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Hybrid PCM-Encoder with Non-Uniform Quantizing

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1. Introduction

For digital transmission of speech information within existing telecommunications networks, on satellite transmission lines, and within future integrated switching and transmission systems broad-band PCM-encoders are required extensively. According to current proposals groups of 30/32 telephone channels are digitalized with one PCM-encoder (primary PCM-system). For common transmission of several primary groups via coaxial cables, radio and microwave links the outputs of various PCM-encoders are multiplexed digitally. From the economic point of view it seems reasonable to use broadband PCM-encoders with either higher degrees of multiplexing for telephone channels or higher bandwidths for multiplexing several broadcasting programmes.

After a short description of non-uniform quantizing and the main principles of analog to digital conversion techniques, a hybrid conversion method is proposed for encoding of speech signals according to the 13-segment companding law. The total PCM-character is generated in three steps: sign (1 bit), segment (3 bits), and linear interpolation within a segment (3 or 4 bits, respectively). The parallel generation of several bits is realized by tunnel-diode networks. Finally, some features of the applied method are discussed as there are adjustment of the companding law, conversion speed, as well as various realization problems.

2. Sampling, Multiplexing, and Quantizing

2.1. *Sampling*

The individual speech channels with upper cut-off frequency f_{max} are sampled according to the sampling theorem with a sampling frequency $f_s \geqq 2 f_{max}$ (PAM). For telephone channels with $f_{max} = 3.4$ kHz, $f_s = 8$ kHz was suggested and is likely to be accepted by CCITT. This sampling frequency corresponds to a frame length $1/f_s = 125\ \mu s$. For broadcasting transmissions with $f_{max} = 15$ kHz a sampling frequency of $f_s = 32$ kHz can be chosen.

2.2. *Multiplexing*

According to current proposals, 32 channels are multiplexed on one PAM-highway. One frame of the PAM-highway is formed by 30 time slots (1 time slot = time for one sample) corresponding to 30 telephone channels. Two additional time slots are reserved for synchronization and signalling, respectively. The duration of one time slot is 3.906 μs. With the same duration of time slots 8 broadcasting programmes can be multiplexed and transmitted simultaneously.

2.3. *Quantizing*

During the encoding procedure, the PAM-samples are usually stored within a hold circuitry. For the digital representation of the PAM-samples, the whole dynamic range of the amplitudes is quantized into a finite number q of discrete levels (usually $q = 2^s$). The function of PCM-encoding is to determine that level closest to the PAM-sample and its digital equivalent in terms of s binary digits (PCM-character).

The discrepancy between the actual PAM-sample and its quantized digital representation causes quantizing noise. There are two main reasons for a non-uniform quantizing of speech signals: high probabilities of small amplitudes, and high sensitivity of the human ear with respect to small amplitudes. From the viewpoint of a nearly constant signal to quantizing noise ratio over a wide dynamic range, the logarithmic "A-law" and "μ-law" companding characteristics have been suggested [1, 2]. The piecewise linear version of the A-law characteristic (13-segment companding law) has been accepted by CCITT [3], cf. *Fig. 1*.

By a non-uniform companding, the sizes of the quantizing steps depend on the actual size of the input amplitude. For the following, the output range is subdivided into 8 equal parts, $n = 1, 2, \ldots, 8$, cf. Fig. 1. Parts 3 through 8 correspond directly to segments, whereas parts 1 and 2 form the upper half of the middle segment of the companding characteristic.

The PCM-character representing the PAM-sample is built up as follows:

1st bit: sign

2nd—4th bit: segment

5th—sth bit: linear interpolation within a segment.

The number of bits per character is $s = 8$ for telephone channels and $s = 10$ for broadcasting channels. The highest resolution (for small amplitudes) corresponds to 12 or 14 bit uniform quantizing, respectively.

3. Main Principles of Analog to Digital Conversion Techniques

Analog to digital (A/D-) conversion techniques can be classified into few major types. The method to be applied depends on criterions as, e. g., conversion speed, accuracy, and cost.

3.1. *Counting Encoders* (level at a time method)

By the counting principle, the signal range is scanned level by level until the digital equivalent is equal or greater than the analog amplitude. The number of scanned levels is counted and represents in binary form the PCM-character. This method is rather time consuming and the conversion time is proportional to the amplitude value. Counting encoders are mostly used for high precision measurement at moderate speed; they have also been suggested for telephone PCM-systems with a lower degree of multiplexing [4].

3.2. *Sequential Encoders* (bit at a time method)

This method decides one bit per conversion step by iterative approximation of the analog amplitude with successively decreasing standards (1/2, 1/4, 1/8, ... of the maximum range). This principle is usually realized as feedback weighting encoder and forms a good compromise between speed and cost. It has been used for PCM-telephone channel encoding [5], broadcasting programme encoding [6] (both with non-uniform companding law), and video signal encoding [7].

3.3. *Parallel Encoders* (character at a time method)

By this principle, the complete character is decided in one step by comparing standards of all possible levels with the analog amplitude in parallel and a subsequent code conversion. This method is the fastest in speed but hardly realized for reasons of cost.

3.4. *Hybrid Encoders*

There is a wide range of methods which apply a mixture of the basic principles referred in Section 3.1 to 3.3. Based on the counting principle, counting can be done, firstly, in coarse and, secondly, in fine steps [8, 9], or in connection with the 13-segment companding law, firstly, by counting down the segments (successive divisions by two) and, secondly, by counting the remaining levels within a segment [10]. Based on the sequential principle, it is possible to decide several bits at a time, e. g., 2 or 3 bits at a time [11, 12]. For encoding broadband video signals, such a method has been used deciding successively 2,2, and 3 bits at a time [13] with uniform quantizing.

3.5. *Principle of the Suggested Hybrid Encoder*

In this paper, a hybrid method is suggested which generates the complete character within 3 steps with respect to the 13-segment companding law:

1st step: sign-decision (1st bit)
2nd step: segment-decision (positive branch) by parallel encoding (2nd—4th bit)
3rd step: linear interpolation within a segment by parallel encoding (5th—7(8)th bit).

The realization of this principle for the PCM 30/32-system will be discussed in the following section.

4. Realization of the Suggested Hybrid Method

4.1. *Tunnel-Diode as Discriminator*

For all A/D-conversion methods discriminators are necessary which have to decide whether the analog signal is greater or smaller than a standard value. Such discriminators can be realized by a tunnel-diode with a definite bias current. *Fig. 2a* shows the principle circuit of a tunnel-diode discriminator and *Fig. 2b* the

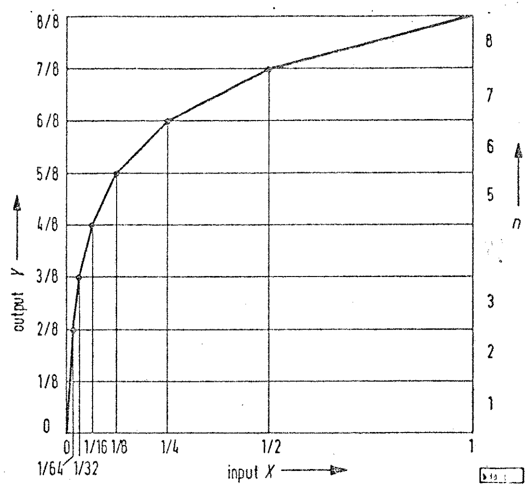

Fig. 1.
13-segment companding law (positive branch).

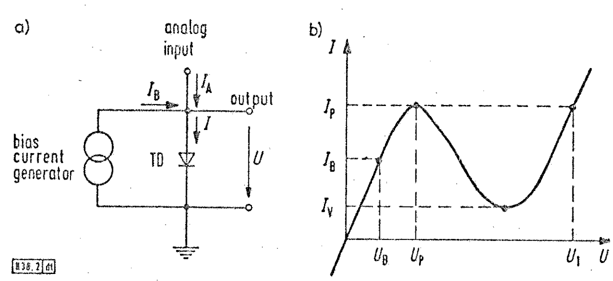

Fig. 2.
Tunnel-diode discriminator.
a) Principle circuit
b) Tunnel-diode voltage-current characteristic
I_P peak current
I_V valley current
I_B bias current
I_A analog input current.

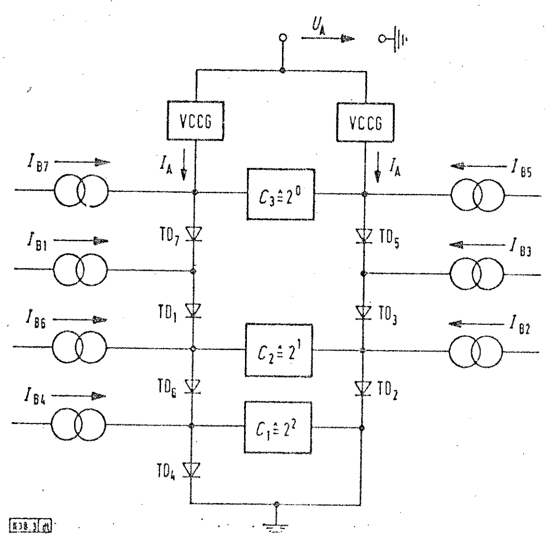

Fig. 3.
Tunnel-diode network for parallel determination of 3 bits.

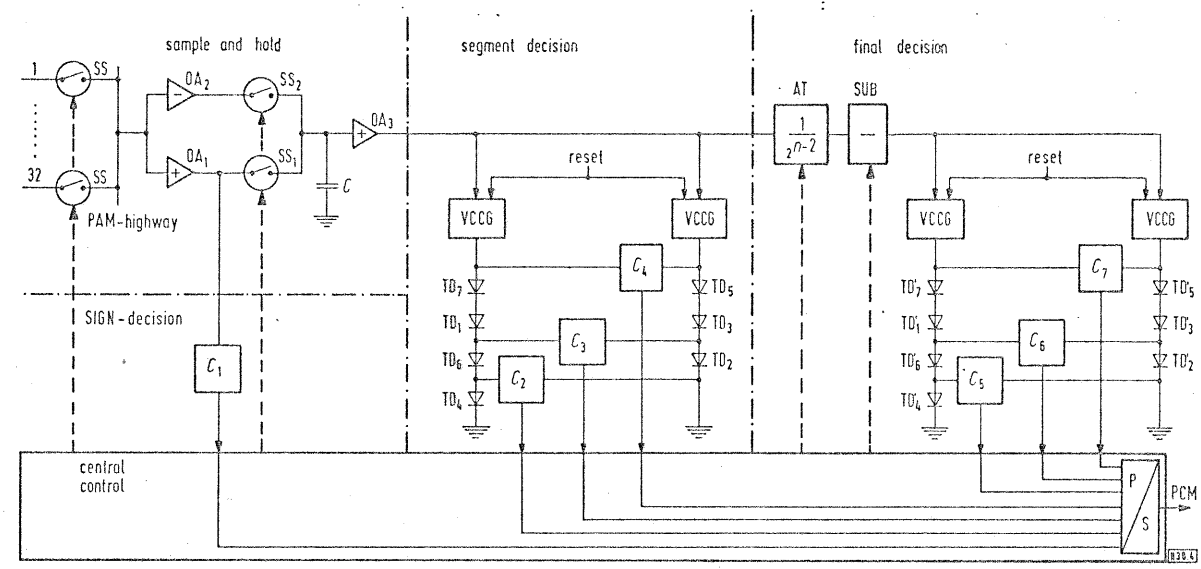

Fig. 4.
Block diagram of a hybrid PCM-encoder with non-uniform encoding.

corresponding voltage-current characteristic of the tunnel-diode itself.

If the current I increases from 0 to I_P (peak of the voltage-current characteristic, cf. Fig. 2b), the corresponding voltage across the tunnel-diode only increases from 0 to the relatively small voltage U_P. But if the current I exceeds the peak current I_P, the voltage across the tunnel-diode "jumps" from U_P to the relatively large voltage U_1. A further increase of I causes only a small increase of U. The "jump" of the tunnel-diode-voltage from U_P to U_1 may be used as an indication that the current I has exceeded the peak current I_P. Using an arbitrary, but constant bias current I_B (cf. Fig. 2a), the tunnel-diode can be used for the indication that the analog input current I_A has exceeded the "standard current" ($I_P - I_B$).

The main advantages of the tunnel-diode are:

i) The switching time from U_P to U_1 is very small (<1 ns).
ii) The peak current I_P is nearly independent of the temperature.

Between two successive decisions, the tunnel-diode must be reset by a current $I < I_V$ to the region $U < U_P$ of the voltage-current characteristic, cf. Fig. 2b.

4.2. *Tunnel-Diode Network for Parallel Determination of 3 bits*

As already outlined in Section 3.5, the suggested method for A/D-conversion includes two partial A/D-converters for parallel encoding of 3 (4) bits. The parallel generation of 3 bits in dual form can be achieved without code conversion by the tunnel-diode network of *Fig. 3*, which was proposed earlier in principle by K. Euler [11].

The analog voltage U_A to be converted is transformed by the aid of voltage controlled current generators (VCCG) into two proportional analog currents I_A. Each of the analog currents I_A is injected into a tunnel-diode line. The operating points of the tunnel-diodes are adjusted by the static bias currents I_{B1} through I_{B7} in such a way that for an increasing current I_A the tunnel-diode TD_1 jumps first and TD_7 jumps last. Thus, each of the 8 levels of the analog signal U_A or I_A, respectively, corresponds to a well-defined pattern of jumped tunnel-diodes. This pattern is indicated directly by the three voltage comparators C_1, C_2, C_3. C_3 corresponds to the least significant bit, C_1 to the most significant bit. If, e. g., only TD_1 has jumped, there are different voltages at the two inputs of comparator C_3, but nearly the same voltages at the two inputs of the comparator C_2 or C_1, respectively. So C_3 indicates an output signal 1, and the other two comparators C_1 and C_2 indicate the output signal 0. Therefore, the three bits of this decision are: 001. The other combinations of the three bits are generated analogously.

4.3. *Block Diagram and Operation of the Suggested Hybrid PCM-Encoder*

The block diagram of the hybrid PCM-encoder is shown in *Fig. 4*. The sample and hold circuit consists of two operational amplifiers OA_1 (noninverting) and OA_2 (inverting) followed by two sampling switches SS_1 and SS_2. The operation mode of this device is such that the hold capacitor C is charged only by unipolar voltages. Thus, only one branch of the companding characteristic (positive or negative, cf. Fig. 1) must be realized.

During the first conversion step, comparator C_1 decides the sign bit which controls also the sampling switches SS_1 and SS_2.

During the second step, the three segment bits are determined in parallel by the segment decision device. This device is a tunnel-diode network as it was shown in principle in Section 4.2. For simplification, the bias current generators for the tunnel-diodes are not shown in the block diagram of Fig. 4. The operating points of the tunnel-diodes TD_1 through TD_7 are adjusted such that each segment of the companding characteristic corresponds to a well-defined pattern of jumped tunnel-diodes. Thus, the outputs of the three comparators C_2, C_3, C_4 yield directly the segment bits.

During the third step, the last three bits are determined by linear interpolation within a segment in parallel as follows:

First, the analog input signal is transformed into the range of part $n = 2$ of the companding characteristic, cf. Fig. 1. This is done by a switchable attenuator AT which is controlled by the three segment bits of the second conversion step. If the analog input signal is located in part n, it must be attenuated by the factor 2^{n-2} (excluding $n = 1$). Then, this range of part $n = 2$ is shifted by a subtraction device SUB to the range of part $n = 1$. If the original analog input signal is already situated in the first part $n = 1$, shifting is not necessary. Therefore, the subtraction device is also controlled by the segment bits of the second conversion step. Now, all parts ($n = 1, 2, \ldots, 8$) are transformed onto the first part $n = 1$ and so only one final location device is necessary for the decision of the last three bits. This decision is also done with a tunnel-diode network analogously to the decision of the segment bits. The operating points of the tunnel-diodes TD'_1 through TD'_7 are adjusted according to a linear encoding within a segment. The outputs of the comparators C_5, C_6, C_7 yield directly the last three bits.

Finally, the PCM-character is generated by a parallel to serial conversion (P/S) of the outputs of the seven comparators C_1 through C_7. Before the conversion of the next PAM-sample, all tunnel-diodes must be reset to their original position (RESET).

It would be possible, however, to decide not only 3 but 4 bits during the third conversion step with the final decision device. Then, the PCM-character would exist of 8 bits as it is usual nowadays. For this case, of course, further 8 tunnel-diodes and one voltage comparator would be necessary for the final decision device.

For the present, the described principle has been applied to an experimental PCM-encoder for 32 channels with sampling frequency of $f_s = 8$ kHz each and 7(8) bits per character [14, 15]. For the realization cheap integrated circuits were used extensively.

5. Conclusion

In this paper, a hybrid A/D-conversion method was suggested which generates the complete PCM-character within 3 steps with respect to the 13-segment companding law. For parallel encoding of several bits at a time, tunnel-diode networks have been applied.

Experience has shown the following advantages of this principle:

i) Non-uniform companding can be realized easily by static bias current adjustment.
ii) The companding law can be changed easily.
iii) Interpolation within a segment must not necessarily be linear; by suitable adjustment of bias currents a smooth characteristic can be achieved as well.
iv) Bias currents are once adjusted statically, they must not be switched on or off.
v) The actual decision time for several bits decided in parallel by the tunnel-diodes is relatively small.
vi) The bits decided in parallel are indicated immediately by the outputs of comparators; no additional code conversion is necessary.
vii) The amount for digital control is very low.

Critical points are: Zero-voltage-threshold adjustment of the sample and hold circuit, exact adjustment of the operating points of the tunnel-diodes, and interference by the TTL-control. It seems further advisable to decide not more than 4 bits in parallel because of the large number of tunnel-diodes in series.

By the method of generating several bits at a time, the time conditions have become less critical in comparison with sequential methods. Using faster analog units, we expect that the conversion speed can easily be raised by the factor of 2 up to 4.

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