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CLEAN SEGMENT AND CONSTANT ENERGY SEQUENCES BASED ON MLS

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RESUMO:
As técnicas de Sequência de Segmento Limpo e de Energia Constante baseadas nas Sequências de Comprimento Máximo (MLS) introduzem uma melhoria significativa na SNR em situações de ruído não-estacionário de energía elevada e limitado no tempo.
A Sequência de Segmento Limpo consiste em anular (limpar) a zona de maior incidência do ruído não alterando o período da sequência. A Sequência de Segmento de Energia Constante ajusta a amplitude do sinal na zona de incidência do ruído de forma que a energia ao longo de toda a sequência se mantenha constante.
A comparação do desempenho das técnicas estudadas em relação técnica MLS clássica é feita com base em vários exemplos. Estas técnicas melhoram significativamente a estimativa de RI. São uma alternativa ao uso da técnica MLS clássica quando SNR é baixa e o ruído é bem localizado no tempo.
As vantagens e desvantagens de cada método são apresentadas.
A utilização destas técnicas não invalida a aplicação da técnica de médias temporais.

Abstract:
Two new measurement methods based on the Maximum Length Sequences (MLS) technique, referred to as Clean Segment and Constant Energy Sequences, are presented for applications where time limited high noise background levels occur.
The two proposed techniques consist in the identification of the segments of the test MLS sequence where noise is dominant. The choice of each technique depends on the Signal to Noise Ratio (SNR) value for the particular noise segment.
The Clean Segment Sequence is used for very low SNR values. It consists in blanking the noise segment keeping the same sequence period. The Constant Energy is used for reasonable low SNR values. The level of the noise segment is reduced while keeping the same energy for the whole sequence.
The computational complexity of these techniques is similar to the classical MLS approach and in some cases the temporal averaging technique can be dispensable.
In order to compare the classical MLS technique against the Constant Energy and Clean Segment Sequences techniques, several examples are presented. The relative advantages and disadvantages of each technique are discussed.

1. INTRODUCTION

The Maximum Length Sequences (MLS) technique for room impulse response measurement usually allows large SNR's due to its noise robustness [1-3]. However, in high background noise environments, the SNR can be very low and the estimation of the room Impulse Response (RI) will yield unreliable results [4-6]. In these cases the temporal averaging method can be applied.

The techniques presented in this paper are to be applied in conditions of disturbing noise well limited in time. Better results are achieved in case of very low SNR and when the noise regions have a short time duration when compared with the MLS sequence period.
Following these assumptions, two kinds of approaches can be investigated for the zones of the sequence more corrupted by noise:

- **Clean Segment Sequence** – consists in *cleaning* the noise region by padding by zeros keeping the same sequence length *L*;
- **Constant Energy Sequence** – the energy of the noise region amplitude (system response plus noise) is adjusted to a predefined level keeping a constant energy for the whole sequence.

Fig.1 depicts the used procedure to implement these two techniques.

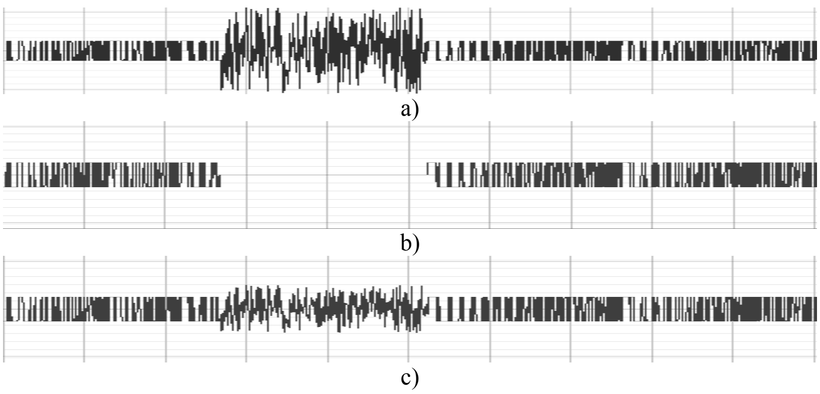


Fig.1 – Implementation of the Clean Segment Sequence and the Constant Energy Sequence techniques. a) Test sequence corrupted by noise with time-limited duration. b) Clean Segment Sequence technique. c) Constant Energy Sequence technique.

Even if with the use of these techniques the SNR value is not high enough to correctly evaluate the acoustical parameters, the temporal averaging method can be applied with the possibility of using the two techniques together [7].

2. PERFORMANCE OF THE PROPOSED TECHNIQUES

Some acoustical analysis related to the RI, namely the Amplitude Impulse Response and the Energy Decay Curve, were used to compare the performance of the Clean Segment Sequence and the Constant Energy Sequence techniques against the classical MLS approach.
The composed test signal was obtained by adding white noise or several rock music tracks at well-defined segments of the MLS sequence. In order to evaluate the noise robustness of the proposed methods, tests were done with different SNR's.
The noise used in this study consists of several types of filtered white noise, white noise and rock music tracks. However, only results for broadband noise and rock music are presented here.

Let one define *Fr* as the ratio of the noise duration in a sequence L_{seg} to the total sequence length L, $Fr = L_{seg}/L$, to conveniently account for the noise in the analysis. The windowed MLS sequence is given by

$$S_{MLS_m}(n) = S_{MLS}(n)\,.\,w(n-m+1), \quad \text{where} \quad w(n) = \left| \begin{array}{ll} 1, & 0 \le n \le L_{seg} \\ 0, & n > L_{seg} \end{array} \right. \tag{1}$$

The cross-correlation can be expressed by

$$\Omega_{SS}(n) = \Omega_{SS_1}(n) + \Omega_{SS_2}(n) + \ldots + \Omega_{SS_N}(n) \tag{2}$$

The cross-correlation in a segment is given by

$$\Omega_{SS_m}(n) = \frac{1}{L+1}\sum_{k=0}^{L-1} S_{MLS}(k) S_{MLS_m}(k+n) =$$

$$\frac{1}{L+1}\sum_{k=0}^{L-1} S_{MLS}(k) S_{MLS}(k+n)\,.\,w(n-m+1) \tag{3}$$

The result of weighting the *m* order noise segment in eq. (2) is

$$\Omega_{SS}(n) = \Omega_{SS_1}(n) + \ldots + \alpha\,\Omega_{SS_m}(n) + \ldots + \Omega_{SS_N}(n) \qquad 0 \le \alpha \le 1 \tag{4}$$

Finally, eq. (4) can be rewritten as follows

$$\widehat{\Omega}_{SS}(n) = \Omega_{SS}(n) - (1-\alpha)\,\Omega_{SS_m}(n) =$$

$$\Omega_{SS}(n) - \frac{(1-\alpha)}{L+1}\sum_{k=0}^{L-1} S_{MLS}(k) S_{MLS}(k+n)\,.\,w(n-m+1) \tag{5}$$

The resulting estimated cross-correlation function is affected by a weighting term that affects the RI reducing the SNR. See that if the term α is set to 1, the estimated cross-correlation function corresponds to the exact one.
As an example, the circular cross-correlation was evaluated by changing the amplitude of the second bit, marked by A, to the value of -3. For a sequence of order $K = 3$ ($L = 2^K - 1 = 7$), this is equivalent to have $Fr = 1/7$.
The results presented in Table 1 compare the proposed techniques against the classical MLS approach with and without noise cases.

Table1. Circular Cross-Correlation and Noise dependence.

MLS Sequence (*K*=3)							**Noise Amplitude in bit 2 - A**			
1	**1**	**1**	**-1**	**1**	**-1**	**-1**	**1 (without noise)**	**-3 (with noise)**	**0 (Clean Segment Sequence)**	**-1 (Constant Energy Sequence)**
1	A	1	-1	1	-1	-1	**7**	**3**	**6**	**5**
-1	1	A	1	-1	1	-1	-1	-5	-2	-3
-1	-1	1	A	1	-1	1	**-1**	**3**	**0**	**1**
1	-1	-1	1	A	1	-1	**-1**	**3**	**0**	**1**
-1	1	-1	-1	1	A	1	**-1**	**-5**	**-2**	**-3**
1	-1	1	-1	-1	1	A	**-1**	**3**	**0**	**1**
A	1	-1	1	-1	-1	1	**-1**	**-5**	**-2**	**-3**

The circular cross-correlations for the several techniques are depicted in the Fig. 2 for comparison purposes.

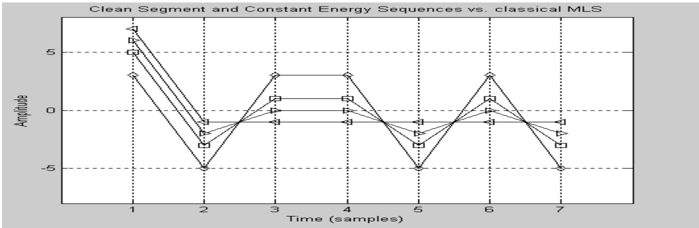
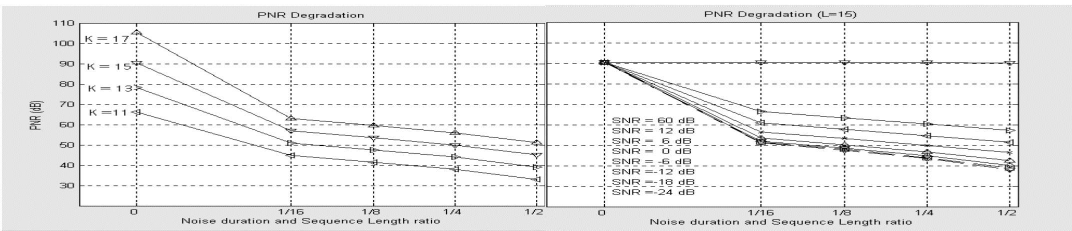


Fig. 2 – Circular cross-correlations for the Clean Segment and Constant Energy Sequences and for the classical MLS techniques for an *Fr* = 1/7 corresponding to change the second bit of the sequence by the -10 value. The curves are related to (i) ◄ with noise missing, (ii) ► Clean Segment Sequence, (iii) □ Constant Energy Sequence and (iv) ◊ classical MLS.

The results presented in Fig. 2 with *Fr* = 1/7 show that if only a part of the sequence is corrupted by noise, the acoustical tests could be completely invalidated (see the results with the classical MLS approach). However, the results achieved with the Clean Segment Sequence and the Constant Energy Sequence techniques are very similar to the noise missing case.
Fig. 3 depicts the Peak to Noise Ratio curves PNR for the proposed techniques when anechoic conditions are used (the PNR relates the RI peak amplitude and background noise). The PNR’s values were estimated for different values of *Fr* (0, 1/16, 1/8, 1/4 and 1/2).



a) b)

Fig. 3 – Peak-to-Noise Ratio PNR for different values of the *Fr* - **a**) for the Clean Segment Sequence technique for different MLS sequence degrees; **b**) for the Constant Energy Sequence for an MLS degree of *K*=15 and with filtered white noise.

The results depicted in Fig. 3 a) show the degradation of the PNR when the *cleaning* process is applied. For *Fr* = 0, the result correspond to the theoretical value (the MLS technique is used with background noise missing). For the same value of *Fr*, the PNR increases 3 dB when the MLS degree is increased by one. The same results (3 dB) can be achieved for each reduction of *Fr* (shorting the cleaning zone). It is obvious that best results are achieved for higher MLS sequence K degrees. The choice of the *K* degree depends on the noise duration.
As an example, consider the curves for *K*=17 and *K*=15. Focus the sequence with *K*=17 and *Fr*=1/8. The noise duration corresponds for *K*=15 @ *Fr*=1/2. The PNR is 60 dB and 45 dB, respectively. This means that the sequence degree must be imposed if a minimum PNR is defined.
The results illustrated in Fig. 3 b) show a PNR degradation not proportional to the decrease of the SNR (for the same *Fr*) and is bounded by a minimum limit value (see the lower curve). This happens because the PNR is estimated for the whole sequence length.

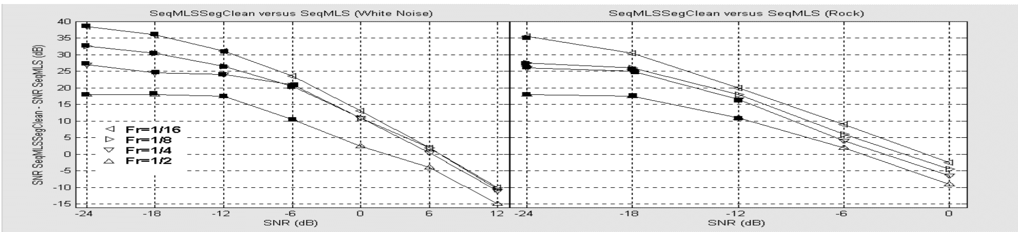
The performance of the presented techniques can be evaluated by comparing the Fig. 3 a) and b). For $K = 15$ and SNR = 0 dB, the Clean Segment Sequence and the Constant Energy Sequence techniques presents the same PNR degradation. As a result, it can be stated that it is advantageous to use the Constant Energy Sequence for SNR > 0 dB and the Clean Segment Sequence otherwise.

3. EXPERIMENTAL RESULTS

The performance of these techniques was evaluated by means of:

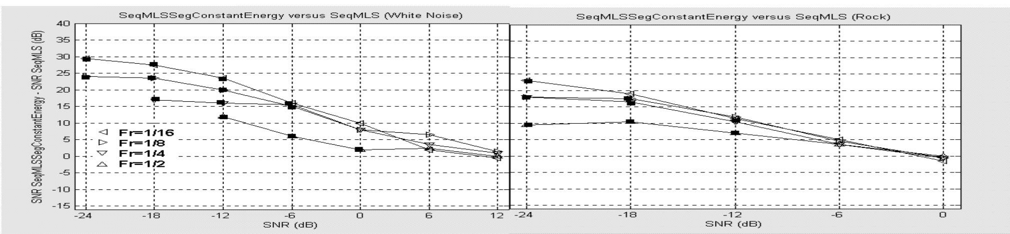
- Difference of SNR's between each technique and the classical MLS technique – quantitative approach;
- Amplitude Impulse Response and Energy Decay Curve – qualitative approach.

Fig. 4 and 5 depict the gain (SNRSeqMLSSegClean – SNRSeqMLS) of the Clean Segment and Constant Energy Sequences (SNRSeqMLSConstantEnergy – SNRSeqMLS) against the classical MLS technique respectively. These analyses are presented for different types of noise (white noise and a rock music track).



a) b)

Fig. 4 – Gain between the SNR's of the Clean Segment Sequence and classical MLS for different SNR and *Fr* values. The solid square values indicate that acceptable results of Reverberation Time are only achieved for the Clean Segment Sequence technique. **a**) corresponds to results using white noise and **b**) to rock music as disturbance.



a) b)

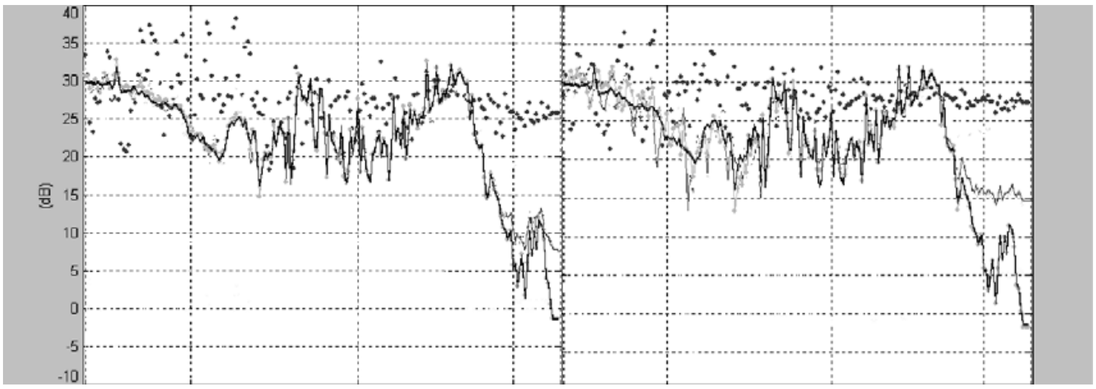
Fig. 5 – Gain between the SNR's of the Clean Segment Sequence and classical MLS for different SNR and *Fr* values. The calculations marked by a filled square indicate that acceptable results for Reverberation Time, RT, are only achieved for the Clean Segment Sequence technique. The calculations marked by the filled circles indicate no acceptable results of RT for either technique. Part a) corresponds to the results using white noise and b) to rock music as disturbance.

As shown in Figs. 4 and 5, the best results achieved by these new techniques correspond to the lower SNR at the reception point and for the smallest *Fr* value. There are some situations for which it is impossible to achieve reliable results using the classical MLS approach (solid black squares).

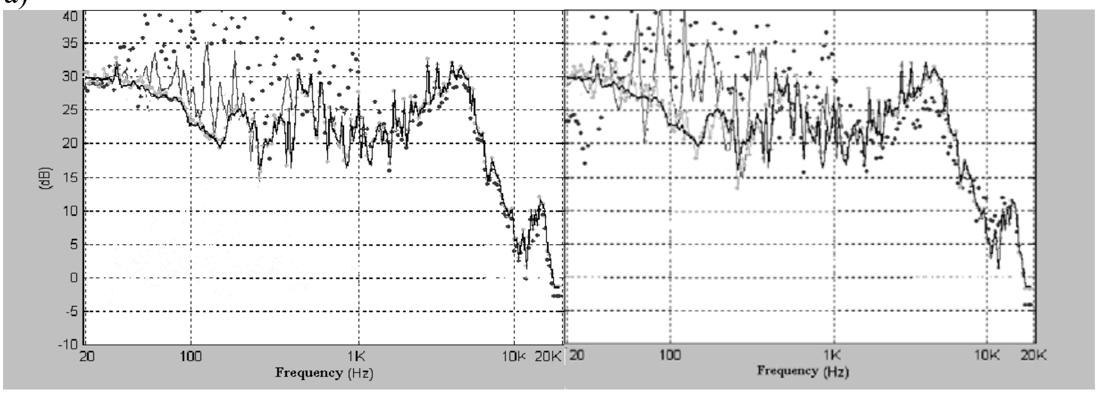
For very low SNR's and/or for low *Fr*'s all the techniques fail to assure reasonable results. In such situations, the averaging method should be applied together with the proposed techniques.

As mentioned above, for SNR < 0 dB, the Clean Segment Sequence works better than the Constant Energy Sequence and vice-versa.

Fig. 6 depicts the qualitative results concerning to the Amplitude Impulse Response. The tests were performed using a sequence degree of *K*=15 convoluted with the IR of a physical room. A sampling frequency *fs* = 44,1 kHz was used and the SNR for the noise region was adjusted to –15 dB.



a)



b)

Fig.6 – Amplitude Impulse Response for the different studied techniques and noise types of a) white noise and b) rock music track. The *K*=15, *Fr* is 1/16 i.e. 2048 samples (left side figures) and *Fr* is 1/4 i.e. 8192 samples (right side figures). The curves correspond to different techniques (i) coarse curve - noiseless case (exact response), (ii) dashdot curve - Clean Segment Sequence, (iii) thin curve - Constant Energy Sequence and, (iii) dotted curve - classical MLS. The SNR is –15 dB.

The results depicted in Fig. 6 show that the proposed techniques compared against the classical MLS approach present much better results. For $Fr = 1/16$, the Amplitude Impulse Response estimation obtained with the Clean Segment Sequence is a very good approximation of the exact curve. Even for the case of $Fr = 1/4$, the deviation is almost not noticeable. In the case of the Constant Energy Sequence the results are not so good as with the Clean Segment Sequence, although, they are much better than those from the classical MLS technique.

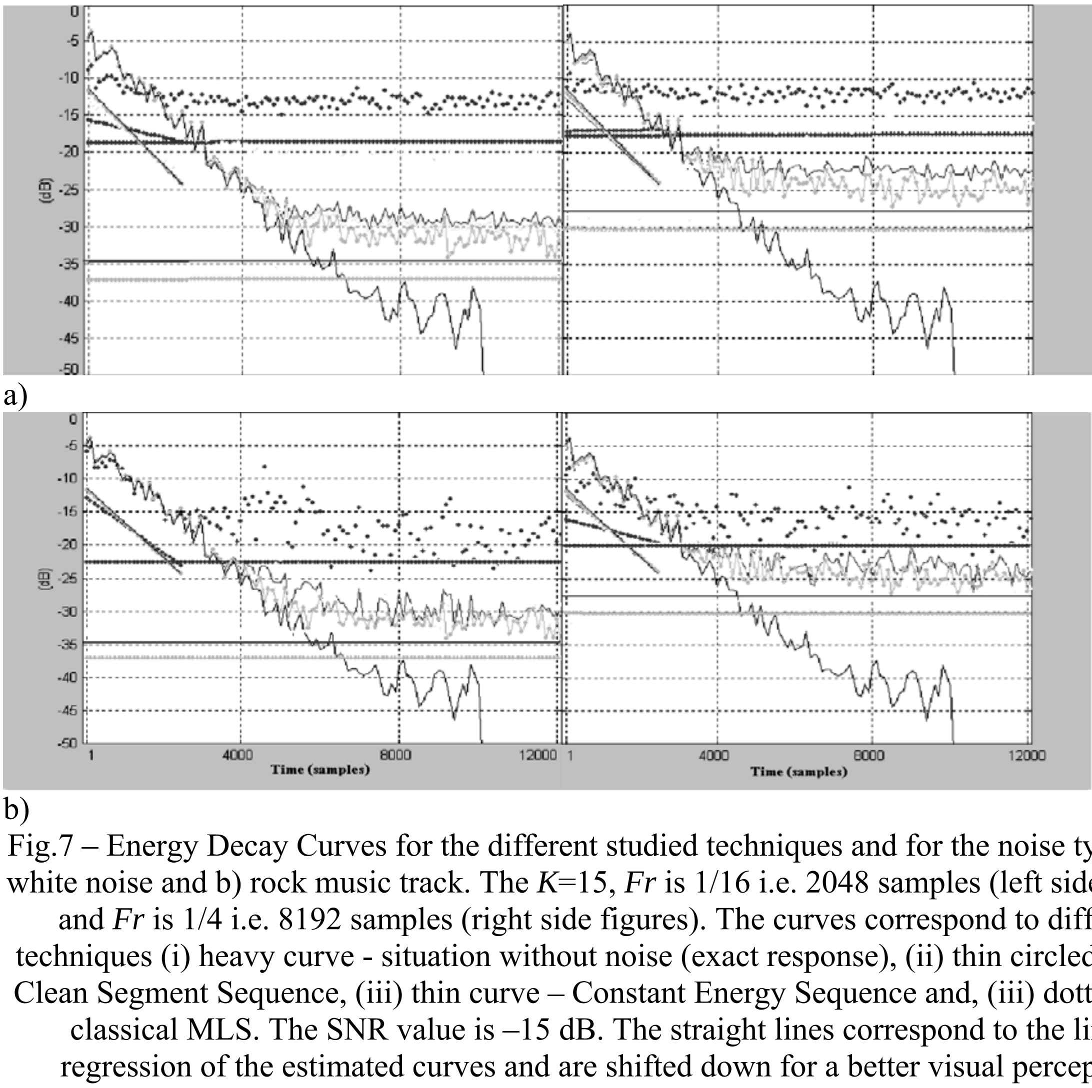


Fig.7 – Energy Decay Curves for the different studied techniques and for the noise types of a) white noise and b) rock music track. The K=15, Fr is 1/16 i.e. 2048 samples (left side figures) and Fr is 1/4 i.e. 8192 samples (right side figures). The curves correspond to different techniques (i) heavy curve - situation without noise (exact response), (ii) thin circled curve – Clean Segment Sequence, (iii) thin curve – Constant Energy Sequence and, (iii) dotted curve classical MLS. The SNR value is –15 dB. The straight lines correspond to the linear regression of the estimated curves and are shifted down for a better visual perception.

The Energy Decay Curves show unreliable results when using the classical MLS technique (see the slope of oblique lines). With the new techniques presented here, the results are much closer to the exact curves (noiseless case). Therefore, they yield to a more reliable Reverberation Time estimation.

4. CONCLUSIONS AND FUTURE WORK

Two modified MLS measurement methods referred to as Clean Segment Sequence and Constant Energy Sequence for room acoustics applications are presented. These techniques are to be applied in limited noise duration conditions and for low or very low SNR.
The proposed techniques compared against the classical MLS approach has lead to a significant increase in the SNR and in turn to better estimates of room acoustic parameters, namely, the Amplitude Impulse Response and the Energy Decay curves. The analyses evaluated with Impulse Responses obtained in real conditions show this.
The results prove that the associated error with the Clean Segment Sequence and Constant Energy Sequence techniques is comparably lower than with the classical MLS technique.
It is shown that the right choice of each technique depends on the SNR of the noise segment. The results point to the use of the Clean Segment Sequence in situations of SNR < 0 dB and of the Constant Energy Sequence otherwise. It is obvious that these techniques can be used together in the same sequence for different segments.
In order to reduce the noise resulting by the time-variant environments, these techniques have to be tested before using an averaging procedure.
The next step of this work is to test these techniques in real conditions and with several types of room environments.

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