Frequency-Domain Techniques in Wireless Communications: OFDM, Precoded OFDM and SCT/FDE

Hikmet Sari

SUPELEC, Plateau de Moulon, 3 rue Joliot-Curie
F-91192 Gif sur Yvette, France

ÉCOLE
SUPÉRIEURE
D'ÉLECTRICITÉ
Supélec

Presentation Outline

- Adoption of OFDM by the DAB and DVB-T projects in the late 1980s and early 1990s, and proposal of single-carrier transmission with frequency-domain equalization (SCT/FDE) as an alternative technique.
- The channel equalization issue; Discussion on SCT/TDE, SCT/FDE and OFDM.
- IEEE 802.16 specifications for broadband wireless access and work towards 4G cellular systems.
- Precoded OFDM and SCT/FDE.
- Recent progress in iterative frequency-domain decision-feedback equalization.
- Summary and conclusions

Some History

- The DAB and DVB-T projects in the late 1980s and early 1990s in Europe adopted and promoted OFDM.
- OFDM was perceived as the only transmission technology that is suitable for DAB and DVB-T applications, and more generally for mobile reception on difficult wireless channels.
- While it is true that OFDM has a number of attractive features, it was quite obvious that there was a lack of understanding of the channel equalization issue.
- At the 1993 Int. Tirrenia Workshop (Pisa, Italy), the present author suggested that a SCT/FDE system could realistically achieve the performance of OFDM while avoiding its PAPR and synchronization problems.

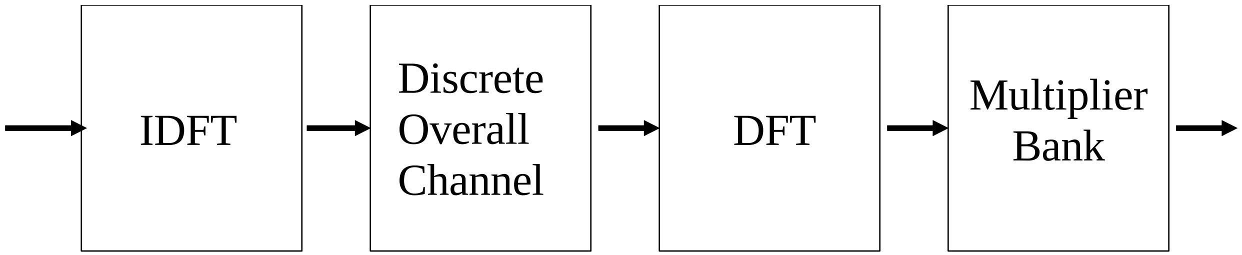
First papers

- The Tirrenia paper clarified a number of issues around OFDM and described a single-carrier alternative.
  - *H. Sari, G. Karam, and I. Jeanclaude, "Channel Equalization and Carrier Synchronization in OFDM systems", presented at the Tirrenia Int. Workshop on Digital Communications, Sept.1993.*
- In the 1993-95 time period, the same authors published several other papers on the subject, the most comprehensive one being the IEEE Communications Magazine paper below:
  - *H. Sari and G. Karam, "Transmission Techniques for Digital Terrestrial TV Broadcasting", IEEE Communications Magazine, vol. 33, pp. 100-109, February 1995.*

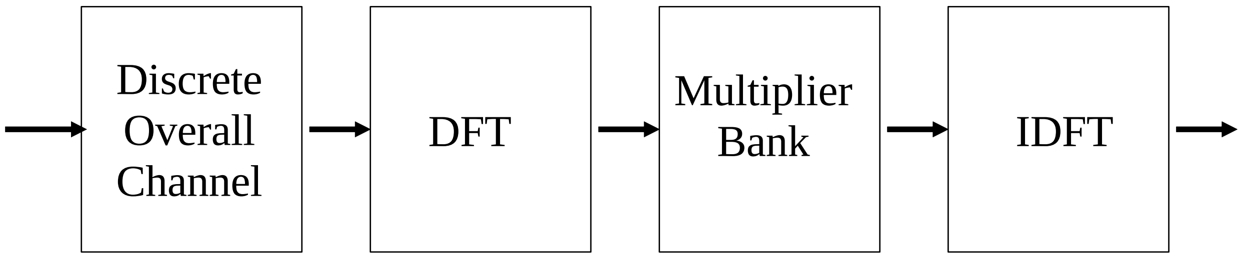
Motivation

- There were a number of statements about OFDM in the literature which did not seem correct or accurate: Increased spectral efficiency, multipath fading and intersymbol interference problems solved, ...
- The Tirrenia paper indicated that OFDM and SCT are similar in terms of spectral efficiency and that OFDM only shifts the multipath fading problem from the time domain to the frequency domain.
- It also indicated that OFDM breaks the frequency diversity and that channel coding was needed to restore it. In contrast, single-carrier systems can be used on multipath fading channels without channel coding.

OFDM and SCT/FDE: Similarities



(a) OFDM



(b) SCT/FDE

Basic building blocks in OFDM and SCT/FDE transmitters and receivers.

The Channel Equalization Issue

- The conventional approach to digital communications over dispersive channels is single-carrier transmission with time-domain equalization (SCT/TDE).
- Time-domain equalization covers the simple linear transversal equalizers, decision-feedback equalizers, as well as maximum-likelihood sequence estimation.
- These techniques have been in use for several decades in voice-band data transmission, digital microwave radio, and more recently in mobile radio systems.
- Time-domain equalization is not adequate for use on channels with very long impulse responses (complexity and adaptation problems).

The Limits of SCT / TDE

- Indeed, the optimum coefficients of a linear transversal time-domain equalizer are the solution of the matrix equation:

$$C = A^{-1}V$$

- The conventional least mean squares algorithm for coefficient adaptation at time *k* is

$$C_{k+1} = C_k - \alpha X_k^* e_k$$

- The adaptation of all coefficients is driven by the same error signal and consecutive input signals are correlated. This is not a serious problem if the number of taps is small, but the equalizer will have convergence problems with a large number of taps.

Ease of Adaptation of SCT/FDE

- Consider next an FDE with N taps. The DFT operator which forms the first stage of the equalizer gives N signal samples denoted (Y_1, Y_2, ..., Y_N).
- These samples are sent to a complex multiplier bank whose coefficients are denoted (F_1, F_2, ..., F_N). The coefficient values which minimize signal distortion are

$$F_n = \frac{H_n^*}{|H_n|^2} = \frac{1}{H_n}$$

- Clearly, each coefficient is only a function of the channel frequency response at the corresponding frequency, and the equalizer is easily adapted to channel variations even if the number of taps is very large.

FDE vs. TDE

- From the above discussion, SCT/TDE is sufficient for channels with a small delay spread, because these channels can be equalized using a small number of taps.
- In contrast, SCT/FDE or OFDM is required on channels with a large delay spread, as these channels require a large number of taps and this leads to convergence and tracking problems with SCT/TDE.
- In fact, these considerations indicate that the real problem is not OFDM vs. SCT, but instead frequency-domain vs. time-domain signal processing.

The Example of BWA Channels

- On some broadband wireless access (BWA) channels, the multipath delay spread spans less than 1 µs, but in some other cases, it spans 10 or even 20 µs.
- To assess performance of BWA systems operating between 2 and 11 GHz, the IEEE 802.16 group adopted the Stanford University Interim (SUI) channel models all of which are characterized by three paths.
- The table on the next slide gives the *rms* value of the delay spread and the delay and attenuation of each propagation path of the SUI models. These are averaged values, each path being also affected by Rayleigh fading.

SUI Channel Models

Model	Tap 1	Tap 2	Tap 3	*rms* delay (μs)
SUI 1	0 0	0.4 - 15	0.9 - 20	0.111
SUI 2	0 0	0.4 - 12	1.1 - 15	0.202
SUI 3	0 0	0.4 - 5	0.9 - 10	0.264
SUI 4	0 0	1.5 - 4	4 - 8	1.257
SUI 5	0 0	4 - 5	10 - 10	2.842
SUI 6	0 0	14 - 10	20 - 14	5.240

Discussion

- The channel dispersion in SUI 4 – SUI 6 models covers a large number of symbol periods. On a 7 MHz channel, the symbol period is 178 ns, and the SUI 5 model spans 56 symbol period.
- The SUI 5 model dispersion spans 112 symbol periods over a 14 MHz channel and 224 symbol periods over a 28 MHz channel.
- The numbers above are doubled for the SUI 6 model whose impulse response spans 20 µs.
- Therefore, the transmission technique to be used in these systems must be able to compensate for channel impulse responses spanning hundreds of symbol periods.

IEEE 802.16 Specifications

- A large consortium proposed SCT/FDE to the IEEE 802.16 group for BWA systems operating on licensed frequency bands between 2 and 11 GHz.
- The other two proposals were based on OFDM: OFDM/TDMA and OFDMA.
- The group could not have the required majority for either of these proposals and decided to include the three techniques as different modes in the standard.
- Since standards do not actually specify implementations, the IEEE 802.16 specifications mention SCT instead of SCT/FDE, but a cyclic prefix is included in the frame structure to allow for SCT/FDE.

More on SCT/FDE and OFDM

- The normalized complexity of both OFDM and SCT/FDE is proportional to log(N), whereas the complexity of SCT/TDE grows linearly with the number of taps N.
- For N large, the complexity considerations clearly favor the use of frequency-domain techniques.
- SCT/FDE avoids the well-known peak-to-average power ratio (PAPR) of OFDM, which leads to an inefficient use of the transmit power amplifier.
- Another important difference between SCT/FDE and OFDM is related to frequency diversity. Since OFDM breaks the frequency diversity, it requires powerful channel coding or precoding to recover it. In contrast, SCT/FDE can work on dispersive multipath channels without any coding.

Precoded OFDM Mimics SCT/FDE

- Precoding in OFDM disperses the energy of symbols over the channel bandwidth, i.e., it restores the frequency diversity broken by the IDFT operator.
- A common precoding matrix is the Walsh-Hadamard matrix which uniformly spreads the symbol energy across the channel bandwidth using orthogonal spreading sequences.
- Another precoding matrix that uniformly spreads the symbol energy over the channel bandwidth is the DFT matrix. This matrix cancels the IDFT matrix that generates the OFDM signal and the system reduces to SCT/FDE.
- From this discussion, it is clear that Precoded OFDM mimics SCT/FDE. That is, by precoding OFDM in order to restore frequency diversity, we get an SCT/FDE-type system.

Work at WWRF

- The Wireless World Research Forum (WWRF) is a large industry forum with member organizations from all over the world.
- The goal is to coordinate research toward the so-called Beyond-3G or 4G systems and publish white papers giving a common vision.
- Air interface topics are handled by Working Group 4. This group has released a white paper which summarizes contributions from different members.
- Multi-carrier and single-carrier based proposals have been gathered under the generic name “Frequency-domain techniques”. There is a general consensus in this group that SCT/FDE would fit better than OFDM on the uplink.

Frequency-Domain DFE

- To improve performance of SCT/FDE, *Falconer et al.* proposed a hybrid equalizer in which the feedforward part is in the frequency domain and the feedback part is in the time domain (*IEEE Comm. Magazine, April 2002*).
- With ideal decision feedback, this structure was shown to yield better performance than OFDM on the SUI-5 channel.
- This paper also highlighted the potential of a dual-mode system employing SCT/FDE on the uplink and OFDM on the downlink. This solution solves the uplink PAPR problem and also reduces the number of FFTs in the user terminal.
- Since SCT/FDE and OFDM use the same building blocks, a software-defined radio modem can be configured to implement both techniques.

Iterative MMSE DFE

- More recently, *Benvenuto et al.* proposed an iterative DFE structure in which both the feedforward and the feedback filters operate in the frequency domain.
- The first decisions are those of a linear MMSE equalizer. The decision process is reiterated by feeding back the decisions from the previous iteration.
- In contrast with conventional time-domain DFEs which cancel causal interference only, iterative block DFEs cancel both precursor and postcursor interference.

Matched-Filter Based Iterative DFE

- Consider a frequency-domain DFE whose feedforward filter performs matched filtering ($F_n = H_n^*$, n=0, 1,...., N) and the feedback filter coefficients are given by $B_n = 1 - F_n H_n$.
- The feedforward filter maximizes SNR and the feedback filter attempts to restore the spectrum. The matched filter bound would be achieved if all decisions were correct.
- But such a DFE is unlikely to converge, because the first decision block is obtained without a feedback part and the matched filter increases channel distortion.
- To implement an MF-based DFE, the feedforward filter can be made to converge from a ZF or MMSE filter to the MF over a number of iterations.

MF-Based Iterative DFE (cont'd)

- One way to do this is to make linear interpolation between the two solutions. At the *k*th iteration, the feedforward and feedback coefficients are given by:

$$F_n^{(k)} = \alpha_k \frac{H_n^*}{|H_n|^2 + \sigma_w^2 / \sigma_a^2} + (1-\alpha_k) H_n^*$$

and

$$B_n^{(k)} = 1 - F_n^{(k)} H_n$$

with

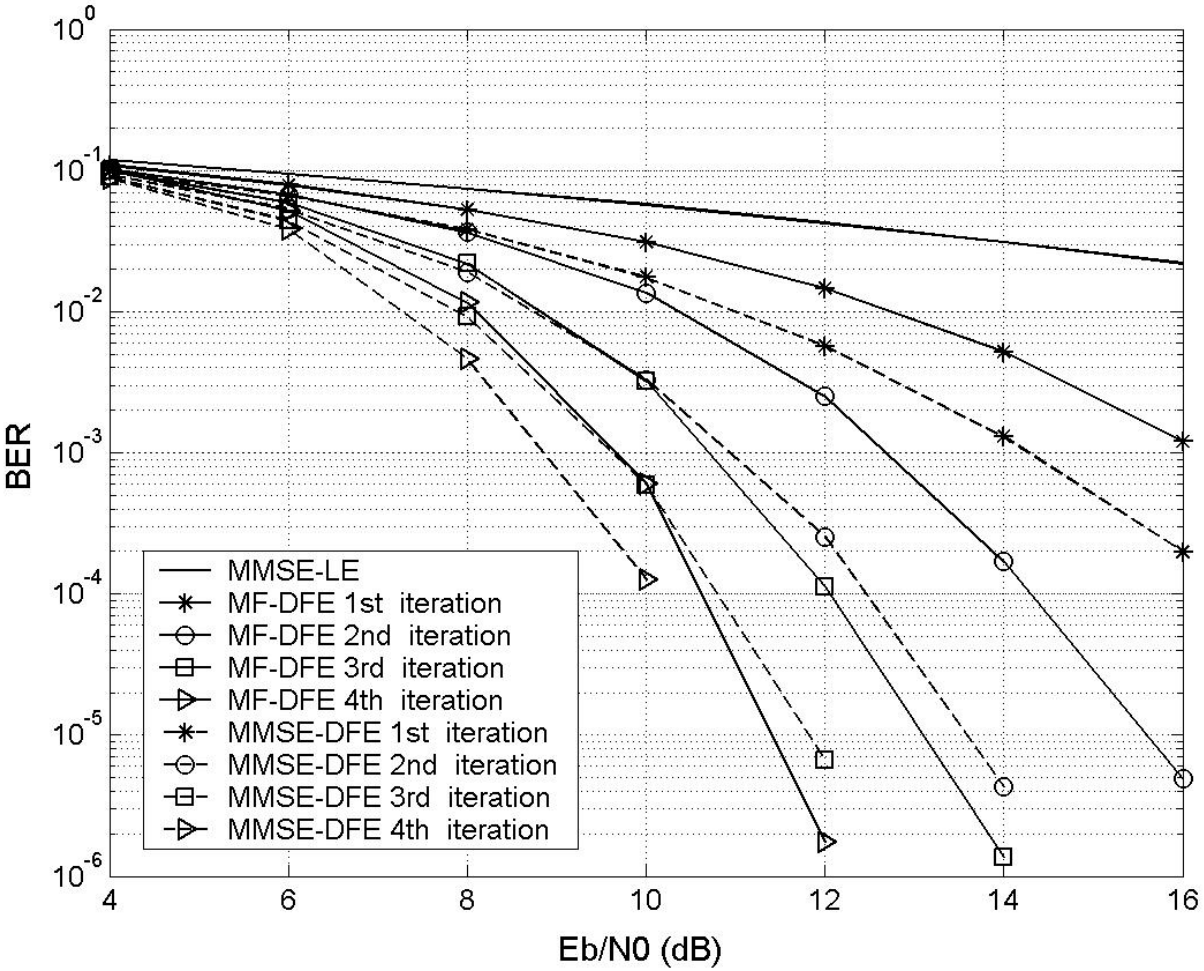
$$\alpha_k = 1 - k / K$$

- For k = 0, the equalizer is an MMSE LE, and for k = K, the equalizer is an MF-based DFE.

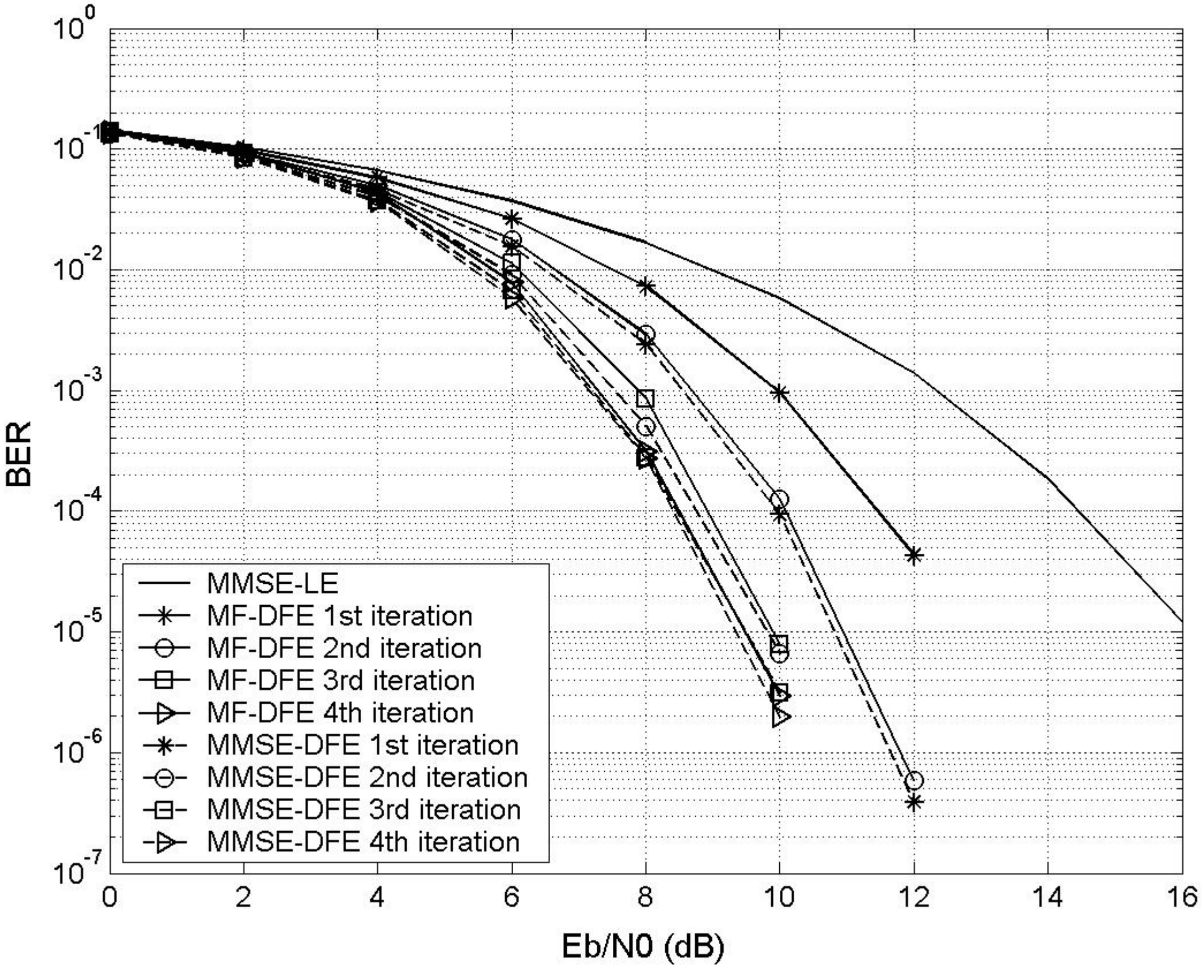
Simulation Results

- Computer simulations were performed to evaluate the performance of the proposed iterative DFE and compare it to the MMSE DFE of *Benvenuto et al*.
- The simulations were carried out using the QPSK signal format and 256-point DFT in the equalizer.
- The K parameter was 4, i.e., 4 iterations were performed after the first set of decisions using an MMSE LE.
- Two channels were used: The first is the Proakis-B channel which corresponds to a static channel with a very deep fade. The second is a multipath channel with equal-power uncorrelated Rayleigh fading coefficients.
- The channel response was assumed perfectly known from the receiver.

Performance on Proakis B Channel



Performance on Multipath Fading Channel



Summary and Conclusions

- We have given a common framework to OFDM, Precoded OFDM and SCT/FDE, and suggested that the real question is not OFDM vs. SCT, but rather frequency-domain vs. time-domain processing.
- We have summarized standardization at IEEE 802.16 for BWA and also work toward 4G systems at WWRF.
- We have summarized the latest developments in frequency-domain equalization: From LE to DFE with time-domain feedback, to DFE fully in the frequency-domain, and finally to iterative frequency-domain DFE.
- The most appealing feature of OFDM is that the frequency dimension can be used for multiple access (OFDMA), and this leads to cell range extension.