Estimation of the Subjective Intelligibility With Superimposition of BN8 in the Environment of the Orthodox Church Built in the Moravian Style

Violeta Stojanović
Department of Environmental Protection
Academy of Applied Technical and Preschool Studies
Niš, Serbia
violeta.stojanovic@akademijanis.edu.rs

Zoran Milivojević
Department of Information Technology
MB University
Belgrade, Serbia
zoran.milivojevic@akademijanis.edu.rs

Dijana Kostić
Institution: Šargan – inženjering d.o.o
Niš, Serbia
koricanac@yahoo.com

Bojan Prlinčević
Department of Information Technology
Kosovo and Metohija Academy of Applied Studies
Leposavić, Serbia
bojan.prlincevic@akademijakm.edu.rs

***Abstract*—In this paper, the estimation of subjective intelligibility in the presence of Babble noise BN8, for certain SNR values, in the ambiance of an Orthodox church, is presented. The first part of the paper describes estimation algorithms for objective and subjective speech intelligibility in enclosed spaces. Following that, as a result of analyzing the relationship between subjective and objective intelligibility, the Subjective Intelligibility Estimation (*SIE*) Parameter β, was defined. In the second part of the paper, an experiment is described in which the intelligibility is analyzed in the environment of the Orthodox church built in the Moravian style. The analysis is based on testing the intelligibility of words created by convolving Room Impulse Responses (RIRs) with clean speech. Intelligibility was tested using objective and subjective methods, and, in that way, objective and subjective acoustic parameters: a) Speech Transmission Index, *STI*, b) Articulation Loss of Consonants, Al_{cons}, and c) subjective intelligibility, *SI*, were determined. The results are presented graphically and in tables. The estimation of speech intelligibility quality was determined through a comparative analysis of objective and subjective parameters with the Standard IEC 60268-16 values. The *SIE* parameter β was calculated for SNR = -10, ..., 50 dB and, after that, the mean value $\overline{\beta(SNR)}$ was calculated. Finally, by applying the numerical method of least squares, the Estimation Parameter β_a (SNR) was calculated.**

Keywords*—*RIRs, BN8, SNR, intelligibility test, Subjective Intelligibility Estimation Parameter.

I. Introduction

The acoustic treatment of the Orthodox church involves the analysis of the aesthetic optimal acoustic response of the space where Orthodox church service is conducted, i.e., the aesthetics of sound. Churches are acoustically complex spaces. The range of possible sound messages is extremely diverse. The Holy Liturgy is the most significant event in the Orthodox Church. It comprises group prayer, sermon listening, priest chanting, and choir and priest polyphonic singing. Lyrics strongly emphasizing rhythm are accompanied by monophonic, mellow Byzantine chant music [1]. As a result, the Orthodox Church's acoustics need to produce an atmosphere conducive to Byzantium chanting and speech intelligibility.

Speech intelligibility is the process of recognizing a spoken message. The message can be a sentence consisting of a series of elementary messages, i.e., words. A word is composed of phonemes, which are the elementary speech sounds representing vowels and consonants of a particular language. Listeners' ability to the intelligibility phonemes is a direct indicator of speech intelligibility.

The algorithm for predicting speech intelligibility in auditoriums and Articulation Loss of Consonants, Al_{cons}, was introduced by Peutz in 1971 [2]. In 1980, Houtgast and Steeneken proposed the Speech Transmission Index, STI, as an acoustic parameter and validated an objective method for measuring the quality of speech transmission in a room [3 – 4]. Subjective methods for assessing speech transmission through intelligibility tests (word tests, commonly with logatoms, sentence tests, syllable tests) were applied by Fletcher and Steinberg in 1929 [5]. This theme has been further explored by Egan in 1944, Miller and Nicely in 1955, House in 1965, Voiers in 1977, and others. Pols in 1991 and Steeneken in 1992 presented an overview of speech intelligibility assessment tests [6].

In 1953, Raes and Sacerdote published one of the earliest studies on the acoustic properties of two Roman cathedrals [7]. Following that, a significant number of Catholic churches were studied: English and French (Fearn 1975), Greek (Tzekakis 1979 and Trochidis 1982), Swiss (Desarnaulds et al. 1998), Portuguese (Carvalho, 1994), Italian and Spanish (Álvarez-Morales, 2015; Martelota, 2009), Polish (Vroblevske 2007 and Kosale, 2013), etc. Balkan Orthodox churches' acoustics aren't as well-represented in the literature [7]. Mijić and Šumarac-Pavlović conducted the first analyses of Serbian churches in 2000 and 2001, respectively. They were followed by Nenadović in 2003 and Đorđević et al. in 2015 with their research [8]. In 2017, Malecki and colleagues compared the acoustics of Polish churches. In 2015, Elicio and Martelotta published the results of an acoustic study of the church in Bari, known as the "Russian church". Their work summarized the available acoustic data for Orthodox Christian churches in Russia and Greece [7]. An overview of published archaacoustic studies on Christian temples was presented by Girón et al. 2017 [9].

In this paper, the Subjective Intelligibility Estimation (*SIE*) Parameter β was proposed for the acoustically treated Orthodox Church built in the Moravian style. Measurements ere conducted using both objective and subjective methods.

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Using the objective method, which is based on recorded RIRs in the church, the mean values of objective parameters were determined: $\overline{RT_{30}}$ (Reverberation Time), $\overline{STI}$ i $\overline{Al_{consO}}$. Using the subjective method, which was realized using a test containing phonetically balanced words masked with Babble Noise BN8 (recorded with 8 speakers) for SNR = -10, ..., 50 dB, the mean values of subjective speech intelligibility, *SI*, were determined. Based on the dependency $SI = f(STI)$ and $STI = f(Al_{cons})$ given by the Standard [10], the mean values of the subjective parameters $\overline{STI_S}$ and $\overline{Al_{consS}}$ as well as the speech quality, are determined. The relationship between the mean values of $\overline{Al_{consS}}$ and $\overline{Al_{consO}}$ is represented by the proposed *SIE* parameter β. After calculating the mean value of the proposed parameter $\overline{\beta(SNR)}$ for the acoustically treated church, the analytical dependence $\beta_a = f(\text{SNR})$ is also presented.

The organization of the paper is as follows: Section II describes the algorithms for assessing the objective and subjective intelligibility of speech in enclosed spaces and defines the proposed parameter for assessing intelligibility. Section III outlines the experiment, presents the experimental results in tabular and graphical form, and conducts an analysis of the results. Finally, Section IV provides the conclusion.

II. Algorithms for Estimation Intelligibility in Enclosed Sraces

A. Algorithms for Estimation Objective Intelligibility

The algorithm for estimation the objective intelligibility of speech is based on measuring RIRs at measurement points MP_k where k = 1, ..., N_{MP} and N_{MP} is the total number of measurement points. Multiple RIR measurements, h_{kl}, were conducted at each MP, where l = 1, ..., L_h. Subsequently, objective acoustic parameters such as RT_{30}, $RT_{30(2kHz)}$, *STI*, and Al_{cons}, as well as their mean values $\overline{RT_{30,k}}$, $\overline{RT_{30(2kHz),k}}$, $\overline{STI_k}$ and $\overline{Al_{cons,k}}$, were calculated by analyzing the RIRs at MP_k. Knowing that the critical distance from the sound source to MPk is $D_C = 0.056\sqrt{\gamma V / \overline{RT_{30}}}$ (γ is the directivity factor of the source and V is the volume of the room), then is [14]:

$$Al_{consO}(k) = \begin{cases} \dfrac{200\left(\overline{RT_{30(2kHz)}(k)}\right)^2 D_{x,k}}{V} \ (\%), & D_{x,k} \le 3.16 D_C \\ 9\overline{RT_{30(2kHz)}(k)} \ (\%), & D_{x,k} > 3.16 D_C \end{cases} \quad (1)$$

where $D_{x,k}$ is the distance from the sound source to the k-th measurement point. The conclusion regarding the quality of speech intelligibility (bad, poor, fair, good, excellent) is drawn by comparing the obtained values $\overline{Al_{consO}}$ with those provided by the Standard IEC 60268-16 [10].

B. Algorithms for Estimation Subjective Intelligibility

The basis of the algorithm for subjective intelligibility estimating is the test of intelligibility of clean phonetically balanced words. The subjective intelligibility (*SI*) in the k-th measurement point ($1 \le k \le MP_C$) for the i-th listener ($1 \le i \le$ PN, where PN is the total number of listeners) in the presence of BN with SNR values is defined as:

$$SI(k,i,SNR) = \frac{WR(i,SNR)}{WN} 100 \ [\%], \quad (2)$$

where is $WR(i, SNR)$ the total number of correctly recognized words by the *i*-th listener, and *WN* is the total number of spoken words. The mean value of subjective intelligibility for all listeners at the *k*-th measurement point for SNR values is:

$$SI_i(k,SNR) = \frac{1}{PN}\sum_{i=1}^{PN} SI(k,i,SNR). \quad (3)$$

The mean value of subjective intelligibility for all listeners on all MP_Cs for SNR values is:

$$SI(SNR) = \frac{1}{MP_C}\sum_{k=1}^{MP_C} SI_i(k,SNR). \quad (4)$$

The mean values of the subjective speech transmission index for all listeners at the k-th measurement point for SNR values, $\overline{STI_{S,k}}$, are obtained from the correlation between the speech intelligibility rating and the speech transmission index for PB words and are determined by the international standard IEC 60268-16 [10]. The mean value of the subjective parameter $\overline{Al_{consS,k}}$ for all listeners in the k-th measurement point for SNR values is determined by the Farrel-Becker empirical formula [2]:

$$\overline{Al_{consS,k}} = 170.5405 e^{-5.419\overline{STI_{S,k}}}. \quad (5)$$

The quality of intelligibility for different SNR values is defined by the Standard [10]. The mean values of $\overline{STI_S}$ and $\overline{Al_{consS}}$ for all MP_C and all listeners were also calculated.

C. Subjective Intelligibility Estimation Parameter

The connection between the subjective and objective parameters of the articulation loss of consonants, $\overline{Al_{consS,k}(SNR)}$ and $\overline{Al_{consO}}$, of all listeners at the k-th measurement point, is achieved by introducing a new *SIE* parameter $\beta(SNR)$:

$$\beta(k,SNR) = \frac{\overline{Al_{consS,k}(SNR)}}{\overline{Al_{consO}(k)}}. \quad (6)$$

The mean value of the *SIE* parameter $\overline{\beta(SNR)}$ for all MP_Cs and all listeners for SNR values is:

$$\overline{\beta(SNR)} = \frac{1}{MP_C}\sum_{k=1}^{MP_C} \beta(k,SNR). \quad (7)$$

The analytical dependence between the mean value of the proposed *SIE* parameter $\overline{\beta(SNR)}$ and the SNR values was realized by the assessment algorithm:

$$\beta_a(SNR) = z \cdot (SNR)^{\gamma}. \quad (8)$$

III. Experimental results and analysis

A. Experiment

The experiment was conducted in the empty Serbian Orthodox Church "Saint Procopius" in Katun, Serbia. For the estimation of subjective speech intelligibility in the presence of BN8, the *SIE* $\beta(SNR)$ was proposed.

The total inner surface and volume of the Orthodox church are S = 646.48 m^2, and V = 1659.68 m^3, respectively. The measurement of the impulse response of the church was performed following ISO 3382 [12]. Fig. 1. shows the arrangement of measurement points, MP, and the position of the sound source, LS. The minimum distance between the microphone and the speaker is d_{min} = 3 m. The critical distance is D_c = 2.32 m. Objective parameters defined in part 2.1 of the paper were determined from the RIRs using the EASERA and Matlab software packages. The parameter Al_{consO} values for measurement points $MP_1 \div MP_4$ were obtained using equation (1).

The estimation of *SI* was conducted using a test of intelligibility of pure phonetically balanced words for measurement points $MP_1 \div MP_4$. The block diagram of the test is shown in Fig. 2 [13], where: u- clean speech signal, h - the impulse response of the church, $v = u \otimes h$ - generated acoustic signal (convolution of signals u and h) w- generated acoustic signal with superimposed BN8 and the corresponding SNR = (-10, -5, 0, 5, 10, 20, 30, 50) dB. The Babble noise was recorded with 8 speakers: 4 male and 4 female, aged between 18 and 25 years.

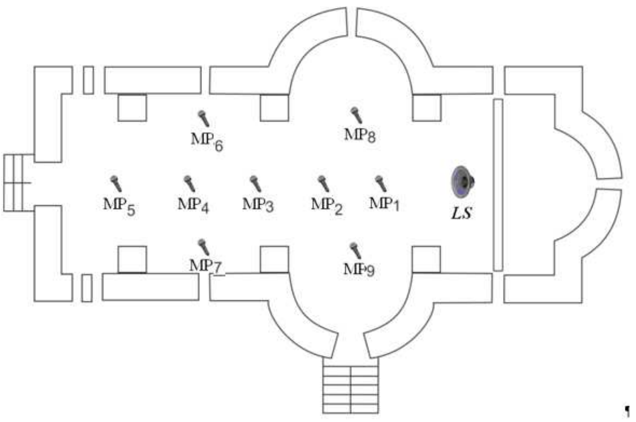

Fig.1 The position of measuring point MP and sound source LS in the church during the recording impulse response.

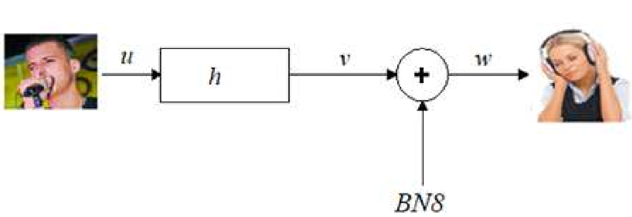

Fig.2 Block diagram of SI Testing.

The intelligibility test was conducted with 20 listeners (10 male and 10 female, aged 18-25), who repeated the words they heard. The coordinator of the experiment records the words spoken by the listener. At the end of the experiment, the results were analyzed based on correctly and incorrectly recognized words. The subjective SI parameters were calculated using the estimation algorithm described in part II. B. of the paper.

B. The Base

1) RIRs

Measuring of the impulse response is carried out using incentive log sweep signal with the duration of 6 s sampling frequency is f_S = 44.1 kHz. The recording of acoustic impulse responses was performed in k = 9 MP (Fig. 1), with 7 recordings made at each measurement point. This formed the database of acoustic impulse responses, comprising 63 wav files in total.

2) Intelligibility test

Clean phonetically balanced words of type (C)CVCV and CCVC(C)V pronounced in the Serbian language [14]. They were recorded in wav format and archived on disk. Recording took place at the Academy of Applied Technical and Preschool Studies in Niš, Serbia. The recording involved third-year students of the Communication Technologies study program (5 male and 5 female, aged 21-23) who pronounced 20 words each (signal u in Fig. 2.) and who until then had not participated in such experiments.

C. The Results

In Table I, the values of objective acoustic parameters $\overline{RT_{30}}$, $\overline{STI}$ and $\overline{Al_{cons}}$ are presented: a) for each MP, and b) for all (MP). Table II shows the values: D_x, $\overline{RT_{30(2kHz)}}$, Al_{consO}, $\overline{Al_{consO}}$ and $\overline{Al_{cons}}$ for $MP_1 \div MP_4$ in which the intelligibility estimation was conducted. Values of SI_i and SI_k for SNRs at MP_C are shown in Table III. Values of $\overline{STI_{S,k}}$ and $\overline{STI_S}$ and intelligibility quality ratings for SNRs are presented in Table IV. Table V provides values of $\overline{Al_{consS,k}}$, $\overline{Al_{consS}}$ and intelligibility quality ratings for SNRs. Table VI presents the values of the proposed *SIE* parameter $\beta(k,SNR)$ and $\overline{\beta(SNR)}$ The dependence of *SI*, $\overline{STI_S}$, $\overline{Al_{consS}}$ on SNRs is illustrated in Fig. (3 – 5). The graphical dependence of *SIE* parameter $\overline{\beta(SNR)}$ and $\beta_a(SNR)$ is shown in Fig. 6.

D. The Results Analysis

Based on the results shown in the Tables (I - VI) and in Fig. (3 – 6), the following conclusion is drawn for:

TABLE I. The Mean Values of Objective Acoustic Parameters for: a) Each MP and b) All MPs in the Church

$\overline{x(k)}$	k									$\bar{x}$
	1	2	3	4	5	6	7	8	9	
$\overline{RT_{30}}$ (s)	2,52	1,94	1,89	1,64	1,74	1,99	2,00	2,51	2,66	2,10
$\overline{STI}$	0,64	0,54	0,5	0,5	0,53	0,53	0,53	0,55	0,56	0,54
$\overline{Al_{cons}}$ (%)	5,25	9,29	11,29	11,44	9,65	9,41	9,78	8,53	8,12	9,2

TABLE II. The Values Some Parameters for MPc

k	1	2	3	4
D_x (k) (m)	3	5	7	9
$\overline{RT_{30(2kHz)}}$ (s)	1.66	1.49	1.41	1.47
Al_{consO} (%)	2.99	6.69	11.74	13.23
$\overline{Al_{consO}}$ (%)	8.66			
$\overline{Al_{cons}}$ (%)	9.32			

TABLE III. THE VALUES OF SI_i AND SI_k FOR SNRS AT MPC

	k	SNR (dB)							
		-10	-5	0	5	10	20	30	50
SI_i (%)	1	0	20	41.05	72.63	78.95	93.68	94.74	95.79
	2	0	7.37	44.21	74.74	82.1	90.53	93.68	94.74
	3	1.05	16.84	56.84	74.74	84.21	90.53	95.79	94.74
	4	1.05	9.47	53.68	74.74	84.21	93.68	96.84	94.74
SI_k (%)		0.52	13.42	48.94	74.21	82.37	92.1	95.26	95

TABLE IV. THE VALUES $\overline{STI_{S,k}}$ AND $\overline{STI_S}$ AND INTELLIGIBILITY QUALITY RATINGS FOR SNRS

		SNR (dB)							
		-10	-5	0	5	10	20	30	50
MP1	$\overline{STI_{S,1}}$	-	0.1	0.18	0.36	0.48	0.62	0.64	0.68
	quality	bad			poor	fair	good		
MP2	$\overline{STI_{S,2}}$	-	-	0.2	0.38	0.45	0.55	0.61	0.62
	quality	bad			poor	poor fair	fair		good
MP3	$\overline{STI_{S,3}}$	-	-	0.27	0.38	0.47	0.55	0.68	0.62
	quality	bad			poor	fair		good	
MP4	$\overline{STI_{S,4}}$	-	-	0.21	0.38	0.47	0.61	0.74	0.62
	quality	bad			poor	fair	good		
$\overline{STI_S}$		-	0.025	0.22	0.37	0.47	0.58	0.67	0.64
quality		bad			poor	fair	fair	good	

TABLE V. THE VALUES $\overline{Al_{consS,k}}$ AND $\overline{Al_{consS}}$ AND INTELLIGIBILITY QUALITY RATINGS FOR SNRS

		SNR (dB)							
		-10	-5	0	5	10	20	30	50
MP1	$\overline{Al_{consS,1}}$ (%)	-	-	64.3	24.24	12.65	5.92	5.32	4.28
	quality	bad			poor	fair	good		
MP2	$\overline{Al_{consS,2}}$ (%)	-	-	57.69	21.75	14.89	8.43	6.25	5.77
	quality	bad			poor	fair		good	
MP3	$\overline{Al_{consS,3}}$ (%)	-	-	39.48	21.75	13.36	8.43	4.28	5.77
	quality	bad			poor	fair		good	
MP4	$\overline{Al_{consS,4}}$ (%)	-	-	53.19	21.75	13.36	6.25	3.09	5.77
	quality	bad			poor	fair		good	
$\overline{Al_{consS}}$ (%)		-	-	53.66	22.37	13.56	7.26	4.73	5.4
quality		bad			poor	fair		good	

1) The objective parameters of intelligibility:

a) The primary parameter for determining intelligibility is $\overline{RT_{30}}$ = 2.1 s, which is an aesthetic optimum for Serbian Orthodox churches [15]. The mean value of the Articulation Loss of Consonants parameter in all MP, $\overline{Al_{cons}(k)}$ = 5.25% ÷ 11.44%, and classifying intelligibility as good to fair. For the entire church, this parameter is $\overline{Al_{cons}}$ = 9.2%, confirming fair intelligibility.

b) For MP1 – MP4 mean values this parameter $\overline{Al_{consO}}$ = 9.32 % and $\overline{Al_{consO}}$ = 8.66 % define fair intelligibility.

TABLE VI. THE VALUES OF THE PROPOSED *SIE* PARAMETERS $\beta(k,SNR)$ AND $\overline{\beta(SNR)}$

	k	SNR (dB)					
		0	5	10	20	30	50
$\beta(k,SNR)$	1	21.5	8.11	4.23	1.98	1.78	1.43
	2	8.62	3.25	2.23	1.26	0.93	0.86
	3	3.36	1.85	1.14	0.72	0.36	0.49
	4	4.02	1.64	1.01	0.47	0.23	0.44
$\overline{\beta(SNR)}$		9.38	3.71	2.15	1.11	0.83	0.80

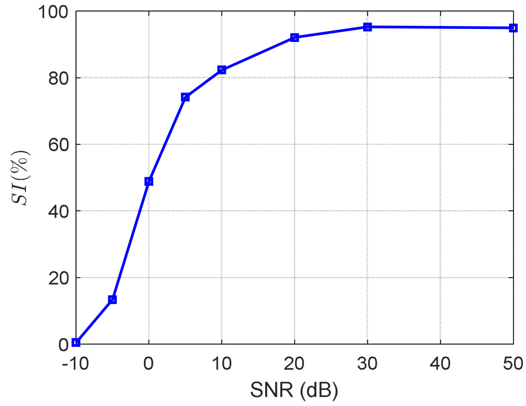

Fig.3 The dependence of *SI* on *SNR*.

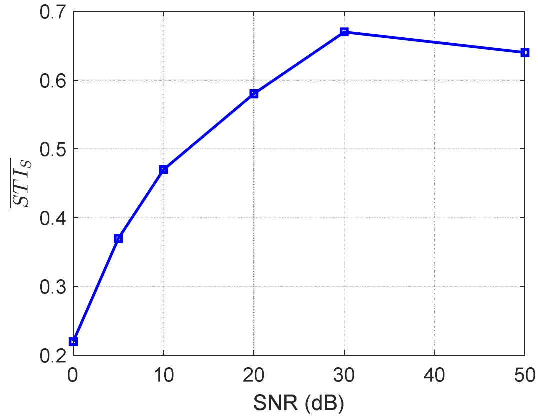

Fig.4 The dependence of $\overline{STI_S}$ on *SNR*.

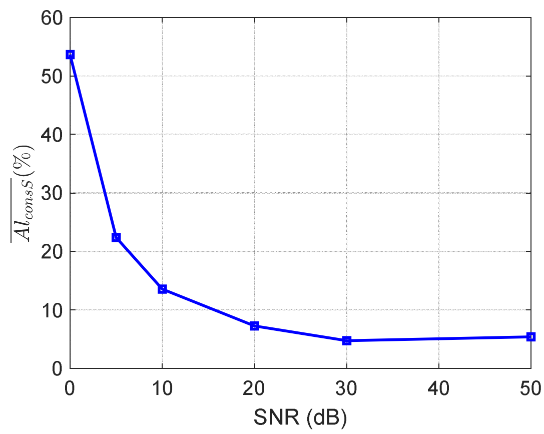

Fig.5 The dependence of $\overline{Al_{consS}}$ on *SNR*.

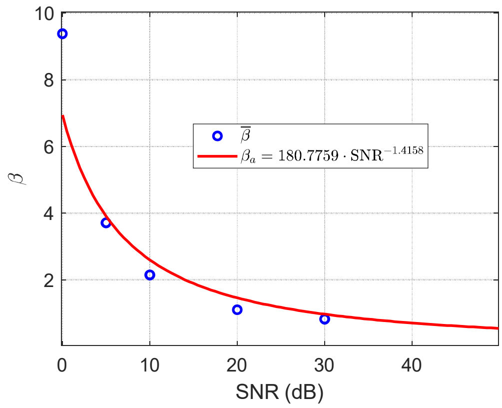

Fig.6 The dependence of *SIE* parameters $\overline{\beta}$ and β_a on *SNR*.

2) The subjective parameters of intelligibility:

a) Clean phonetically balanced words, represented by the input signal with RIRs of the church and BN8, with: i. SNR = (-10, -5) dB have bad intelligibility SI_k = (0.52, 13.42) %, respectively, ii. SNR = 0 dB have poor intelligibility SI_k = 48.94 %, iii. SNR = (5, 10) dB have fair intelligibility: SI_k = (74.21, 82.37) %, iv. SNR = 20 dB have good intelligibility because the SI_k = 92.1 % and v. SNR = (30, 50) dB have excellent intelligibility in listeners: SI_k = (95.26, 95) %, respectively.

b) Based on the mean values of the subjective parameters $\overline{STI_S}$ and $\overline{Al_{consS}}$ phonetically balanced words, represented by the input with RIRs and BN8 with: *i*. SNR = (-5, 0) dB have bad intelligibility, *ii*. SNR = 5 dB have poor intelligibility ($\overline{STI_S}$ = 0.37 and $\overline{Al_{consS}}$ = 22.37 %), *iii*. SNR = (10, 20) dB have fair intelligibility ($\overline{STI_S}$ = (0.47, 0.58) and $\overline{Al_{consS}}$ = (13.56 %, 7.26 %), respectively) and *iv*. SNR = (30, 50) dB have good intelligibility ($\overline{STI_S}$ = (0.67, 0.64) and $\overline{Al_{consS}}$ = (4.73 %, 5.4 %), respectively).

3) The SIE Parameter

a) All values of the *SIE* parameters β and $\overline{\beta(SNR)}$ decrease as SNR increases. For the test words represented by the input signal with RIRs church and BN8 with SNR = (0, 5, 10, 20, 30, 50) dB, the mean values of the *SIE* parameter are $\overline{\beta(SNR)}$ = (9.38, 3.71, 2.15, 1.11, 0.83, 0.8), respectively.

b) The analytical dependence between the Estimation parameter β_a and the SNR value was obtained using the least squares numerical method: $\beta_a = 180.7759 \cdot SNR^{-1.4158}$.

IV. Conclusion

In this paper, a Subjective Intelligibility Estimation (*SIE*) Parameter, β, has been proposed, representing the outcome of an empirical analysis of the interrelationship between subjective and objective intelligibility in the environment of a Serbian Orthodox church built in the Moravian style.

Based on the conducted analysis, it has been demonstrated that applying *SIE* parameter makes it possible to evaluate subjective intelligibility in the presence of Babble noise, for different SNR values. It is the ratio of the mean values of the subjective and objective parameters of Articulation Loss of Consonant. Its relationship with different values of SNR is given by the equation: $\beta_a = 180.7759 \cdot SNR^{-1.4158}$. For the acoustically treated Orthodox church, the average values of this parameter for SNR = (0, 5, 10, 20, 30, 50) dB are $\overline{\beta(SNR)}$ = (9.38, 3.71, 2.15, 1.11, 0.83, 0.8), respectively.

This paper also demonstrated that the mean values of subjective intelligibility of clean phonetically balanced words represented by the input signal with RIRs of the church and Babble noise are: a) SNR = (5, 10) dB, SI_k = (74.21%, 82.37%), b) SNR = 20 dB, SI_k = 92.1 % i c) SNR = (30, 50) dB, SI_k. = (95.26 %, 95 %). By comparison with the values determined by the International Standard IEC 60268 - 16, it is concluded that speech intelligibility in the environment of the Orthodox Church belongs to the classification from fair to excellent.

The proposed Subjective Intelligibility Estimation (*SIE*) Parameter, β, will be the subject of further research by the authors of this paper.

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