SMPTE Meeting Presentation

The Origins of Audio and Video Compression:

Some Pale Gleams from the Past

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Abstract. *The paper explores the history that led to all audio and video compression. The roots of digital compression sprang from Dudley's speech VOCODER, and a secret WWII speech scrambler. The paper highlights these key inventions, details their hardware, describes how they functioned, and connects them to modern digital audio and digital video compression algorithms.*

The first working speech synthesizer was Homer Dudley's VOCODER. In 1928, he used analysis of speech into components and a bandpass filter bank to achieve 10 times speech compression ratio.

In 1942, Bell Telephone Laboratories' SIGSALY was the first unbreakable speech scrambler. Dudley with Bell Laboratories invented 11 fundamental techniques that are the foundation of all digital compression today. The paper concludes with block diagrams of audio and video compression algorithms to show their close relationship to the VOCODER and SIGSALY.

Keywords. audio compression, speech compression, video compression, spread spectrum, coded orthogonal frequency-division multiplexing, COFDM, mobile phone compression, speech synthesis, speech encryption, speech scrambler, MP3, CELP, MPEG-1, AC-3, H.264, MPEG-4, SIGSALY, VOCODER, VODER, National Security Agency, NSA, Homer Dudley, Hedy Lamarr.

Introduction

The origins of modern digital audio and video can be traced back to the first electronic speech synthesizer in 1928 and to a secure speech scrambler used during WWII. Homer Dudley's VOCODER paved the way towards modern audio and video compression. An early connection to digital imaging is the very first digitized image: a 2.5 megapixel woven silk portrait made in 1849, of Joseph-Marie Jacquard, inventor of the punched card programmed loom, Fig. 1.

Fig. 1. A 2.5 megapixel woven silk portrait made in 1839 on punch card programmed loom

Bell Telephone Laboratories' SIGSALY secure communications system marked the invention of a number of techniques that lie at the foundation of virtually all DSP and signal processing for coding and audio transmission today. SIGSALY also included frequency division multiplex, an early form of spread spectrum.

Dudley's VOCODER

1. Dudley's pioneering work

Homer Dudley, at Bell Telephone Laboratories, Fig. 2, applied signal analysis to determine speech variation in time and frequency domains. He started with the goal of compressing speech bandwidth down from 3 kHz to 300 Hz for transmission over transcontinental telegraph cables. Speech-capable transcontinental cables were not available until 1956. Dudley conceived the first working speech analyzer and synthesizer, the VOCODER.

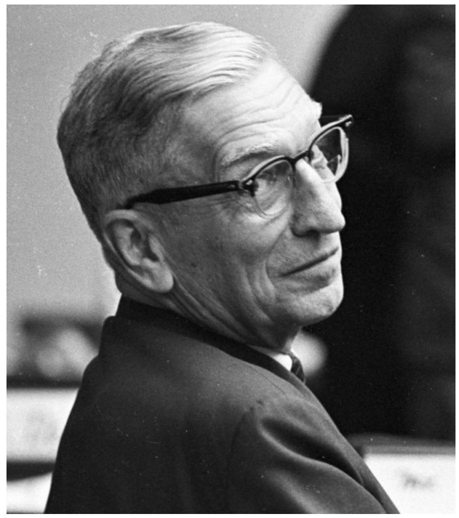

Fig 2. Homer Dudley at Bell Telephone Laboratories

1.1 Dudley's VOCODER

The concept of the VOCODER is a based on speech analysis and synthesis using the carrier nature of speech, Fig. 3. In 1928, Dudley discovered that the lungs, vocal chords, tongue and nasal cavities, are analogous to that of a power supply, carrier oscillator and time varying filter.

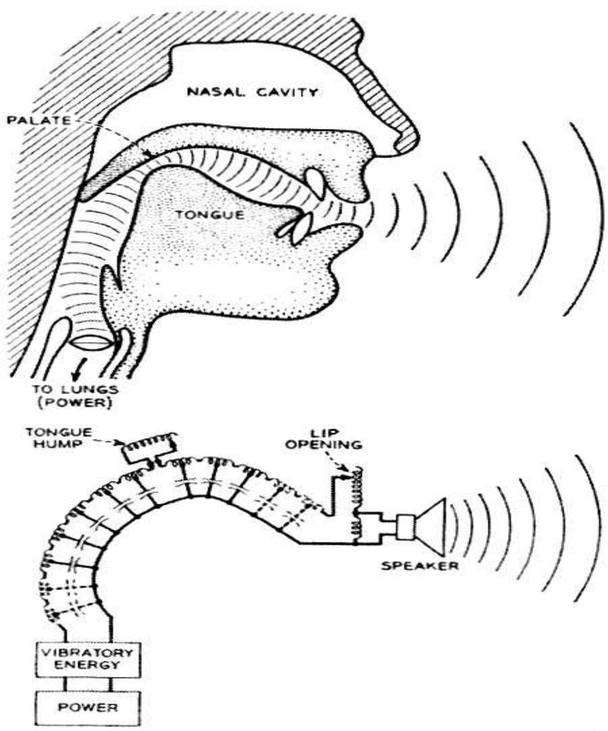

Fig 3. Dudley's VOCODER concept

First, the VOCODER determines whether a speech sample is voiced or unvoiced. If it is voiced, the pitch is extracted, Fig. 4. The frequency spectrum of the speech sample is then divided into sub-bands by a filter bank, and the amplitude of each sub-band is detected. The output of the analyzer section of the VOCODER consists of a voiced/unvoiced binary, a pitch signal and ten detected sub-bands. These signals each have ~25 Hz bandwidth. The VOCODER analyzer output contains the original speech information in ~300 Hz bandwidth. The result is a 10 times compression of the speech bandwidth.

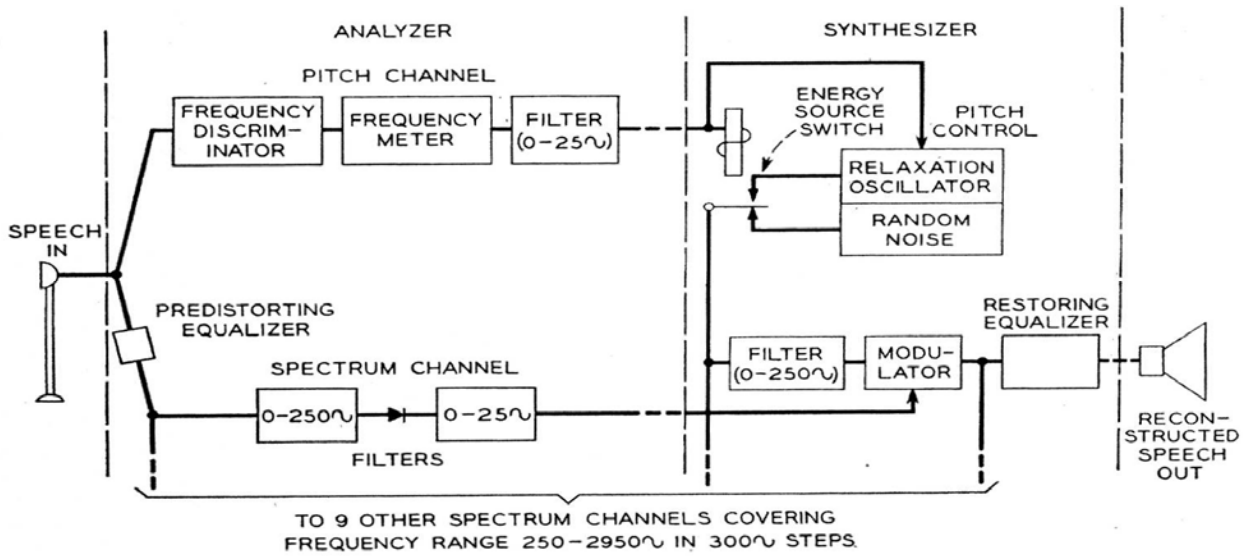

Fig 4. Block diagram of the Dudley VOCODER

Speech can be reconstructed from these signals using the VOCODER synthesizer, which performs the inverse process. The synthesizer of the VOCODER has a noise generator and a variable-frequency relaxation oscillator, rich in harmonics. The voiced bit selects the oscillator and the unvoiced bit, the noise generator. The oscillator frequency is controlled by the pitch signal. The voiced/unvoiced bit selects the type of source, whose output is applied to a filter bank whose sub-bands are varied in gain according to the synthesizer sub-band outputs. The filter bank dynamically modifies the harmonic spectrum of the oscillator. Inter-syllable pauses are inserted by a muting control signal. The result is reconstructed and synthesized speech.

The analyzer signals are sampled in time and quantized. Good speech quality requires a sample rate of 20 ms. Recognizable speech can be reproduced with as little as six levels of quantization on the sub-band detector outputs. The pitch signal requires higher resolution, 36 levels. Applications include speech research, speech compression and speech encryption, by scrambling the VOCODER analyzer outputs.

1.2 VOCODER compression with transmission

Fig. 5 shows the Dudley VOCODER principle, emphasizing the separation of encoder and decoder and the transmission of the compressed 300 Hz bandwidth signals, via radio or other transmission (or storage) means. The general processes of analysis into components, multiplex, transmission, reception, demultiplex and synthesis is used in all forms of compression today.

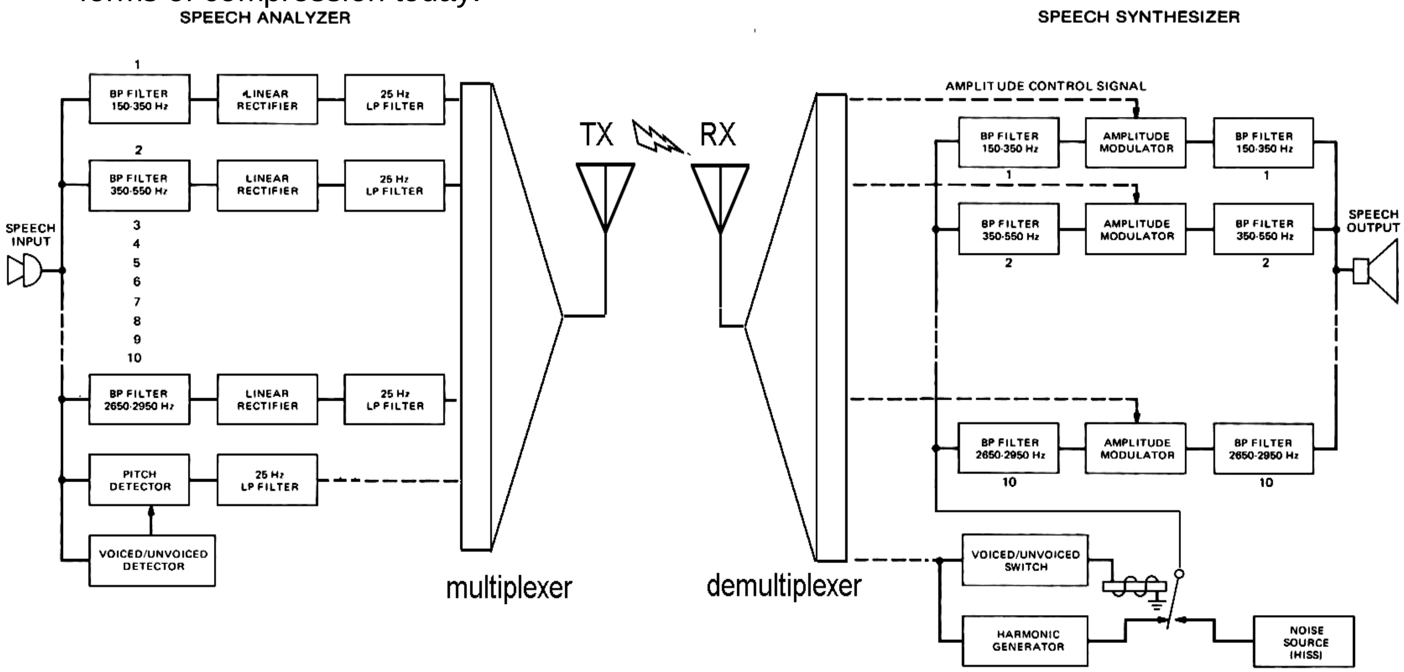

Fig 5. VOCODER with Transmission Path

2. Secret Telephony Development

2.1 Generalized Secrecy Systems

Codes and ciphers have been in use since the Roman Empire. The basic principles of secret transmission apply to codebooks, mechanical, or modern computer encryption, as well as to modern compression where encryption or digital rights management (DRM) is employed. A message and key are input to a cipher system. The key is transmitted via a secure method to the recipient. The enciphering device mixes the message and key to produce unrecognizable output.

The enciphered message or cryptogram can be transmitted over a channel, but it is subject to eavesdropping by the enemy, e.g., a radio transmission to a ship at sea. The ciphered message and the key are combined at the receiving station in a deciphering device. The decryption process recovers the original message only if the correct key is used. The essence of cryptology is the design of an enciphering algorithm and the generation, transmission, synchronization and destruction of a unique key.

2.2 Secret Telephone System, Band splitting Frequency Inversion: AT&T A-3

Frequency inversion was an early speech encryption system. Other techniques consisted of mixing or modulation of the speech with noise. In the frequency inversion method, incoming speech is divided into several sub-bands by band-pass filters, then a double-balanced mixer, modulates the output of each filter. The mixer outputs go to another bank of band-pass filters which select the difference frequency of the mixer output.

The band-pass filter outputs are summed together. The summed signal has the same bandwidth as the speech input. The result is the frequency order of the sub-bands is scrambled, and the sub-bands themselves are inverted. The receiver performs the reverse process, reconstructing the original sub-bands.

This system was realized in the AT&T A-3 speech scrambler. Fig 6. shows the principle of the A-3. Although it worked, it did not provide a good level of secrecy. As speech is very redundant, a trained listener could interpret the scrambled speech.

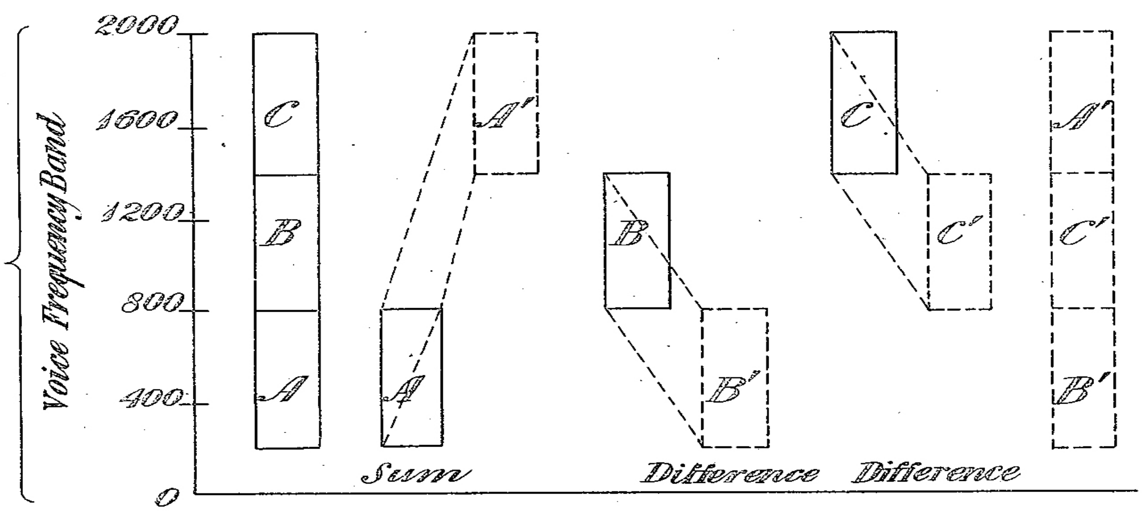

Fig 6. AT&T A-3 Frequency Inversion speech scrambler block diagram

2.3 Dudley Patent, Secret Telephony

Homer Dudley approached the speech secrecy problem in 1941 by using his VOCODER combined with a random key stored and distributed on a phonograph record. A random noise source is sampled to generate the key. The key is stored by recording on a record. The output of the key record is analyzed with a filter bank into a number of sub-bands, which are detected as in a VOCODER. The filter bank sub-bands are detected, sampled in time, combined with the VOCODER output, and transmitted via time-division multiplex.

The reconstruction process requires a second key record with the identical key, and a multiplex switch precisely synchronized with the transmitter key and its multiplex switch. The deciphered VOCODER sub-band and pitch signals go to the VOCODER's synthesizer to reconstruct the speech.

3. The SIGSALY system

3.1 SIGSALY Motivation and Development

Before World War II, the USA and Britain used transatlantic high-frequency radio for high-level conferences. The AT&T A-3 scrambler provided marginal security. This band-shifting cipher was extremely vulnerable to enemy eavesdropping. Despite this, the A-3 was used early in the War, as nothing better was available. The German Post Office developed a real time audio spectrum analyzer in 1935, which was used to analyze intercepted speech scrambler signals. That led to their breaking the A-3 and descrambling intercepted speech, from a German listening post in Holland.

The U.S. National Defense Radio Communications Committee decided to develop a totally secure speech encryption system with highest war priority, and contracts were signed with Bell Telephone Laboratories. The final design was reviewed by a number of independent cipher and mathematics experts, including Shannon, Nyquist, and Alan Turing, and found to be unbreakable. The SIGSALY system was ready for deployment by 1943.

3.2 SIGSALY Basic Block Diagram and Concepts

SIGSALY used many of the concepts in the VOCODER and the Dudley Secret Telephony patent, with the innovation of 6-level quantization of the analyzer outputs and a complex Vernam cipher with modulo-6 addition of the input and a one-time key, Fig. 7. It was also called System-X, Ciphony or Green Hornet.

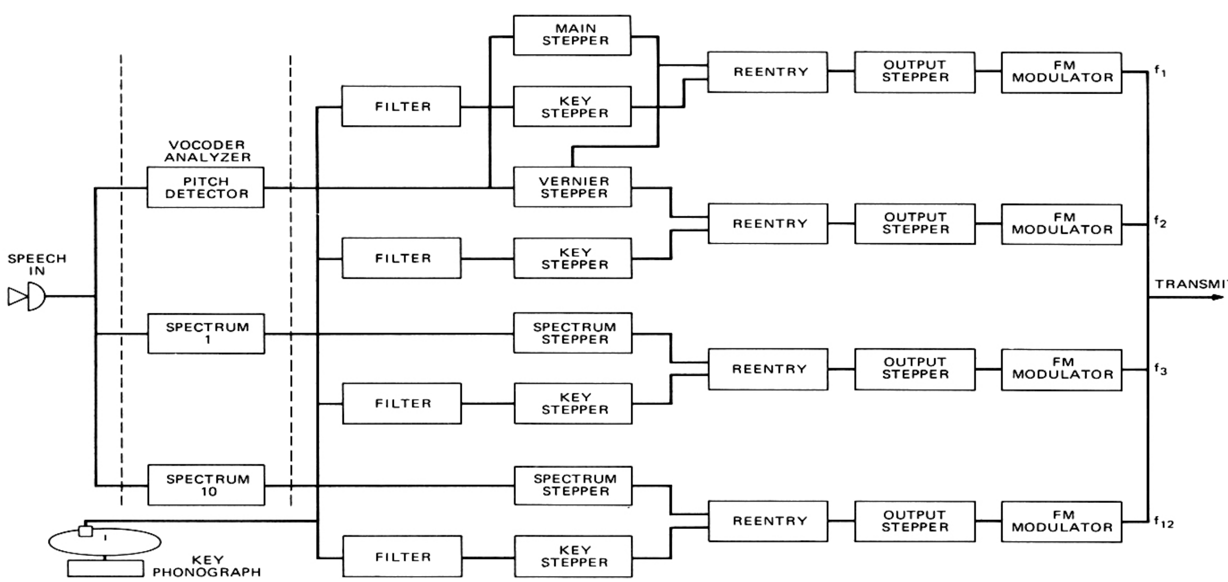

Fig. 7. SIGSALY block diagram

3.3 SIGSALY Vernier Quantizing for the Pitch Channel

Bell engineers found that 6-level quantization was just sufficient for the 10 sub-bands of SIGSALY. The analog signal was quantized using a set of six gas triode tubes, each conducting at a different voltage level, thus quantizing to six levels. The six amplitude levels were in 6 dB steps. This was the very first use of companding.

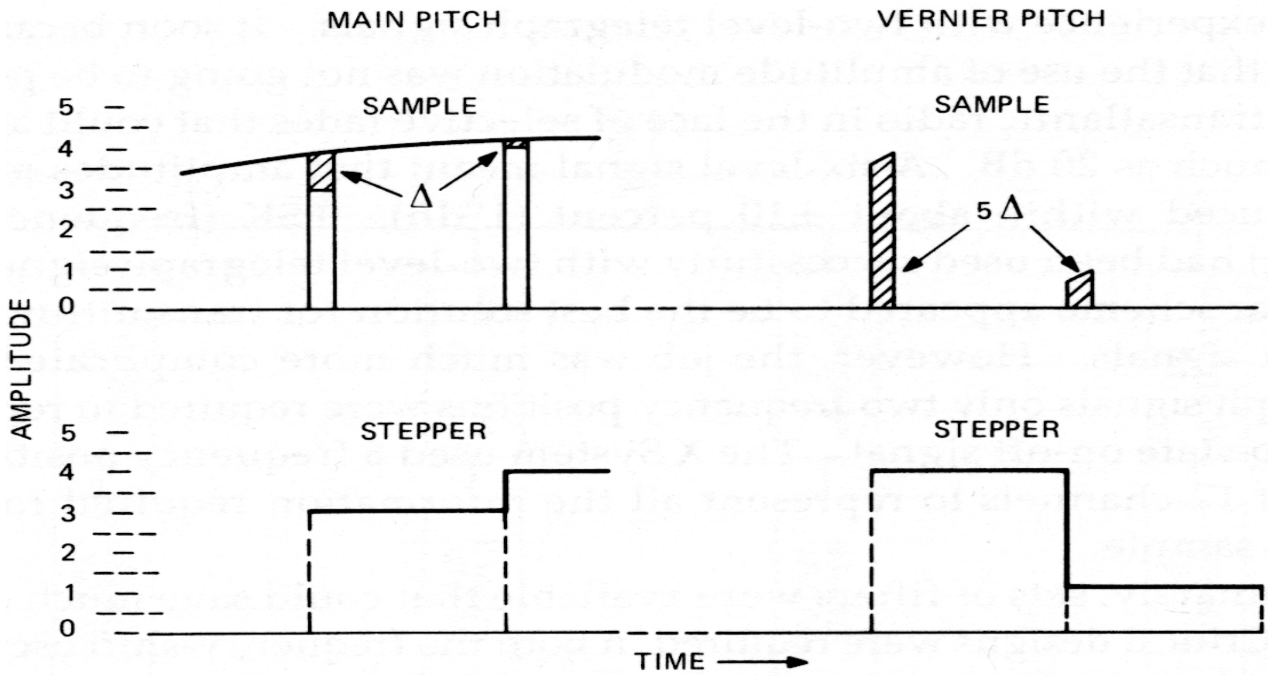

Fig. 8. SIGSALY 36 level pitch channel Vernier quantization

The pitch channel of a VOCODER's analyzer requires higher resolution than the frequency sub-bands, see Fig. 8. The pitch signal is first coarsely quantized to 6 levels. The resulting 6-level quantized signal is subtracted from the original analog pitch signal, to yield a difference error or "residue," which is amplified 6 times and applied to another 6-level quantizer.

The result is a 2-part quantization, first a coarse 6-level quantization, and another 6-level Vernier quantization of the residue. These two quantized signals represent a 36-level (~5 bits) quantized pitch signal. This is sufficient resolution for good quality speech reconstruction. This 2-step Vernier quantization principle has been applied ever since to many types of A/D conversion for video. The modern name is pipeline A/D.

3.4 Vernam Cipher Algorithm, Companded, Quantized Input and 6-Level Random Key Added Modulo-6

SIGSALY transmitted 12 6-level quantized signals, which represented the 10 frequency sub-bands from the speech analyzer, the coarse and Vernier pitch signals. A random noise one-time key was also 6-level quantized with the same 20 ms quantization interval.

Because the transmission and modulation system was based on 6-level quantization, a “re-entry” or modulo-6 addition was used; any result greater than five would have a voltage equivalent to six subtracted, see Fig. 9. The original values can be recovered after transmission by performing the inverse operation, in the manner of the Vernam XOR cipher with binary inputs.

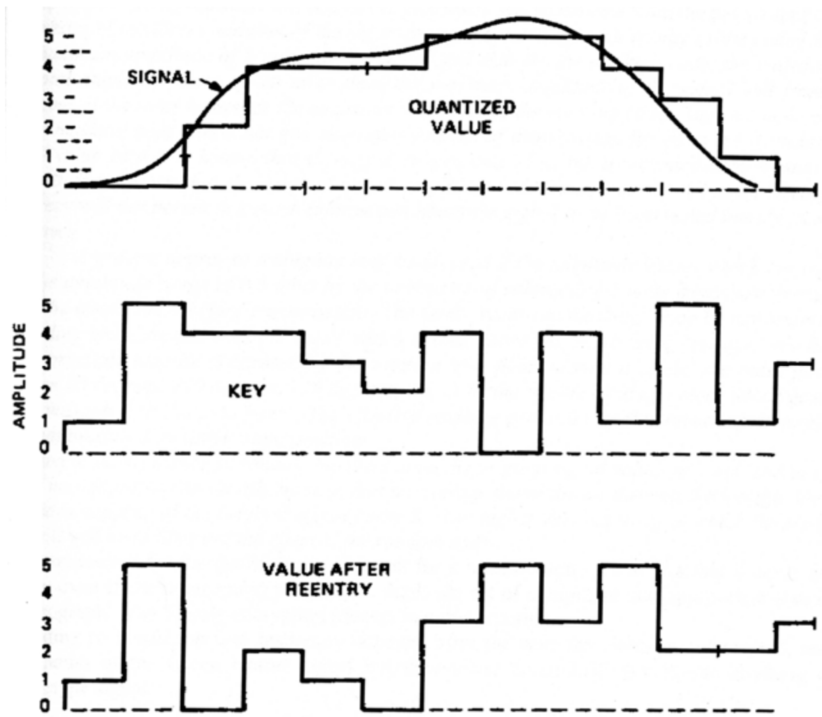

Fig. 9. SIGSALY Cipher Algorithm: "Reentry" and Vernam

3.5 SIGSALY use of spread spectrum

SIGSALY used frequency division multiplex (FDM) to improve the reception of the encrypted SIGSALY signals transmitted via transoceanic short wave. The FDM spread the 12 channels and 300 Hz bandwidth of the VOCODER over a 3 kHz voice channel. Although the FDM was not "frequency hopping" or encrypted, it was the forerunner of all modern spread spectrum transmission. Modern examples include encrypted military radios in the 1960s, CDMA mobile phones, Wi-Fi, digital radio and digital TV broadcast (DTV-B) employing Coded Orthogonal frequency-division multiplexing (COFDM).

The beautiful actress Hedy Lamarr also invented a coded communications system which was frequency hopping for use in torpedoes! She patented it in 1943. It was a parallel development to SIGSALY, a complete coincidence, and unknown to the SIGSALY inventors in 1942. The Lamarr patent was forgotten for decades, until the US Navy employed it during the Cuban Missile Crisis in 1962.

3.6 SIGSALY Characteristics and Specifications

SIGSALY satisfied the requirement for secure and unbreakable speech encryption over radio-telephone channels. The system was in use from 1943 until 1946. Twelve terminals were built worldwide, all manned continuously. The Axis cipher bureaus never penetrated SIGSALY. It was a gargantuan assembly, Fig. 10, comprising 40 racks, consuming 30 kW and weighing 50 tons. Thirteen technicians were required to operate SIGSALY. Cooling was a major issue, which was handled by a huge air conditioning system.

Fig. 10. SIGSALY equipment in service during World War II

3.7 SIGSALY Reconstruction by the National Cryptographic Museum

The National Security Agency's (NSA) National Cryptographic Museum wanted a SIGSALY exhibit but lacked the historical details. Don Mehl, a technician and operator of the original system during WWII, supplied his two books and other information to the NSA (as well as to this author), resulting in a complete modern reconstruction of

SIGSALY. The NSA made a computer simulation of SIGSALY's processing to provide samples of enciphered and reconstructed speech for use in the museum exhibit.

3.8 Random One-Time Key, Key Distribution on Phonograph Records

A truly secure encryption system requires a source of unique, one-time key equal in length to the input data to be transmitted. SIGSALY used 6 huge 10 x 40 cm mercury vapor arc rectifier tubes to generate random noise. The resulting six analog channels were quantized into a 6-level signal in the same manner as the VOCODER sub-band and pitch channels. Because there were 12 VOCODER channels enciphered at a 20-ms intervals, (10 sub-bands and two pitch channels, coarse and Vernier), the SIGSALY key required 600 random key numbers per second of transmission.

The 6-level quantized key signal was frequency-shift key (FSK) modulated and recorded on 16" records (transcription discs) with a precision turntable. A gold master was used to make just two pressings. One pressing was kept at the Army Security Agency for use in Washington, D. C., the other was sent to the distant terminal by diplomatic bag. The two different key records were played in sequence for each SIGSALY conference. Two turntables were automatically sequenced by an end-of-record pulse, providing up to 25 minutes of key per conference. The key records were destroyed after a single use.

The keys had to be precisely synchronized at each terminal. The output of a 100-kHz, quartz crystal oscillator was divided by a Morrison multivibrator, to drive the synchronous motor of the turntables and other circuitry. A short-wave receiver was tuned to radio time signals from Arlington, VA. The receiver provided time signal ticks used for synchronization and simultaneous start-up of turntables at both the near and far sides of the communication channel. Fine synchronization to within 200 µs was done by manually adjusting the phase of the timing signal for best intelligibility, while listening to the reconstructed speech.

3.9 SIGBUSE Pseudorandom Key Source

The lengthy and difficult process of generating and distributing the random key records led to the design of an alternate pseudo-random key system, SIGBUSE for personnel training, setup, testing and adjustment of SIGSALY. SIGBUSE used existing cipher machine rotors similar to the German Enigma machine rotors. The rotors had 26 contacts on each face and scrambled wiring connecting the two faces of a rotor.

Banks of six rotors were turned by a stepping motor, with the set moving like an odometer: each rotor would mechanically increment the adjacent rotor at a rate of 1/26th its speed of rotation. The six signals were applied in parallel to the rotors and each signal had a different scramble by each of the six rotors. The result was a 6-bit pseudorandom binary output, which in turn operated hundreds of telephone stepping relays. The relays generated the pseudo-random key.

The rotor motion and the exact setup were duplicated and synchronized to a similar unit on the other end of the radio-link resulting in reconstruction of the identical key. The pseudorandom key pattern was eventually repeated as the rotors rotated. For that reason, SIGBUSE was not considered sufficiently secure for operational use. The noise of the stepping relays gave SIGBUSE the nickname "threshing machine".

3.10 SIGSALY Terminal Usage in 1943 - 1946

After SIGSALY was proved reliable and completely secure, the Army Signal Corps ordered Bell Laboratories to construct 12 terminals worldwide. These formed a secure network for the exclusive top secret use by Army and Navy chiefs of staff and heads of state. One terminal was deployed onboard a ship, which followed General Douglas McArthur in his rapid campaign towards Japan through the South Pacific. After the War ended, new terminals were constructed in postwar Germany, among other places. SIGSALY was used until 1946. Newer secret telephony systems were based on SIGSALY techniques.

3.11 SIGSALY Clients

The most famous user of SIGSALY was Winston Churchill. A special telephone room was built in the Cabinet War Rooms, the secure underground bunker from which Churchill directed the War effort in blitz-plagued London Fig. 11. Due to its enormous size, the SIGSALY terminal was located some distance away, in the basement of Selfridge's department store, connected by a secure 4-wire private phone line. As a test of SIGSALY, General Eisenhower once used it to talk with his wife, Mamie. On that occasion, technicians shifted the pitch generator to simulate her higher pitch-range. Generals George C. Marshall and Douglas McArthur Fig. 12, made extensive use of SIGSALY for conferences to direct the Philippines Campaign. Over 3,000 telephone conferences were handled by the system during World War II.

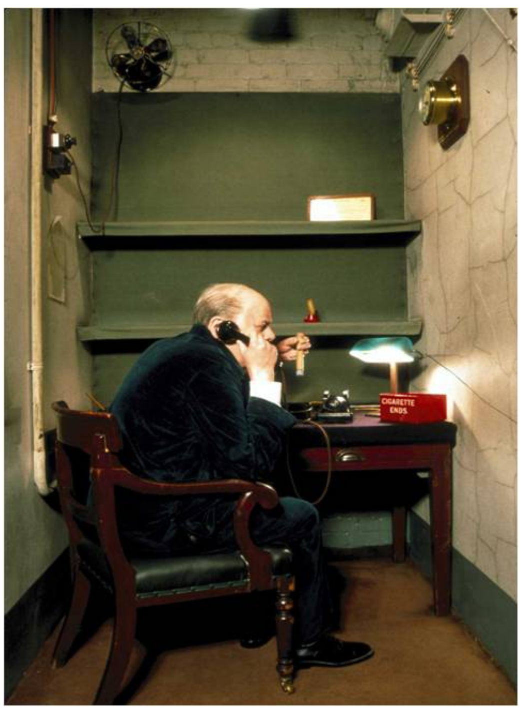

Fig. 11 Winston Churchill

Fig. 12 Gnl. Douglas McArthur

3.12 SIGSALY Innovations

SIGSALY was the result of many years of research by dozens of scientists and engineers at Bell Telephone Laboratories. From that research, 32 patents resulted, some remained classified secret until 1976. SIGSALY was the first digital voice transmission system. Eleven fundamental innovations can be traced to Dudley's VOCODER and SIGSALY. These advances (listed below) are in constant use in today's mobile, audio and video technology.

1. Quantized speech transmission
2. Unbreakable enciphered telephony
3. Speech transmission by pulse code modulation
4. Companded PCM by logarithmic A/D converter
5. Multilevel Frequency Shift Keying (FSK)
6. Realization of 10 times bandwidth compression
7. FSK-FDM over a fading medium (frequency division multiplex)
8. Multilevel eye pattern adjusts sampling intervals
9. First flash A/D converter
10. Two-step quantization (the first pipeline A/D converter)
11. Spread-spectrum transmission

4. Links to Current Audio Compression Technology

4.1 Modern Speech Encryption and Compression Using Vocoders

A number of modern speech compression systems use techniques that find their roots in the VOCODER and SIGSALY. They are: LPC-10, Code Excited Linear Prediction, (CELP), Continuously Variable Slope Delta-modulation (CVSD), Mixed Excitation Linear Prediction (MELP), Adaptive Differential Pulse Code Modulation (ADPCM). Below are discussed the linkages of three of these modern technologies with the VOCODER and SIGSALY.

4.2 CELP: Code-Excited Linear Prediction: digital mobile phones and VOIP

Code-excited linear prediction, Fig. 13, is used in digital mobile phones. The basic Dudley speech synthesis with voiced and unvoiced generation and shaping of the resultant signals is a characteristic of CELP. The CELP analyzer uses FFT techniques to realize the filter bank concept of Dudley. Modern DSP provides the pitch estimation and other parameter generation.

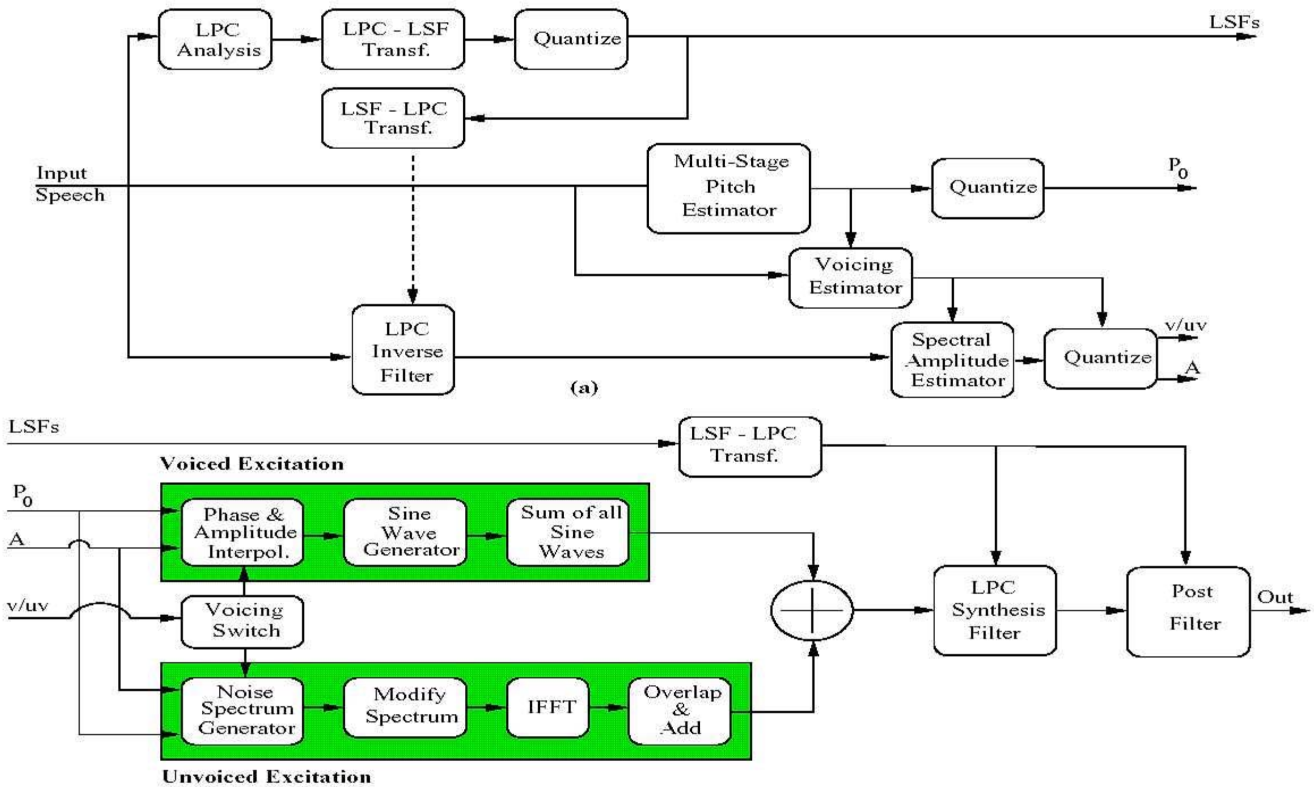

Fig. 13. CELP: Code-Excited Linear Prediction

4.3 MPEG-1 Layer 3

Fig. 14 shows MPEG-1 Layer 3 compression. It uses the filter bank concept of Dudley, but without the pitch channel or the voiced/unvoiced switching of the VOCODER. By using 32 sub-bands, it achieves substantial compression of speech and music.

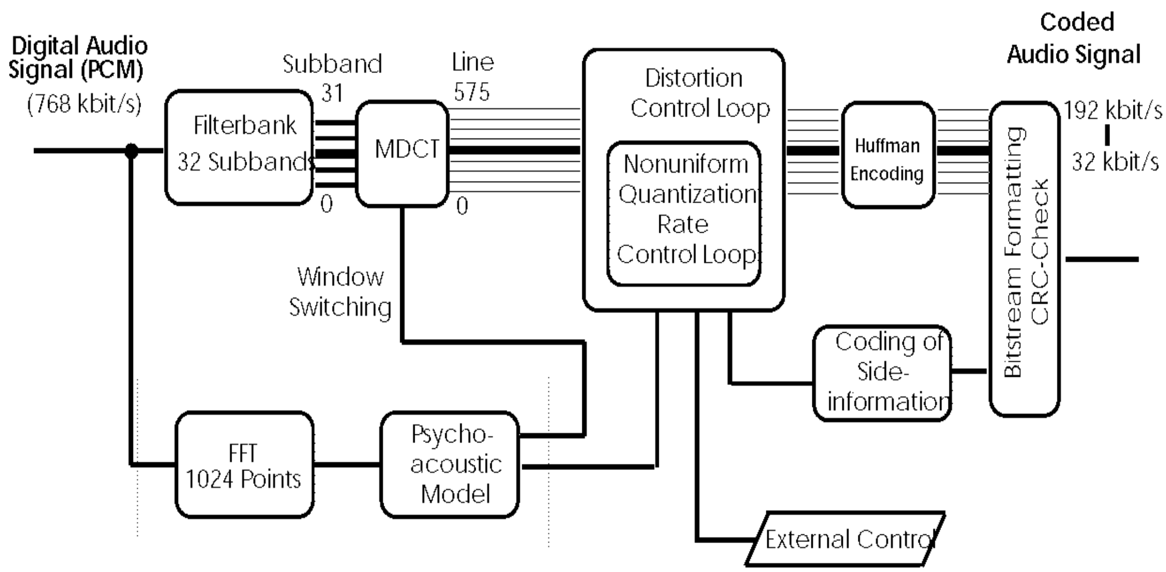

Fig. 14. MPEG-1 Layer 3 ("MP3") Block Diagram

4.4 Dolby AC-3

Dolby AC-3, Fig. 15, uses a filter bank, quantizer and multiplexer, analogous to the VOCODER and SIGSALY.

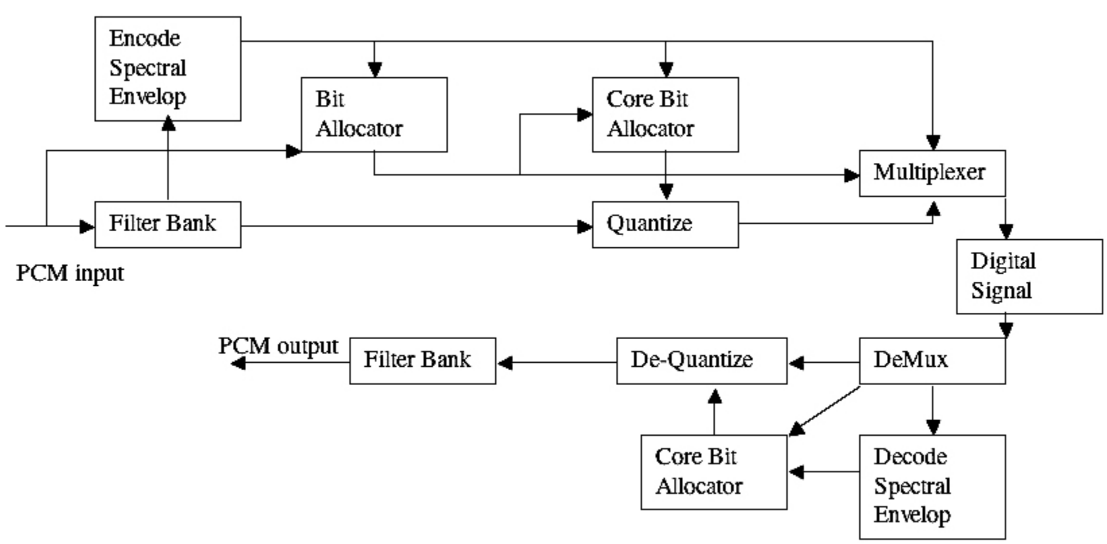

Fig. 15. Dolby AC-3 Block Diagram

5. Links to Modern Video Compression Technology

Video compression is a natural extension of audio compression, to a much wider bandwidth and more complex signal. The video compression block diagrams below show different topologies, but they share many common techniques, e.g., frequency analysis (FFT or DCT), quantization in time, amplitude and space, and separation into analysis components. All these methods were first developed in the VOCODER and SIGSALY.

5.1 MPEG-1 Compression

MPEG-1, Fig. 16 uses DCT, quantization in space and amplitude, nonlinear weighting and multiplex. All of these methods are common to the VOCODER and SIGSALY.

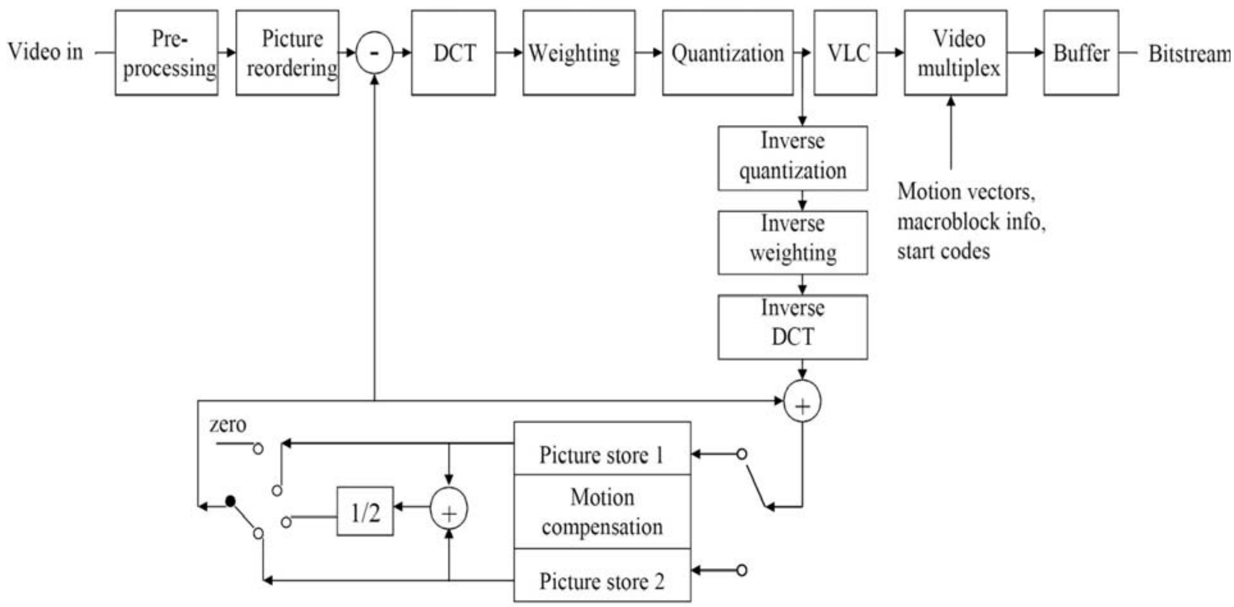

Fig. 16. MPEG-1 Block Diagram

5.2 H.264/MPEG-4

MPEG-4 adds motion prediction and entropy encoding to MPEG-1, Fig. 17. The roots of MPEG-4 can be traced to the VOCODER and SIGSALY.

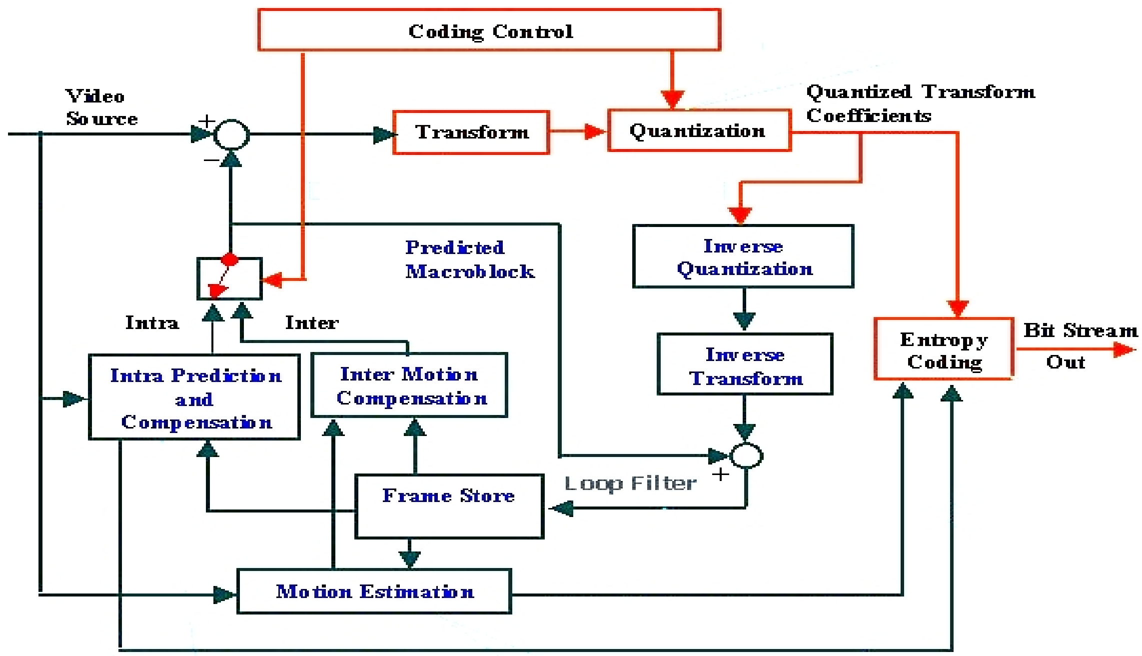

Fig. 17. H.264/MPEG-4 Block Diagram

5.3 Generalized Compressed Transmission System

All modern compression and transmission systems have much in common with the original general concept of Homer Dudley in the VOCODER, Fig. 18: signal analysis, multiplex of the resultant components, transmission, reception, demultiplex, and synthesis of the original signal.

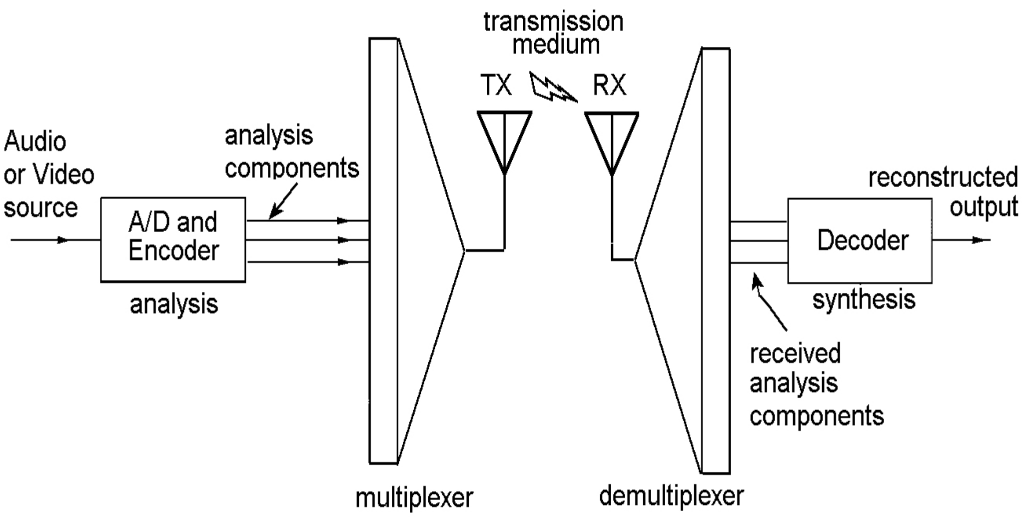

Fig. 18. Generalized Compressed Transmission System

5.4 Audio and Video Compression Characteristics Table

Table 1 summarizes the many common features and properties that the VOCODER and SIGSALY share with various modern speech, audio and video compression techniques in constant use.

Characteristics	Dudley's Vocoder	SIGSALY	digital speech compression	digital audio compression	digital video compression
First use	1928 - 1936	1943	1960s	1972 - 76	1984 - 1986
Example	unique	unique	CELP	MP3	MPEG-4
Signal type	speech only	speech only	speech only	audio	video
Quantization	temporal 20 ms sampling, analog system	temporal, 6 amplitude levels	temporal, amplitude	temporal, amplitude	temporal, frequency domain, amplitude
Quantization type	PAM, PCM, pipelined ADC, Vernier pitch	PAM, PCM, pipelined ADC Vernier pitch	ADPCM, CELP	PCM or ADPCM	PCM pipelined ADC
Sub-band technique	10 band 300 Hz bandpass	10 band 300 Hz bandpass	FFT	FFT, QMF	DCT, wavelets
Analysis Components	pitch, 10 frequency bands, voiced/unvoiced	pitch, 10 frequency bands, voiced/unvoiced	pitch, loudness voiced/unvoiced	Filter bank, psychoacoustic	luma, chroma motion estimation
Companded	yes, nonlinear conversion	yes, nonlinear conversion	yes	Yes or no	yes
Flash ADC	no	yes, six 6 level	no	no	yes
Clear or encryption, DRM	clear	unbreakable random key encrypted	encrypted only in speech scramblers	clear, can have DRM	generally encrypted, with DRM
Compression Ratio	10	10	4 - 16 CELP	5 - 20 MP3	20 - 200 MPEG-4
Lossy or lossless, Speaker recognition	lossy, no speaker recognition	very lossy, no speaker recognition	lossy, perfect speech recognition	lossy or lossless	lossy
Predictive Coding	no	no	LPC	LPC	motion estimation
Perceptual coding	no	no	yes	yes	yes
FDM, spread spectrum, COFDM	No, however VOCODER 10x compression is essential for FDM	Yes, first use of FDM	Military encrypted radios, CDMA phones	Digital Radio Mondiale, HDRadio, T-DMB,SDARS	Digital broadcast: DVB; DVB-T uses COFDM

Table 1. Audio and Video Compression Common Techniques and Characteristics

Conclusion

Dudley's VOCODER was the first successful electronic speech analyzer and synthesizer. Modern speech, audio and video compression began with Dudley's inventions and the World War II speech encryptor SIGSALY. Despite many attempts, SIGSALY was never broken by the enemy and was secure enough for top secret conferences at the highest levels of military and executive government.

SIGSALY's many innovations are still used in current technologies. SIGSALY represented the first use of frequency-division multiplex and spread-spectrum techniques. Modern speech scramblers are partly based on SIGSALY's principles. It is impossible to find any digital signal processing for coding, compression or transmission of audio, which does not have at least some roots in the VOCODER and SIGSALY.

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