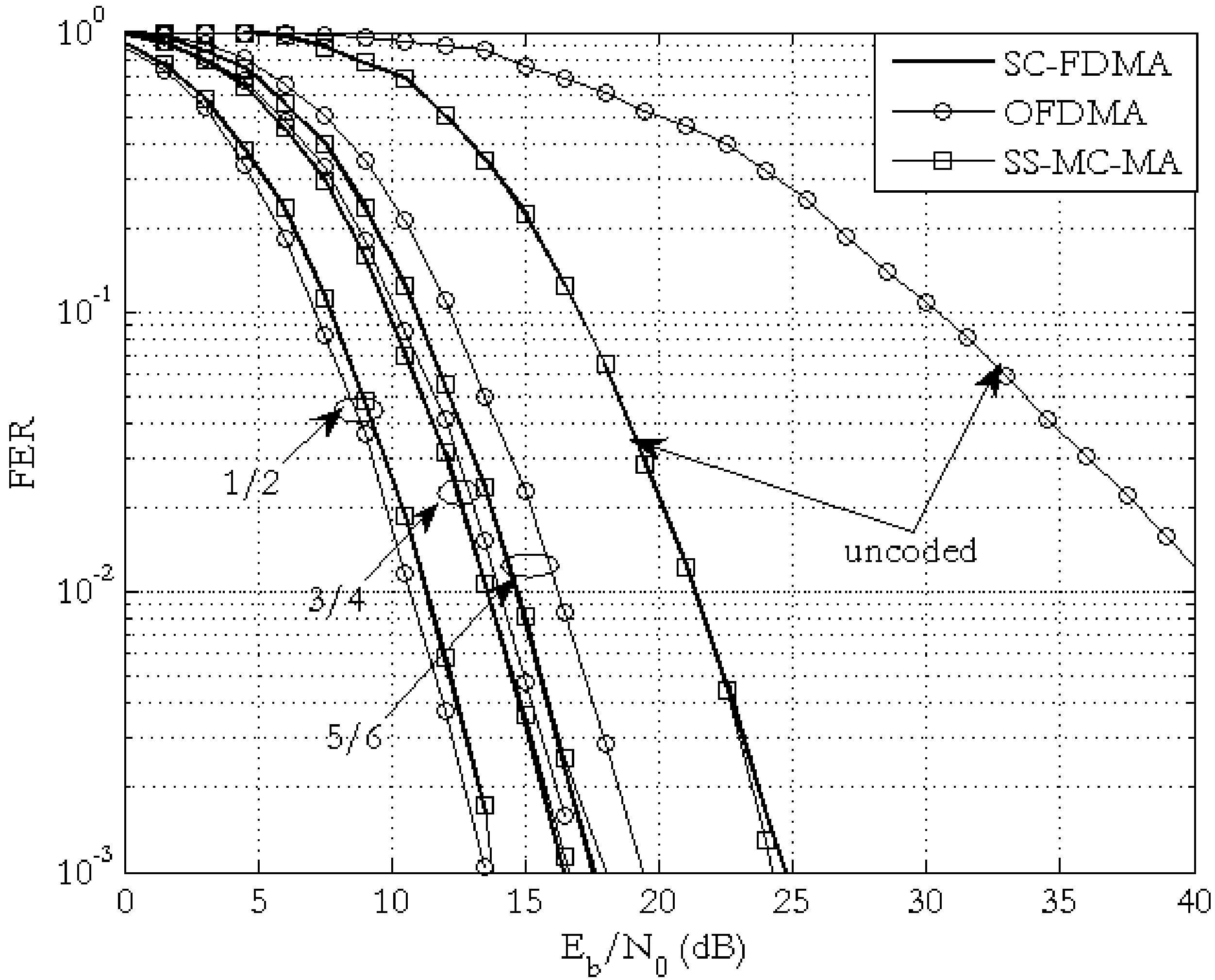


Supélec

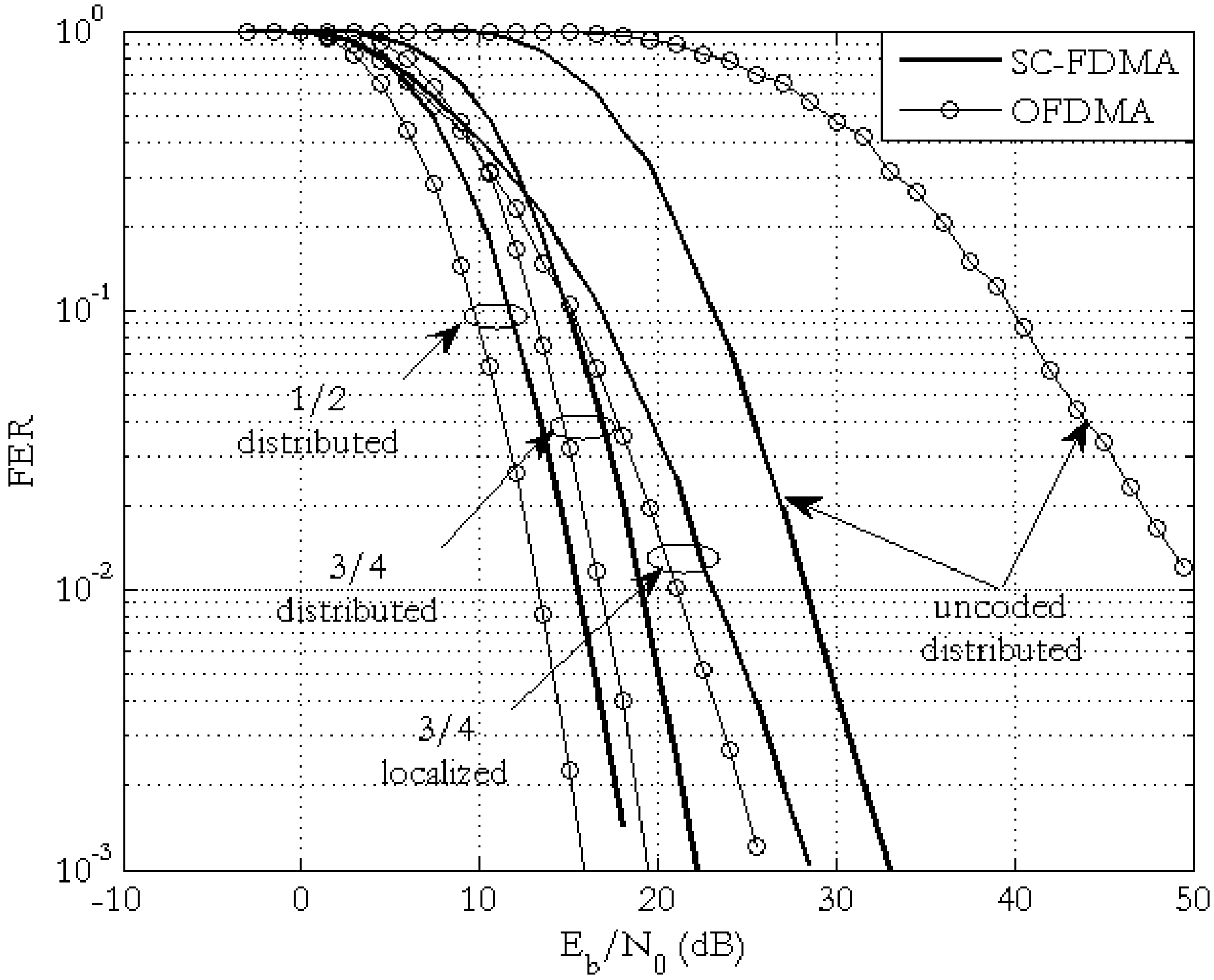
Performance Analysis

- The computer simulations were performed using the 3GPP LTE specifications. The number of subcarriers was 512, 300 of which were data subcarriers. The cyclic prefix had 31 samples.
- The data subcarriers were divided into 25 resource blocks (RBs) of 12 subcarriers each.
- The channel bandwidth was 5 MHz, and the sampling frequency was 7.68 MHz.
- The channel used was the vehicular A profile with 6 taps and a maximum delay spread of 2.51 μs.
- Perfect channel estimation was assumed at the receiver.

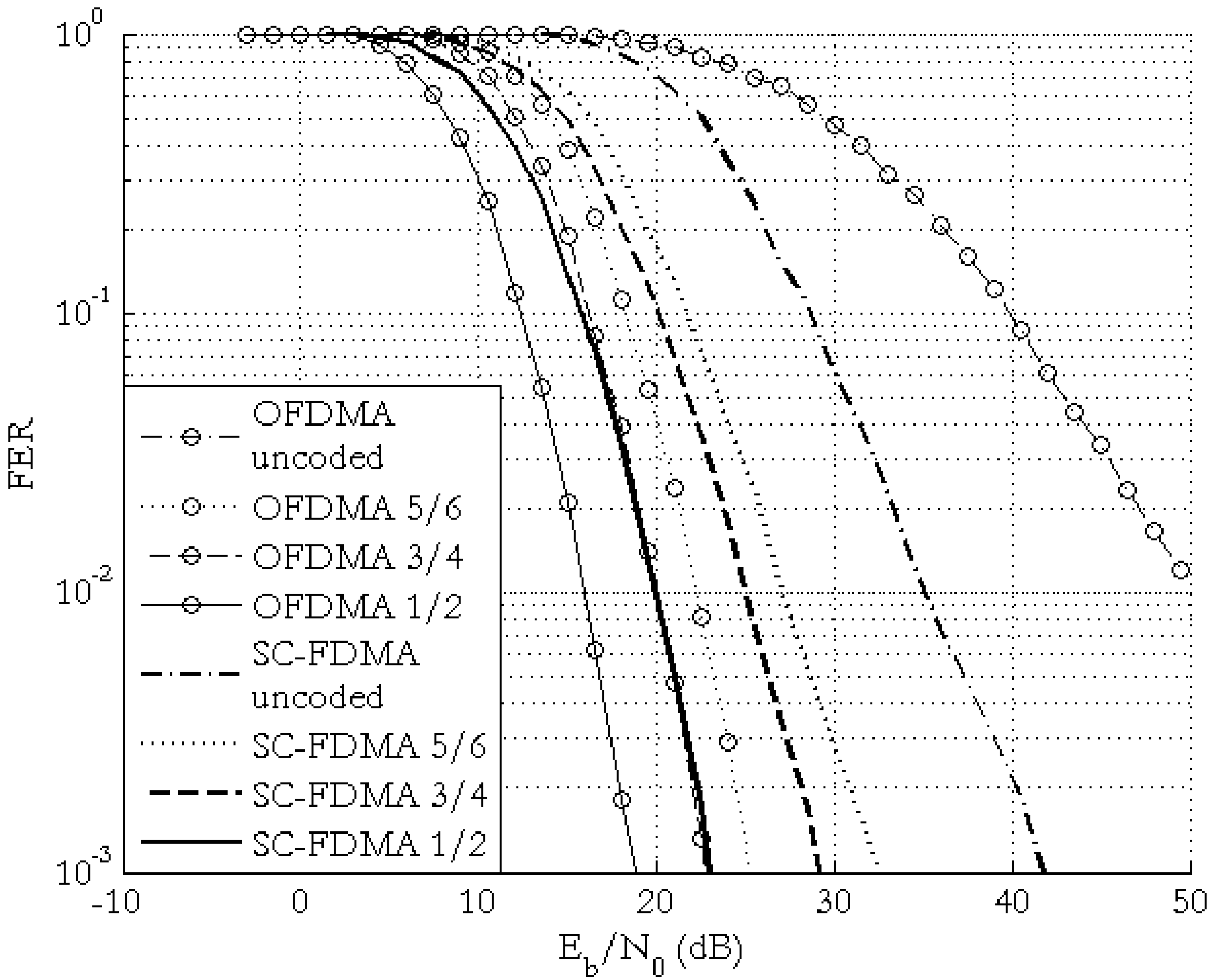
SC-FDMA vs. OFDMA with QPSK



SC-FDMA vs. OFDMA with 16-QAM



SC-FDMA vs. OFDMA with 64-QAM



Supélec

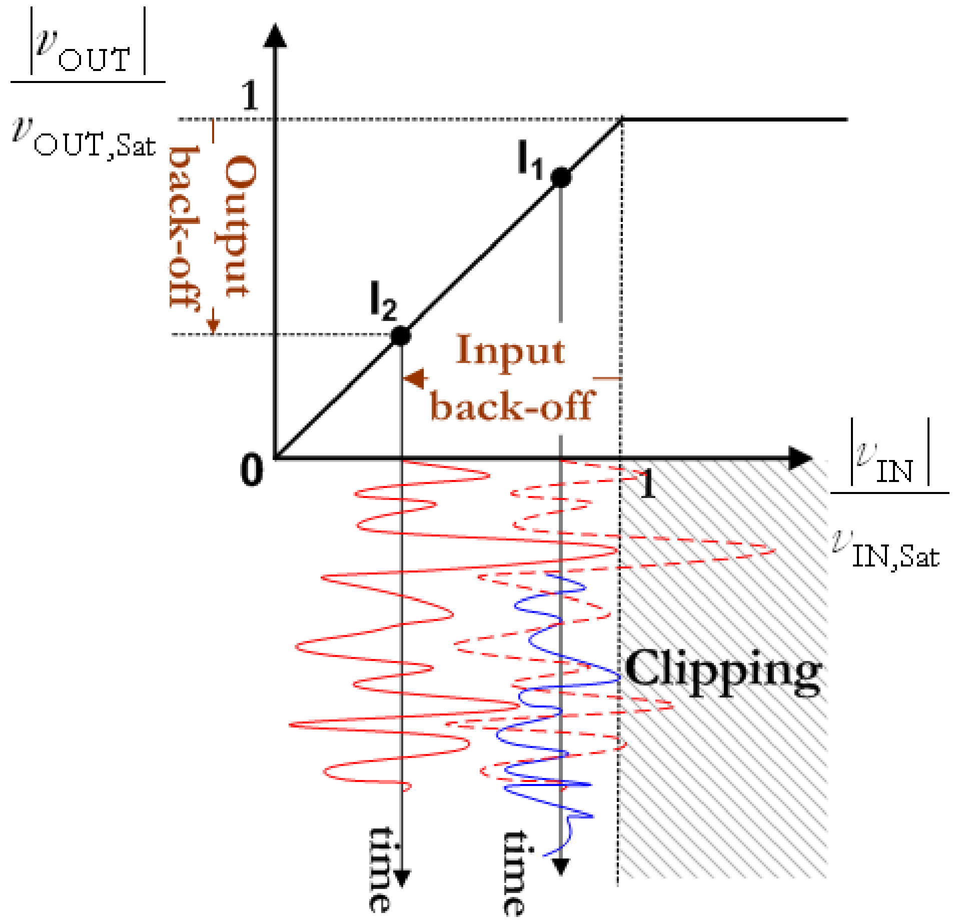
Gain of OFDMA over SC-FDMA

FER = 1%		QPSK (dB)		16QAM (dB)		64QAM (dB)	
		1 RB	5 RB	1 RB	5 RB	1 RB	5 RB
Local.	1/2	0.4	0.5	1.8	2.6	2.5	4.4
	3/4	-0.8	-0.8	1.1	2.0	1.9	4.8
	5/6	-1.7	-1.8	0.3	1.0	1.2	3.9
	uncoded	-4.2	-13.6	-3.8	-13.2	-3.5	-12.8
Distr.	1/2	0.6	0.6	2.9	2.2	6.7	3.9
	3/4	-1.4	-0.5	3.8	2.3	7.9	5.2
	5/6	-2.0	-1.6	3.1	1.4	6.7	4.9
	uncoded	-13.4	-19.3	-10.3	-17.5	-8.63	-14.9

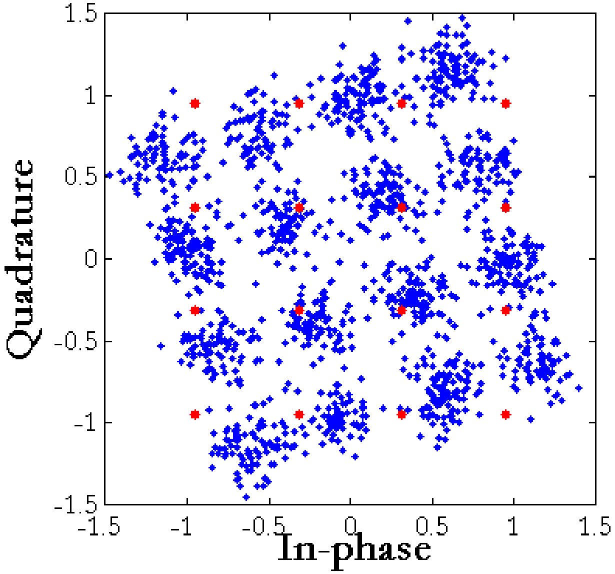
Supélec

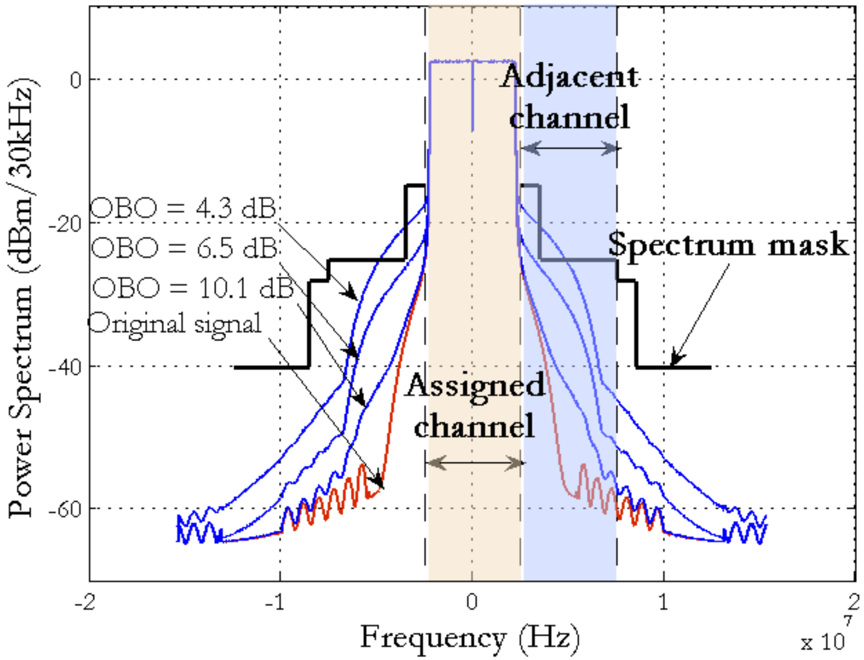
High-Power Amplifier Nonlinearity

- High power amplifiers (HPAs) cause both nonlinear signal distortion and spectral regrowth. They must be backed off from their saturation power to limit these effects:



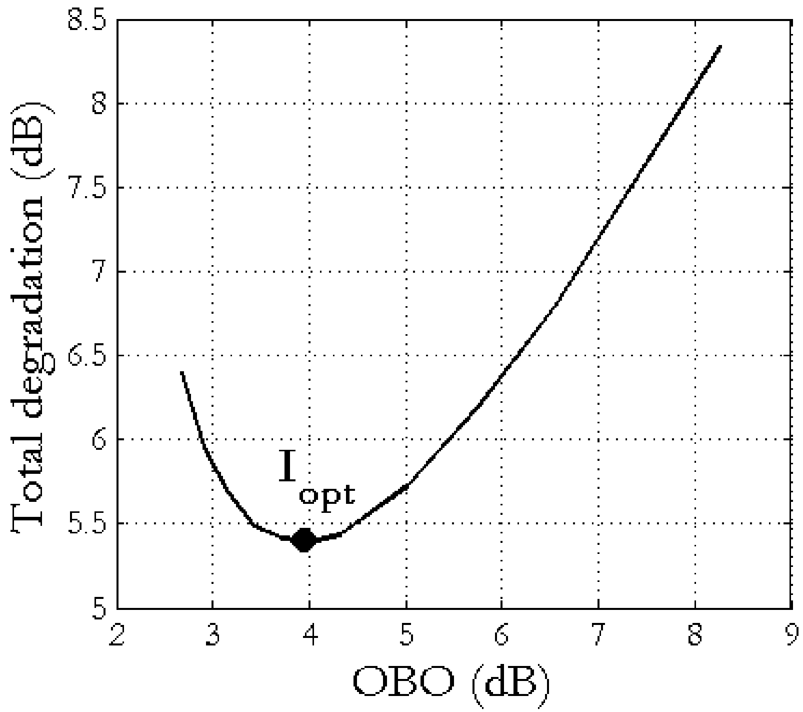
Signal Distortion and Spectral Regrowth





Optimizing HPA Back-Off

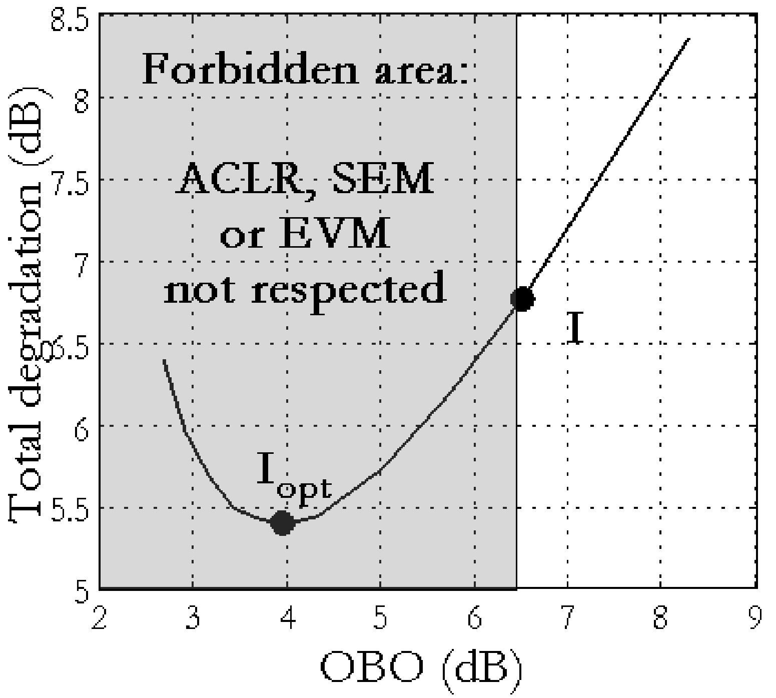
- Nonlinear signal distortion causes SNR loss (ΔSNR). To reduce ΔSNR, the HPA must be backed off from its saturation power, but increasing output back-off (OBO) reduces transmit power. The total degradation can be defined as ΔSNR + OBO. The optimum operating point is determined by minimizing total degradation.



Supélec

HPA Back-Off in Practice

- Often the optimum operating point of the HPA cannot be reached in practice because of the stringent spectral mask imposed to limit radiation in adjacent bands. Those considerations require operation at a higher output back-off.



Signal Predistortion

- The effect of nonlinear signal distortion can be compensated at the receiver by means of nonlinear equalization based on Volterra series expansion, but this does not solve the problem of spectral regrowth of the transmitted signal and it does not help reducing the HPA output back-off.
- The most common way to handle this problem is to perform signal predistortion at the transmitter. Signal predistortion consists of synthesizing the inverse function of the AM/AM and AM/PM characteristics of the HPA.
- This technique reduces both nonlinear signal distortion and out-of-band emission. The HPA back-off can be reduced by several dB.

OFDM PAPR Reduction

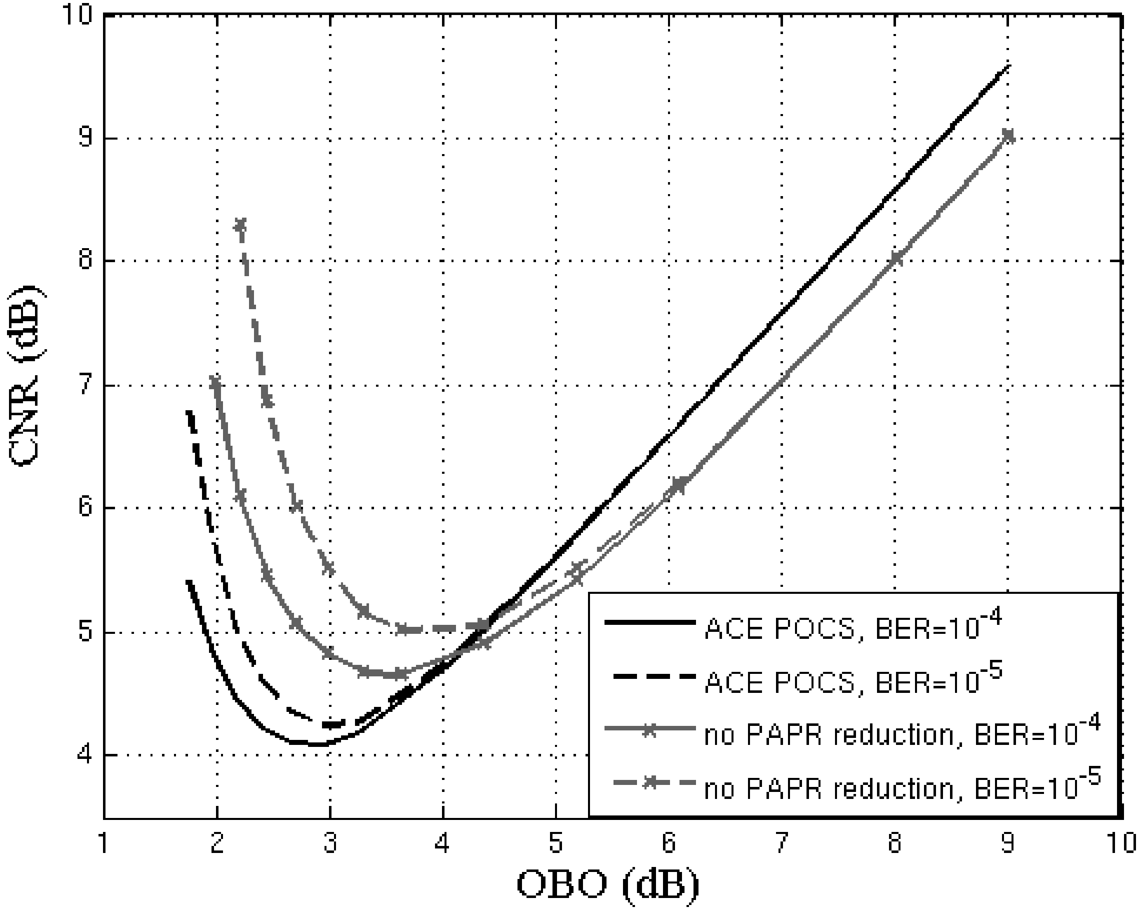
- Since OFDM based systems suffer from a high PAPR compared to single-carrier systems, there has been a significant research effort to reduce the PAPR of this type of signals.
- The PAPR can be reduced by several dB, but unfortunately the gain in PAPR does not directly translate in gain in terms of output back-off reduction.
- The reason is that peak values in OFDM occur with a very low probability, and after PAPR reduction peak values occur much more frequently.
- The CCDF of the instantaneous normalized signal power (INP) is more relevant than the PAPR CCDF for performance evaluation:

$$\mathrm{CCDF}(INP(v_N)) = \Pr\left(\frac{|b_i|^2}{P_{avg,N}} > \gamma^2 \right)$$

$$\mathrm{CCDF}(PAPR(\mathbf{b})) = \Pr(PAPR(\mathbf{b}) > \gamma^2)$$

Supélec

OFDM PAPR Reduction



Comparison using the Rapp Model

Rapp HPA, p_{Rapp}=2		**SC-FDMA**		**OFDMA**	
		1 RB	5 RB	1 RB	5 RB
Loc.	OBO (dB)	3.1	3.6	4.5	5.6
	IBO (dB)	2	2.8	3.3	4.8
	CM (dB)	1.97	1.96	4.4	4.7
	EVM (%)	14.6	11.6	17.1	12.2
	ACLR (dB)	30.9	31.7	31.8	32.7
Dist.	OBO (dB)	7.9	6.1	9.6	7.8
	IBO (dB)	7.8	5.8	9.5	7.5
	CM (dB)	1.96	1.99	4.4	4.7
	EVM	1.9	4.3	2.4	5.4
	ACLR (dB)	36.1	34.5	35.9	33.8

Supélec

Comparison using the Saleh Model

Saleh HPA, $\alpha=1$, $\beta=1/4$, $\alpha_p=\beta_p=1$		SC-FDMA		OFDMA	
		1 RB	5 RB	1 RB	5 RB
Loc.	OBO (dB)	8.9	8.9	10.6	10.7
	IBO (dB)	11.5	11.6	13.3	13.5
	CM (dB)	1.97	1.96	4.4	4.7
	EVM (%)	17.4	17.3	17.4	17.4
	ACLR (dB)	31.6	31.9	31.9	32.8

Conclusions

- In the first part of this talk, we presented a brief historical review of OFDM, SC-FDE, and OFDMA which form the basis of the recent WiMAX, LTE, and LTE-Advanced standards.
- Next, we discussed the performance of OFDMA and SC-OFDMA in various conditions and gave results indicating that on a linear channel, OFDMA has a significant advantage particularly with high signal constellations
- Then, we highlighted the major issue related to power amplifiers and showed that SC-FDMA gains 1.5 – 2.0 dB over OFDMA in terms of HPA output back-off. We also pointed out that PAPR reduction leads to small improvement in terms of HPA back-off.
- The final conclusion is that OFDMA performs better than SC-FDMA for users near the base station with high-level constellations, and that SC-FDMA performs better for users near the cell edge with low-level signal constellations.