Keynote Speech

A Brief History of OFDMA and SC-FDMA

Prof. Hikmet Sari

SUPELEC

Plateau de Moulon, 3 rue Joliot-Curie

F-91192 Gif sur Yvette, France

hikmet.sari@supelec.fr

Presentation Outline

- A historical review of single-carrier transmission with frequency-domain equalization (SC-FDE)
- The birth and development of OFDMA
- The principle of SC-FDMA
- IEEE 802.16e and 3GPP LTE
- OFDMA vs. SC-FDMA in cellular environment
- Summary and conclusions

Introduction

- In the early 1980s, Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) were very hot topics, and OFDM was the technology selected and developed for Digital Terrestrial Broadcasting in Europe.
- By many, OFDM was actually perceived as the only technology that is able to cope with difficult multipath conditions and 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 he decided to take a close look at the problem.

SC-FDE vs. OFDM

- The first paper which proposed an SC-FDE system 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"
  The conference book was published by Elsevier in 1994.
- This paper reviewed OFDM and highlighted its interesting 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!

SC-FDE vs. OFDM (cont'd)

- 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 was published in the IEEE Communications Magazine in February 1995: Transmission Techniques for Digital Terrestrial TV Broadcasting.

The Road to OFDMA

- In the early 1990, 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.

The Road to OFDMA (cont'd)

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

First OFDMA Papers

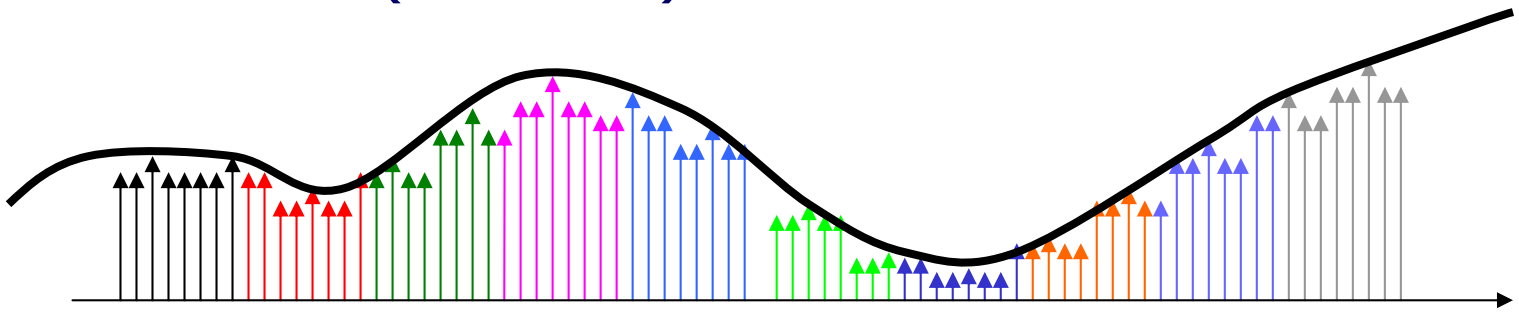
- H. Sari, Y. Levy, and G. Karam, "Orthogonal Frequency-Division Multiple Access for the Return Channel on CATV Networks", ICT 1996 Conf. Rec., April 1996, Istanbul.
- H. Sari, "Orthogonal Frequency-Division Multiple Access with Frequency Hopping and Diversity", in Multi-Carrier Spread Spectrum, Kluwer 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

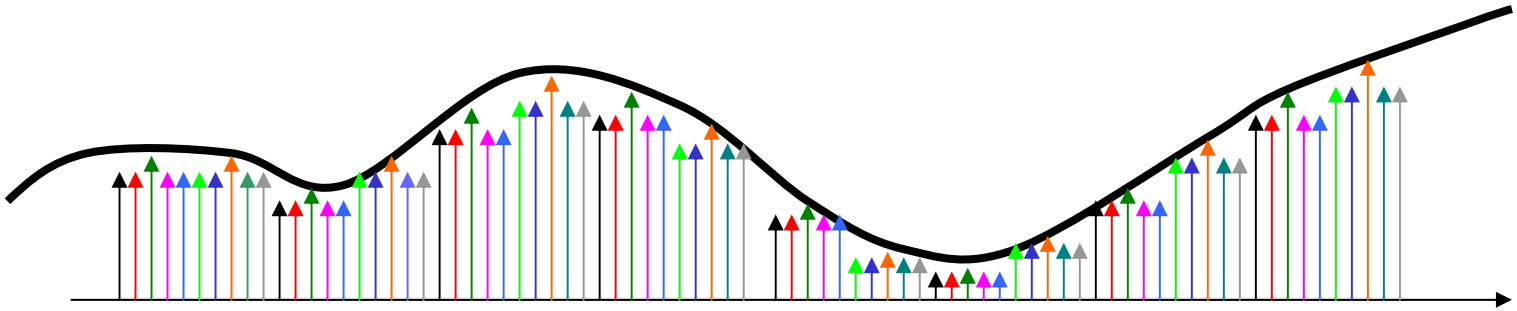
- In the IEEE 802.16e specifications, on which mobile WiMAX is based, OFDMA is used on both the downlink and the uplink. In contrast, OFDMA is only used on the downlink in the 3GPP LTE specifications.
- In modern OFDMA, the base station assigns a group of carriers to each user, and the physical carriers 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.

Basic Variants of OFDMA

1. Clustered (Localized) OFDMA



2. Distributed OFDMA



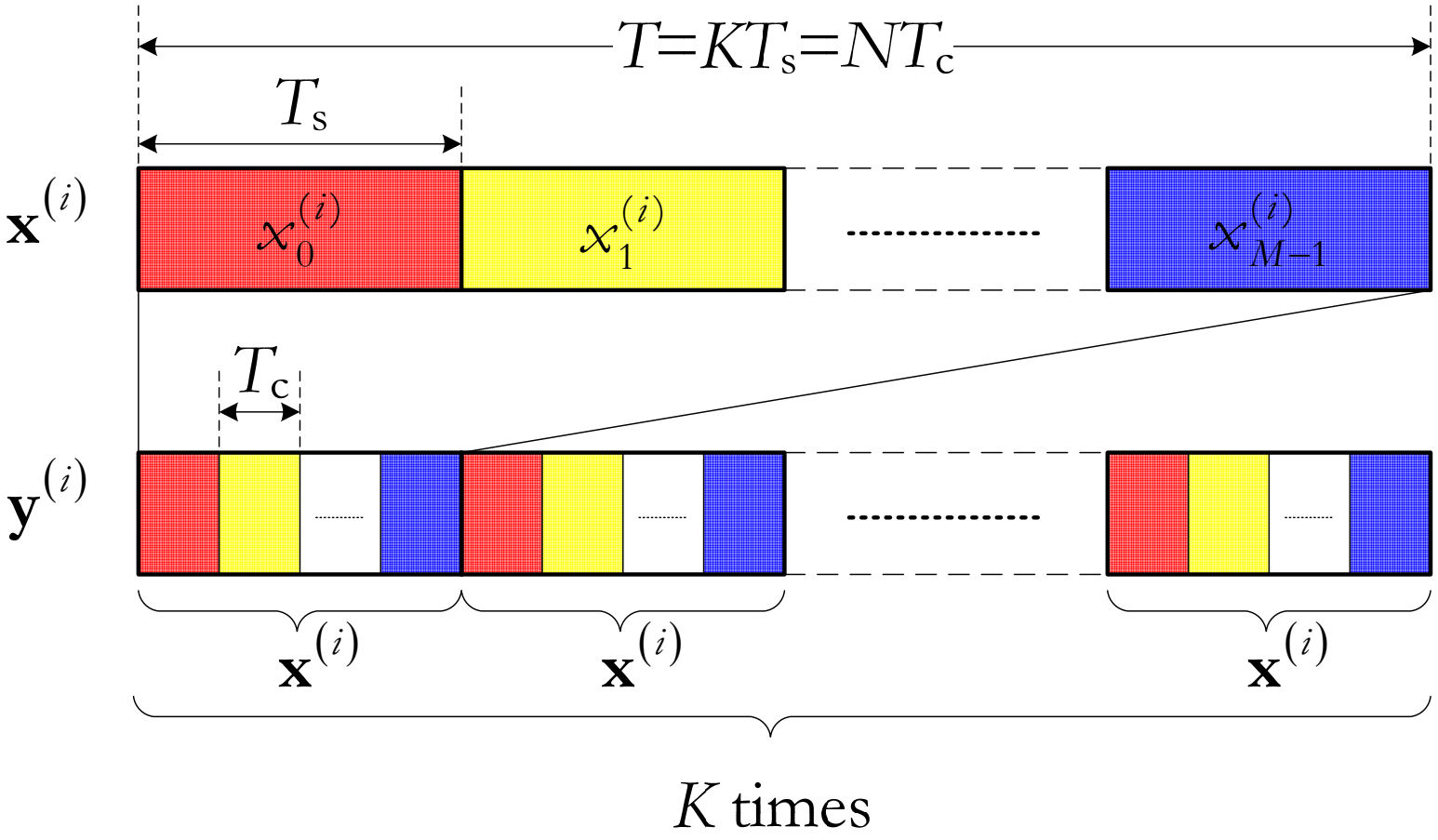
Advantages of OFDMA over TDMA

- 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 referred to as DFT-Spread OFDM(A).
- Time-domain generation of SC-FDMA is illustrated on the following slide.

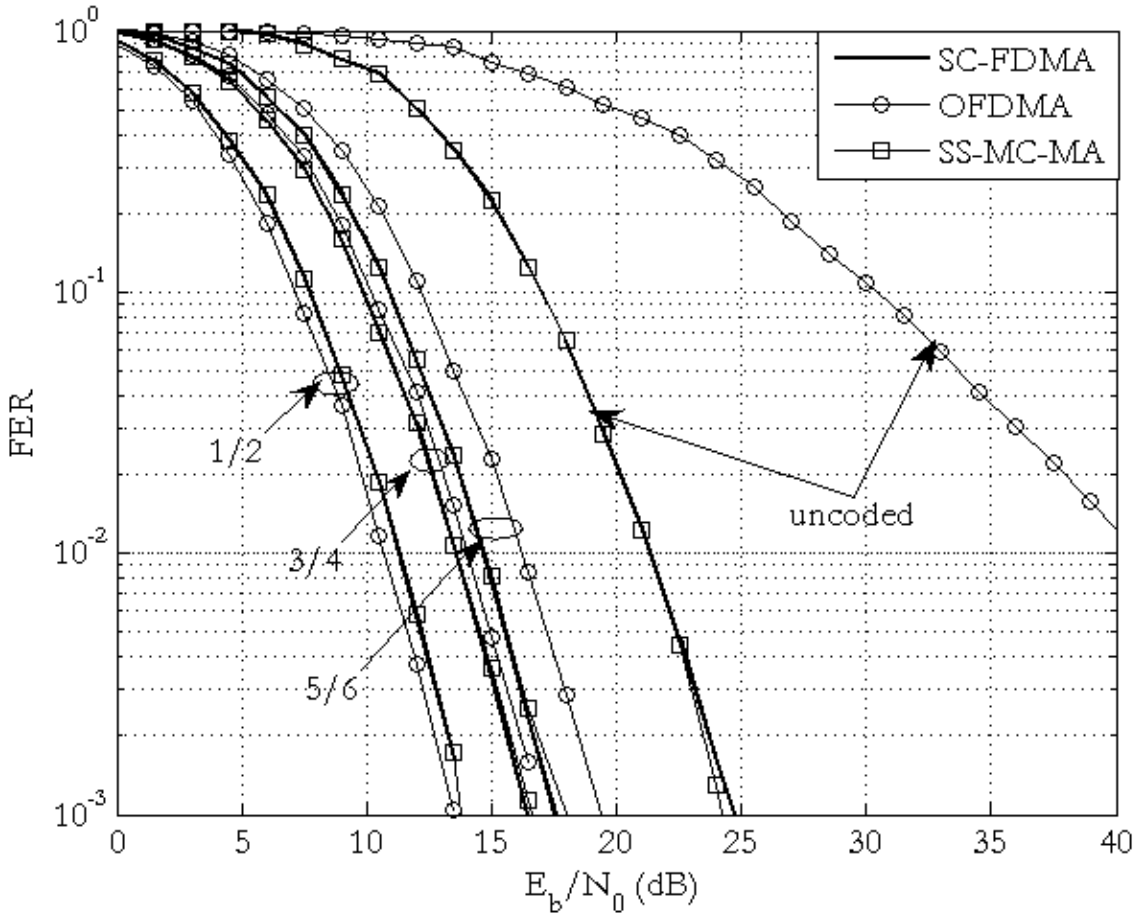
Time-Domain Generation of SC-FDMA



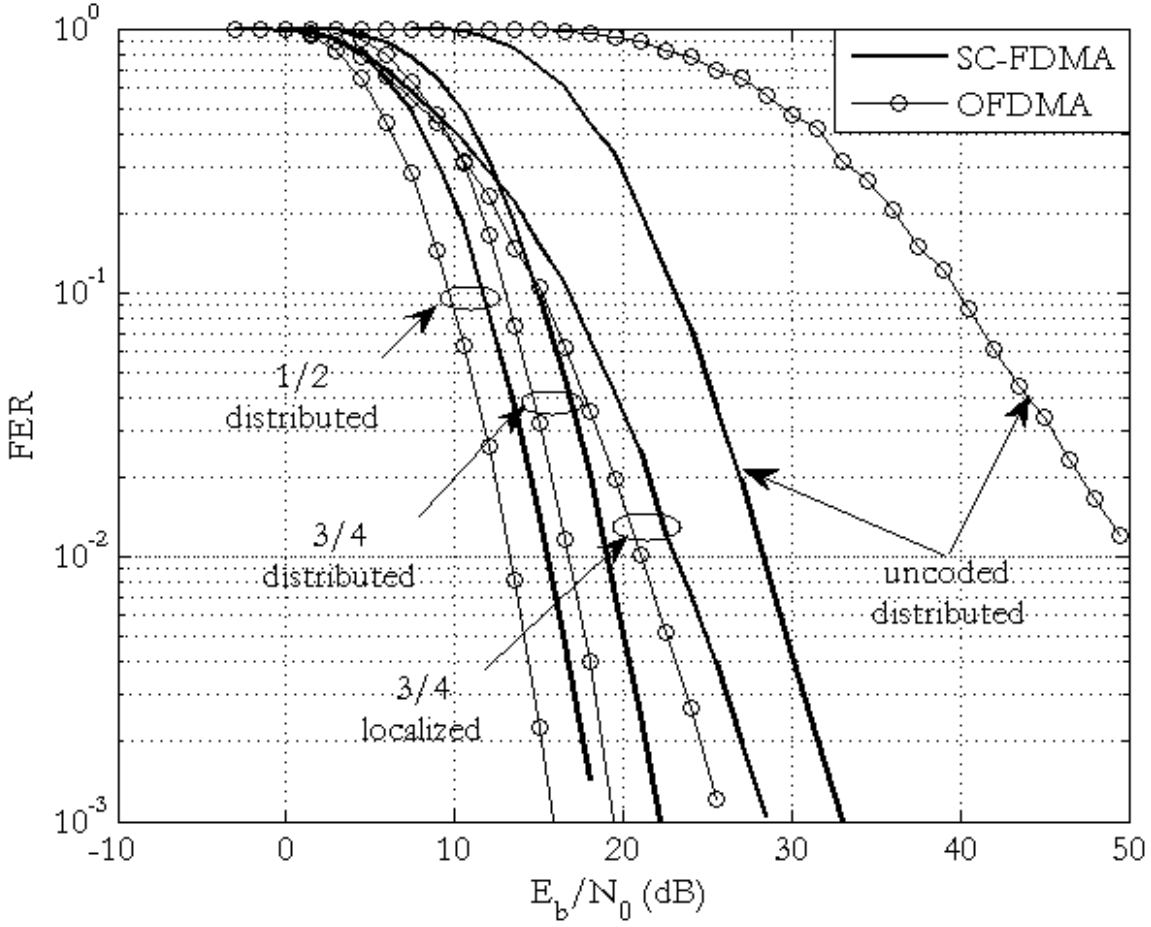
Performance Analysis

- 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.

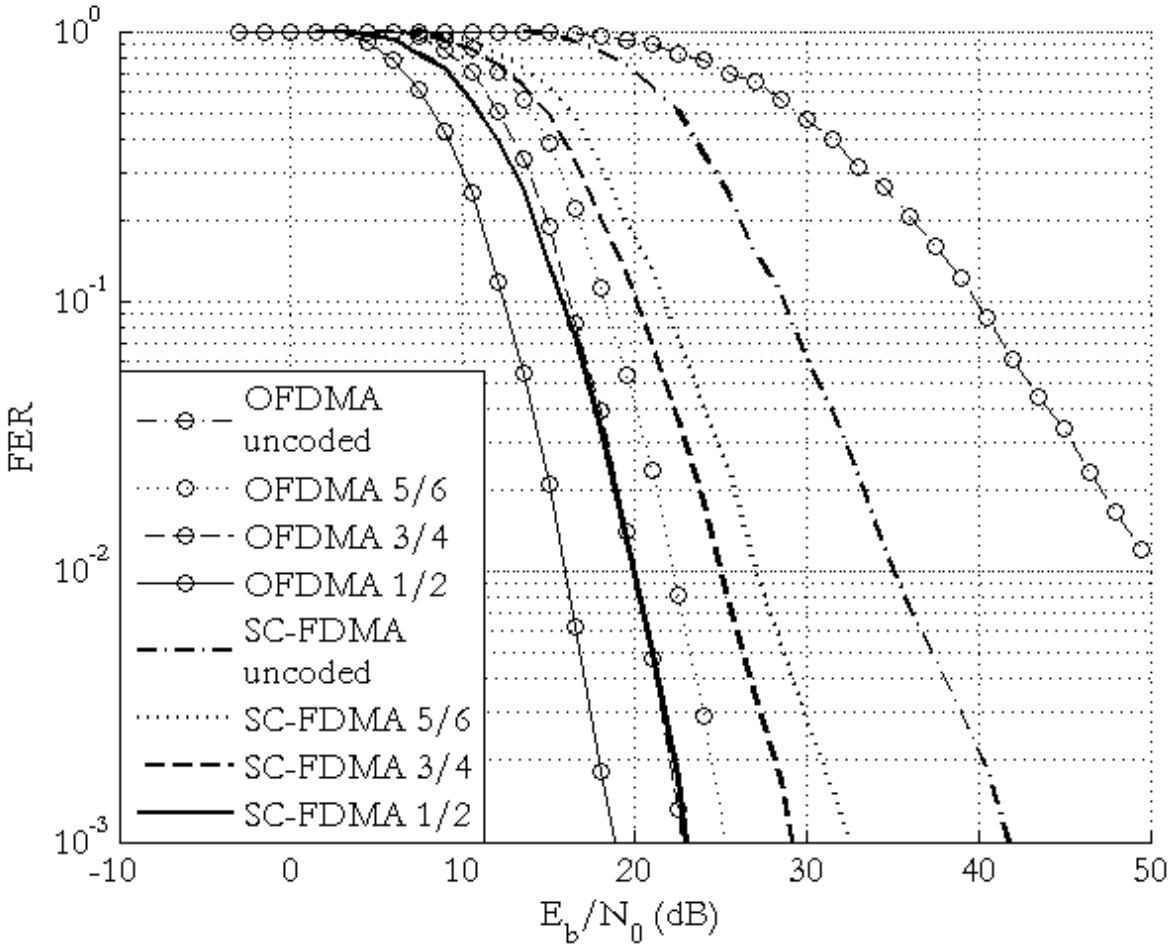
SC-FDMA vs. OFDMA with QPSK



SC-FDMA vs. OFDMA with 16-QAM



SC-FDMA vs. OFDMA with 64-QAM



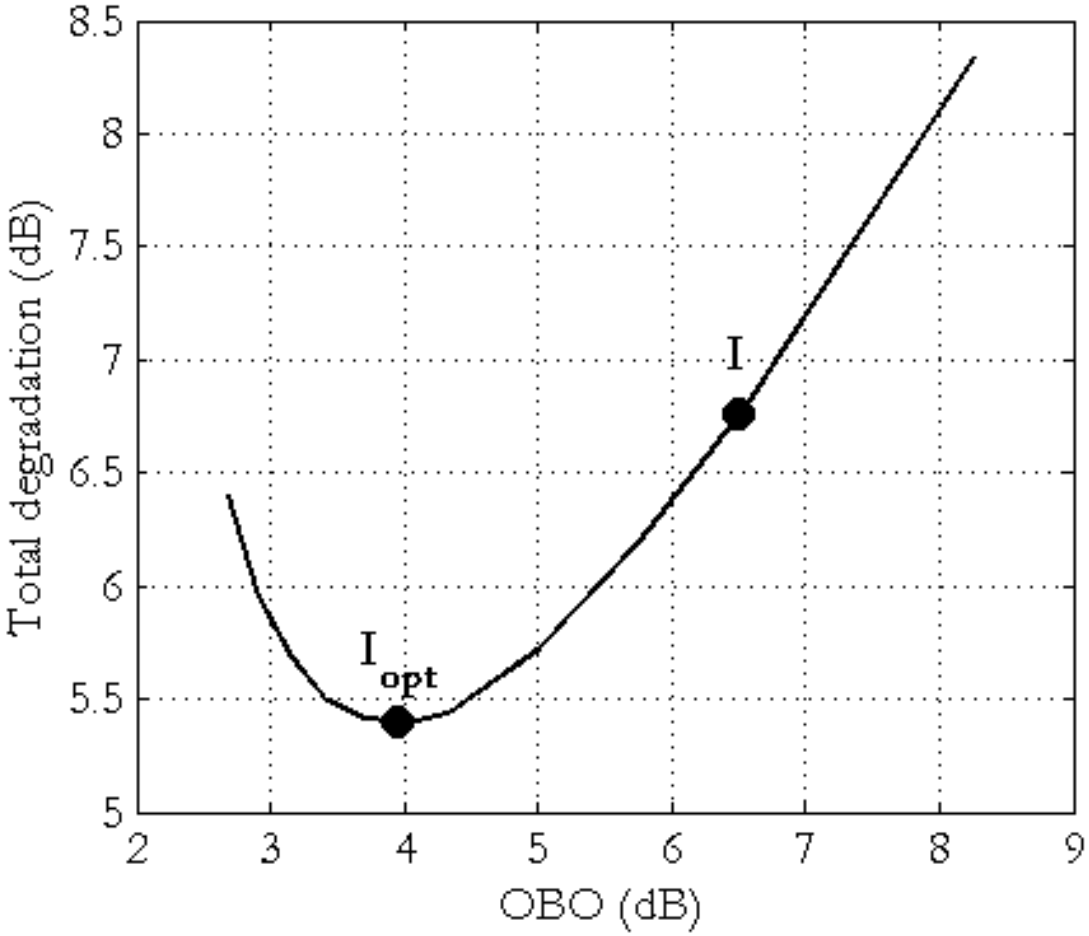
Gain of OFDMA over SC-FDMA

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

Impact of Nonlinear HPA

- Next, we investigated the impact of the HPA nonlinearity on the performance of the two multiple access schemes using the spectrum mask and other constraints of the LTE.
- The HPA output back-off was computed using two HPA models: the Rapp model and the Saleh model
- The simulations were performed for localized and distributed subcarrier allocations, and also for different numbers of RB allocations to users.

System Degradation due to Nonlinearity



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

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

Summary and Conclusions

- In the first part of this presentation, we gave a historical review of single-carrier transmission with frequency-domain equalization (SC-FDE) and of OFDMA.
- In the second part, we discussed the issue of SC-FDMA vs. OFDMA in the context of uplink for next-generation wireless communications systems.
- We have given results indicating that on a linear channel, OFDMA has a significant advantage particularly with high signal constellations.
- In contrast, SC-FDMA has a 1.5 – 2.0 dB advantage in terms of HPA output back-off.

Summary and Conclusions (cont'd)

- An overall comparison leads to the conclusion that SC-FDMA is superior when QPSK is employed, but OFDMA is superior with higher signal constellations.
- Since QPSK along with low code rates are used for users close to the cell edge, SC-OFDMA extends the cell coverage with respect to OFDMA.
- In contrast, OFDMA reduces the threshold of using higher-level signal constellations and increases the data rates of users not close to cell boundaries.
- This analysis suggests that neither multiple access scheme has a clear advantage over the other in all conditions.