Signal Processing Challenges from Audio-Video Coding to Telecommunication: A Living Piece of History

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ABSTRACT

When I was invited to contribute to the celebrations in honour of Prof. Giovanni Sicuranza, I accepted with enthusiasm. Giovanni is a prominent figure in Italian DSP (Digital Signal Processing) research history and I am fortunate enough to have been acquainted with him since the beginning of my career. When I joined *Telettra* and began working in Audio-Video Coding research, Giovanni had already started his long-lasting and fruitful cooperation with the *Telettra* DSP Laboratory. This highly constructive relationship continued after *Telettra* was acquired by *Alcatel*, and I enjoyed the invaluable experience to share with Giovanni an exciting research season.
Not only. In 2000, the DSP Lab started working in the area of Telecommunication and also in this research field the studies conducted with Giovanni deeply influenced the activity developed by *Alcatel*, first, and by *Alcatel-Lucent* later on, and prompted their Italian branch to produce outstanding results.

Index Terms **—** Signal Processing, Telecommunication, History, DSP, ASIC.

1. INTRODUCTION

This paper aims at drawing a historical path of Audio-Video Coding research, starting from the beginning stage, when Prof. Giovanni Sicuranza began to collaborate with the *Telettra* DSP Laboratory.
The first paragraph introduces the key research topics at which the DSP Lab started working in the Eighties: non-linear filtering, Discrete Cosine Transform (DCT), non-linear prediction, and eventually, after the acquisition of *Telettra* by *Alcatel*, also neural networks and sampling frequency conversion algorithms**.**
The second paragraph describes the industrial impact of this research activity, which allowed *Telettra* to be the first company in the world able to broadcast live HDTV signal at 45Mbit/s during the FIFA World Cup in 1990.
The third paragraph highlights the very significant results in the field of Telecommunication produced by the strong background created in almost twenty years of research. To that effect, it is worthwhile mentioning, among the most advanced challenges, one of the most recent applications, *e.g.*, coherent optical transmission.
As a conclusion, I shall underline that the most advanced telecommunication applications are still based on the innovations that were introduced at that time.

2. LAYING THE FOUNDATIONS

2.1. Non-Linear Filtering

In the Eighties, the team at the DSP Lab was working on identifying an echo canceller algorithm. At that time, this issue was still an unresolved one and was at the forefront of scientific investigation. The researchers found a solution based on a class of non-linear digital filters that was implemented by means of discrete Volterra series. These studies led to an appreciated publication of an international level [1].

2.2. DCT and Non-Linear Prediction

Digital television had its beginning in the Eighties, when standardization activity, in ETSI first, and in MPEG later on, was at its top. The quest for a video coding algorithm was one of the highest priorities in *Telettra*, which had already realized the first prototypes. The DSP Lab was working on different algorithms, including DCT transform [2], which was later recognized as the key fundamental block for image compression. We also studied image interpolation technique, based on non-linear filtering, which was needed for prediction schemes.
At that very early stage of video compression, the key challenge was to develop a fully digital system for broadcasting applications. There were two separate aspects to consider: on the one hand, scientific research, with a view to selecting the best algorithm; on the other hand, implementation design, in order to keep the algorithm complexity within the bounds of the available state-of-the-art of microelectronics.
Simulation activity was essential to demonstrate the effectiveness of this compression methods and several steps were required to obtain the optimal compromise between the algorithm complexity and its performance, which affects the final video quality.
The research team in particular focused on analysing the compression performance, taking into account the effect of coefficient quantization and finite precision arithmetic implementation [3], [4] and [5]. Eventually *Telettra* DSP

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Lab succeeded in implementing of one of the first DCT chips, able to process digital video (CCIR 601, i.e. 216Mbit/s). It was developed using LSI HCMOS process @27MHz with a complexity around 50Kgates. A lot of effort was spent to reduce the complexity by means of sophisticated serial arithmetic.
The activity on non-linear interpolation was very important to improve the video-codec introducing prediction schemes and motion compensation [6] and [7], which was later used in MPEG2 encoder for quality enhancement [8], [9] and [10].

2.3. New Challenges

After the acquisition of *Telettra* by *Alcatel*, the DSP Lab's activities continued to address audio and video coding with a broadened scope.

2.3.1. Neural Networks

At the beginning of the Nineties, our interest was taken by Neural Networks (NN) that seemed to promise that adaptive systems could converge to optimal solutions for almost any application. We started to apply these techniques to video coding, trying to replace the "standard" subsystem that was used for video coding (*i.e.*, transformation, quantization and motion estimation). We eventually reached the genuinely academic objective to build a complete video codec based on NN technology. Even though it could not have a practical impact in the industry, this result was widely recognized in academic literature, since it proved that performance of DCT is very close to a complex adaptive system after training convergence. This activity lead to a couple of publications, [12] and [13] that raised a high academic interest. Moreover, we organized on this topic an international workshop that was hosted by *Alcatel*.

2.3.2. Sampling Frequency Conversion Algorithms

We subsequently concentrated on sampling frequency conversion algorithms, with outstanding achievements. The target application was audio signal, for which AES-EBU standard foresees different possible values (32, 44.1, 48, 96, 128, 192 kHz). We reached a brilliant solution using an adaptive filter bank and a spline interpolation function. The real time implementation on a standard DSP showed outstanding performances [11]. This work deserved general recognition in the scientific community and was referred to in the fundamental text in this research field, *i.e.*, *Digital Signal Processing* by Prof. Sanjit Mitra.

3. BUILDING ON: ACHIEVMENTS ON AUDIO-VIDEO APPLICATIONS

In the Nineties, the DSP Lab conducted a highly significant research activity on audio-video coding. We played a crucial role in the MPEG2 standardization both for video and audio coding. As is well-known, *Telettra* was the first company in the world able to broadcast live HDTV signal at 45Mbit/s during the FIFA World Cup 1990, cooperating together with RAI, the Italian broadcasting corporation. We gained a formidable, worldwide reputation in the scientific community and in the eyes of industry (see *The Italian Connection* in [14], p. 76).
A few months after that historical exploit, *Telettra* was acquired by *Alcatel*. However, the Lab, that was awarded the title of *Alcatel Corporate Research Centre*, continued investigating DSP research area in audio and video coding.
In a couple of years, the DSP Lab further extended its competence to speech processing, including speech recognition and text to speech applications. We assisted many *Alcatel* divisions all over the world providing platforms and implementation of a large variety of algorithms.

4. A NEW RESEARCH PHASE FOR THE LAB IN TELECOMMUNICATION

A few years later, however, *Alcatel* abandoned audio-video coding and signal processing research. The DSP Lab was closed in 2000, and the same team of researchers ultimately started to work as *Alcatel Advanced Research Lab* in telecommunication area.
It was surprising how the previous experience immediately found interesting applications in the new field. I should recall here that the theory of digital signal processing had evolved after the milestone of Shannon's work published in 1948, until reaching full maturity in the Eighties. At that time, new developments in microelectronics eventually allowed to convert scientific results into industrial products. When we began to work in the Telecommunication field, the research challenge was integrating packet function into legacy PDH/SDH network. We took advantage of our ability to work on processing platforms in order to design new functionalities. We eventually realized that the same search algorithm that was used for vector quantization could be employed as well for packet header matching. Similarly, we ascertained that the algorithms that was being used for managing the packet scheduler were very close to variable rate video source adaptation to a constant rate channel.
Different examples could be brought here. However, the case for coherent optics digital receiver seems to me of particular interest, because it is at the edge of present technology and best represents the most advanced trend of telecommunication network evolution.

4.2. Coherent Optics Digital Receiver

One of the challenges that signal processing theory is facing these days is serving optical transmission [16]. The digital transmission has evolved from the very old PCM system (F_s=8 kHz, 8 bit/sample), in parallel to microelectronics capability It has become able to deal with analog line first, with radio links second, and eventually optical transmission. AD/DA devices can work today at 56 GHz with 8 bit/sample [17] and CMOS integrated circuits, working in the range of 0.5 to 1 GHz, with a complexity up to 20B gates.

The booming bandwidth demand justifies investments in the new optical technology to provide end-to-end solutions. Coherent optics has been recognized as the most promising solution for long-haul optical transmission [19]. The term "coherent" indicates that the reference timing of the receiver has to be reconstructed in order to be synchronous with the source.

The actual challenge of digital signal processing section is to compensate the highly non-linear phenomena involved in the electro-optical conversion and in the optical propagation.

The transmission section [20] addresses the following items:

– data mapping onto phase, amplitude, and polarization;
– transmitter synchronization and timing;
– dispersion pre-compensation;
– RF drivers and E/O equalization, as well as non-linearity compensation.

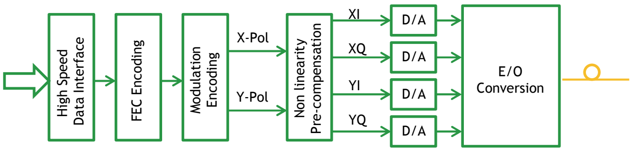

Fig. 1 – Coherent Transmitter Architecture.

The receiving section [19], [20] is even more complex and challenging. It comprises:

– dispersion compensation;
– carrier recovery, polarization recovery, clock recovery, framing;
– channel equalization;
– receiver synchronization and timing;
– data detection and de-mapping.

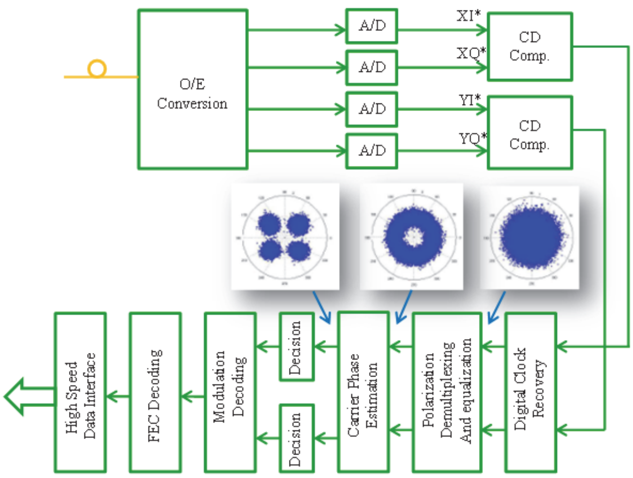

Fig. 2 – Coherent Receiver Architecture

However, since the CMOS technology has evolved more in space than in frequency, the past use of serial processing has been substituted by a massive usage of parallel processing. For a 100 Gb/s transmission, system sampling frequency is set to around 60GHz with an 8bit/sample resolution, while the processing clock speed is about 1/100 of the sampling frequency. This choice exploits the intrinsic parallelism of the DSP algorithms.

Many techniques that were developed for audio and video applications are now being reused in coherent receivers. For instance, it is possible to digitally compensate frequency and phase shift, instead of synchronizing the local oscillator with the source. The implementation takes advantage of the adaptive interpolation filter, which is similar to the one that was developed in 1991 for audio processing.

Fast filtering needed for chromatic dispersion compensation uses FFT circuits with an architecture comparable to the DCT employed in video coding. It implements an equivalent filter of about 3000 taps and the entire system performs about 20T multiplications per second.

Trigonometric functions are carried out with the same CORDIC circuits that were employed in video demodulation, and equalization is based on LMS filtering, that was applied in voice coding.

Finally, the experience on line coding that was developed for video transmission (*i.e.*, Reed Salomon) is also fully reused for this application.

Thanks to our contribution, *Alcatel-Lucent* was the first company in the world to be able to commercialize a 100Gbit/s solution for its products.

5. AS A CONCLUSION

The experience that has been accumulated throughout thirty years of DSP research instructs us on the importance of investing on fundamental research. Only fundamental research indeed permits to lay the foundations to build upon subsequent results. Furthermore, feeding the virtuous circle of cooperation between universities and industry is crucial not only in order to support research, but also with the view to make innovation and business.

ACKNOWLEDGMENTS

I am grateful for his friendship and inestimable cooperation to Prof. Giovanni Sicuranza, who has been one of the driving forces behind this research adventure.

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