Minimal requests on high-fidelity audio recording and reproduction

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***Abstract**. Sound recording quality, whether digital or analogue, presupposes true-to-life recording of the original audio signal. Contemporary audio media do not meet the requirements of high-fidelity recording since they do not insufficiently utilize the bandwidth for D/A conversion and sufficient word length. The bandwidth should cover frequency range from 20Hz to 20kHz together with related harmonics and transients that couse frequence range enlargement. The word langht should cover the signal dynamic range and transmit fine voltage differences – amplitude of the continuous analogue signal.*

The fidelity quality of the audio recording depends on the quantity of information selected and stored during recording using digital and analogue technology, respectively. In digital recording, the amount of information is represented by the number of samples used for audio recording and reproduction as well as their dynamic. This paper deals with the values of these parameters in high-fidelity recording. The paper presents the results of the research into characteristics of faithful and high-fidelity audio recording considering the frequency range, signal-to-noise ratio and dynamic range.

Keywords. high-fidelity, audio quality, audio recording and reproduction, Nyquist's theorem

1 Introduction

There are different audio signals according to their complexity, frequency range and dynamic (for example, plain speech audio signal as opposed to that of a symphony orchestra). The audio signal pertaining to a symphony orchestra is characterized by a large dynamic range (containing both very quiet and very loud sections), with a variety of instruments producing a multitude of frequencies. The same tone played various musical instruments has a different range of frequencies and different wave motion (eg in Figure 1, 2, 3, and 4 C shows the tone played trumpet and organ).

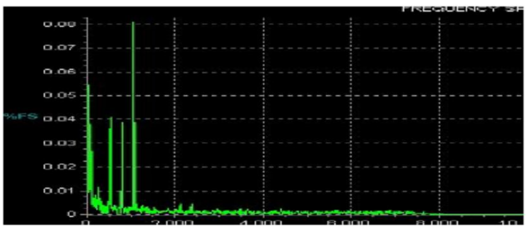


Figure 1: Frequency spectrum of tone C played organ (Source:Lukavečki,.M, Fourier analysis of acoustic signals in real time, pp. 37.,38.,39.)

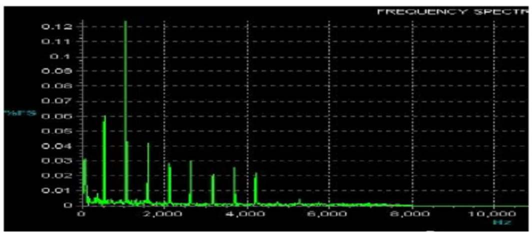


Figure2:Frequency spectrum of tone C played trumpet (Source:Lukavečki,.M, Fourier analysis of acoustic signals in real time, pp. 37.,38.,39.)

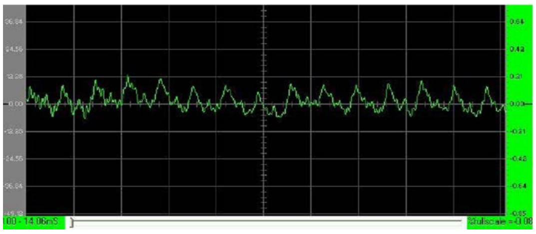


Figure 3: Wave motion tona C played organ (Source:Lukavečki,.M, Fourier analysis of acoustic signals in real time, pp. 37.,38.,39.)

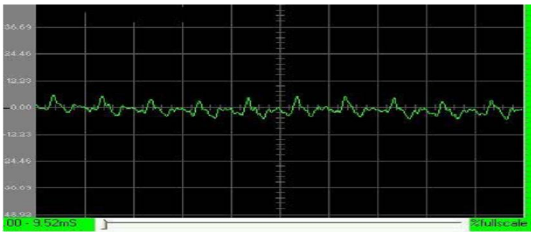


Figure 4: Wave motion tona C played trumpet (Source:Lukavečki,.M, Fourier analysis of acoustic signals in real time, pp. 37.,38.,39.)

Each tone produced by an instrument also contains harmonics and transients, which determine the tone colour of a particular instrument. The dynamic of the audio signal pertaining to a symphony orchestra is wide, ranging from 20 dB to 100 dB, whereas the frequency range which can be produced by its instruments is 10 Hz to 20 kHz [Shorter, D.E.L. - Borwick, J., *Sound Recording, Transmission and Reproduction*, New Grove Dictionary of Music and Musicians (ed. Sadie, S.), vol. XVII, Macmillan – Grove's Dictionaries of Music – Peninsula Publishers, London - New York - Hong Kong, 1985[6], pp. 567-590].

To meet the requirements of high-fidelity audio recording, recording devices need to have the technical ability to record a fairly wide frequency and dynamic range and to faithfully transmit the audio signal onto the storage medium. In analogue technology, the characteristics of audio recording devices and audio storage media are determined by standards: for frequency range, between 20 Hz and 20 kHz (that is, the limit of audibility of the human ear) and for dynamic range, between 104 dB. In digital audio recording technology the electroacoustic converter has to meet all the afore-mentioned requirements. There are two specific components of analogue signals: a) frequency signals – time component, and b) amplitude of the signal - a component of signals level. In converting the analogue signal into its digital counterpart, however, key factors to be considered are the analogue signal sampling frequency (which has to be four or even ten times higher than the highest signal frequency) and the number of signal amplitude degree (which is used to directly determine the number of digits in a recording, that is, the word length used in recording the signal). [Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, pp 216-299].

Contemporary audio media, such as the compact disc, use double of the rate of the highest frequency in a signal (44.1 kHz) and 16 bit word length in converting the analogue signal into its digital counterpart [Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, pp 216-299]. Hereby, high fidelity requirements are not satisfied with the results, because a sampling frequency twice the highest frequency signal, can not convey all the odd and even harmonics and transients, who make up one whole tone. Converted signal is not in the time phase related to the original signal (Figure 5, 6 and 7). Signal, whose frequency can not be sampled because of too small sampling frequency, should be "replaced" by already taken signal sample of analogue signal (Figure 8 and 9).

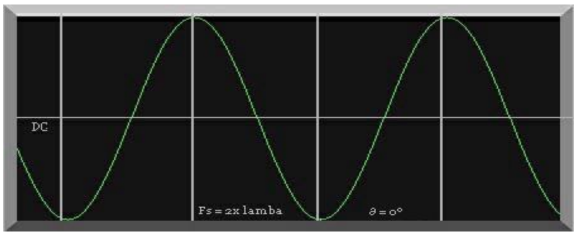


Figure 5: Analogue signal (Source: http://www.serifsound.com, Accesed 12th July 2009

Word length of 16-bit recording directly limits the level of the signal, the amplitude of the signal (Figure 10). This record is a record with error; therefore, there is no quality that matches the quality of high fidelity record.

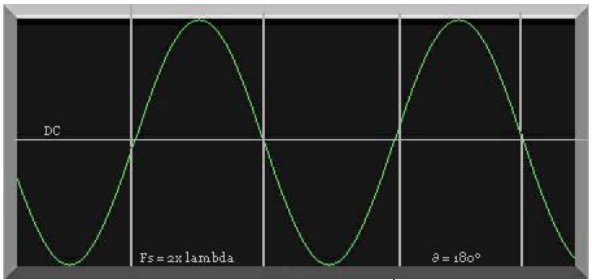


Figure 6: The shift in phase for 180^0 compared to the original signal F_s=2xF_{max}, (Source: http://www.serifsound.com, Accesed 12th July 2009

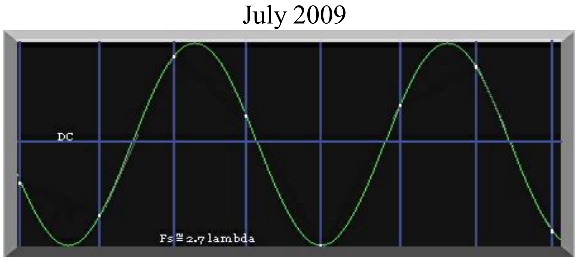


Figure 7: Increasing the sampling frequency, decreases in the phase shift between the original and the sampeld signal, Fs≈2,7xFmax, (Source: http://www.serifsound.com, Accesed 12th July 2009

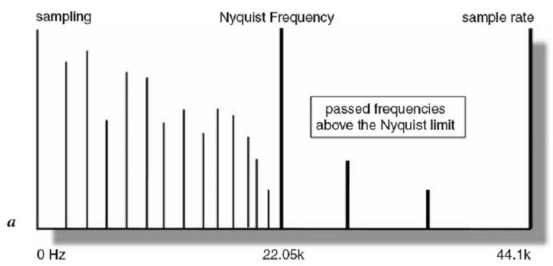


Figure 8: Frequency recognized by sampling (Source: Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, str. 222)

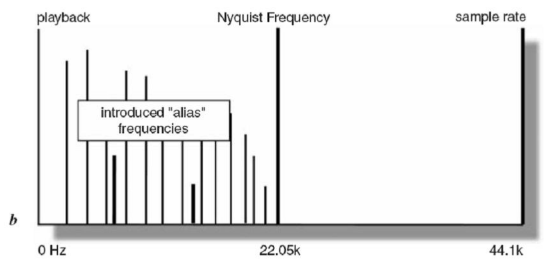


Figure 9: Frequencies replaced by sampling (Source: Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, str. 222)

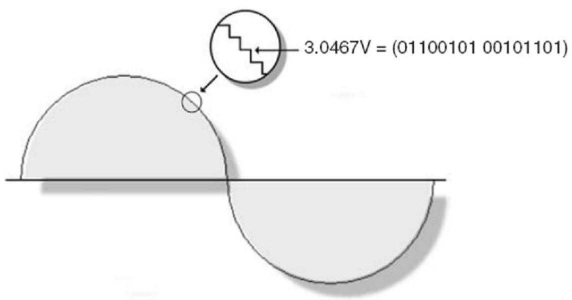


Figure 10: Discrete voltage level amplitude of analogue signal
(Source: Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, str. 223)

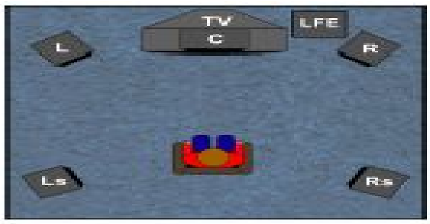
The amplitude of the analogue signal during sampling is converted to a series of discrete voltage levels which are then converted to a digital equivalent for the appropriate length.

- 8-bit word = (nnnnnnnn) = 256 steps,
- 16-bit word = (nnnnnnnn nnnnnnnnn) = 65,536 steps,
- 20-bit word = (nnnnnnnn nnnnnnnn nnnn) = 1,048,576 steps,
- 24-bit word = (nnnnnnnnn nnnnnnnn nnnnnnnn) = 16,777,216 steps,
- 32-bit word = (nnnnnnnn nnnnnnnn nnnnnnnn nnnnnnnn) = 4,294,967,296 steps,

where n = binary 0 or 1.

A high-fidelity audio recording is defined by the frequency range between 20 Hz and 20 kHz ±3 dB and the dynamic range of up to 104 dB. In a digital recording, by increasing the word length, due to finer signal voltage differences, a more faithful rendering of the original sound is obtained as well as larger dynamic[1] [Huber.D. and Runstein.R. Modern Recording Techniques, 7th Edition, 2009, pp 216-299]. Data on measuring the quality of audio storage on various media primarily refer to signal / noise values, dynamic, frequency range, sampling frequency and word length. The literature dealing with the comparative relations between the faithfulness of recoding in a particular format and the number of samples used in sound reproduction is scarce and can only be obtained from the producer. Information on this topic is not easily available, and there are no comparative analyses[2].

DVD devices and media are primarily intended for recording films, that is, for recording video but, owing to their capacity, they are also convenient for high-fidelity audio recording. The main issue in using them for audio recording, however, is a unique audio recording and reproduction standard. DVD recorders and players do not support all formats within the DVD family, only the media belonging to certain producers, whereas in case of other media recording cannot be performed. If a common standard for DVD discs was introduced, primarily that for video and two-channel audio recording, DVD discs would be the ideal medium for high-fidelity audio recording due to their high storage capacity and easy handling and storage. Recording / reproduction devices support DVD-5, DVD-9, DVD-R and DVD-RAM media, whereas other media from the DVD family are supported by only a limited number of devices.



Key: TV – television receiver, L- front left speaker, R – front right speaker , C – central speaker, LFE – Low Frequencies Effect speaker , Ls – rear left speaker and Rs – rear right speaker
Figure11.: Home cinema system in a showroom (Source: Sharpless,G, DVD-Audio for High Quality Music, p. 14.)

Sampling frequency, quantization and small compression ratio are key conditions for a quality audio recording, and all of them are closely related to

[1]Theoretical relation between word length and dynamic: 8-bit word– 49.8 dB, 16-bit word – 97.8 dB, 20-bit word – 121.8 dB, 24-bit word – 145.8 dB and 32-bit word – 193.8 dB).

[2] Eindhoven Blue Book, Philips, 1998., Tokyo. Green Book, Sony and Philips, 1986., Paris. Orange Book, Sony and Philips, 1990., Amstredam. Red Book, Sony and Philips, 1980., Geneva. Standard ECMA-267, EMA General Assembly, December 1999, Amsterdam. Yellow Book, Sony and Philips, 1983, Osaka. White Book, JVC, Matsushita, Philips and Sony, 1994.

the digital data size. It is by means of DVD discs that the home cinema system, in other words, the Surround Sound System, was introduced on a wider scale. Such systems can also be used for DVD audio, whereas the television receiver or the monitor are used for video reproduction.

Table 1: Relation between sampling frequency and playing time for two-channel stereo recording on DVD-5 and DVD-9 discs.

BROJ KANALA	FREKVENCIJA UZORKOVANJA I DULJINA RIJEČI	VRIJEME REPRODUKCIJE ZA DVD-5 (4,7GB)	VRIJEME REPRODUKCIJE ZA DVD-9 (8,45GB)
2	192 kHz, 24 bita	120min	215 min
6	96 kHz, 24 bita	86 min	156 min
2	44.1 kHz, 16 bita	780 min	1416 min

(Source: Sharpless, G, DVD-Audio for High Quality Music, p. 9)

Nowadays a wide array of small, cheap and low-quality home cinema systems is produced. The system consists of 'satellites' (small front and rear speakers), the central speaker, and the low frequencies reproduction speaker, or the subwoofer. The satellite speakers reproduce audio recordings in the range starting from 150 Hz, whereas the subwoofer reproduces frequencies in the range between 25 and 150 Hz. Figure 11 shows a possible speaker placement in a surround stereo system with five satellite speakers and one subwoofer. Although such solutions are convenient for watching DVD films, as they imitate the cinema theatre, they do not meet the high fidelity standards of DVD audio. Conventional two-channel sound systems are the basis for faithful reproduction of sound recorded onto DVD audio discs by meeting the highest recording criteria.

At the highest sampling frequency of 192 kHz and a 24-bit word length, only a two-channel audio recording can be obtained (Table 1). Audio DVD players mainly support DVD-5, DVD-9, DVD-R and DVD-RAM formats with 4.7 GB to 8.54 GB capacity. In DVD discs, playing time depends on the sampling frequency and word length and ranges from 120 minutes to 13 hours for the DVD-5 format, and from 215 minutes to approximately 23 hours for the DVD-9 format.

In this paper, research into the high and inferior audio recording quality was made by hard recording at varying sampling frequencies and word lengths. The obtained results were statistically processed with a view to obtaining optimal parameters and establishing standards. In the following sections the experiment is described.

2 Methodology

To establish the relation between sampling frequency, signal dynamic and the size of the recorded file, various experiments were conducted in which the following devices and music sources were used:

- gramophone – TECHNICS SL-DV;
- gramophone needle – TECHNICS 270 C;
- mixer – MC CRYPT – SM 25 MK II;
- M Appeal sound card and Waveterminal 192M breakout box;
- sampling frequencies used: 11, 16, 22, 32, 44.1, 48, 64, 88.2, 96 and 192 kHz;
- word lengths used: 16, 20, 24 and 32 bits;
- ten (10) audio samples from POLYDOR gramophone records.

Experiment description: Owing to their features, the M Appeal sound card and Waveterminal 192M breakout box are devices enabling hard recording at DVD audio quality. According to manufacturer specifications, M Appeal and Waveterminal devices allow for audio recording at a dynamic of up to 100 dB (provided that the sampling frequency of 96 kHz and 24-bit word length are used in recording) and that of up to 104 dB (provided that the sampling frequency of 192 kHz and 24-bit word length are used in recording). In addition, these devices support the sampling frequency ranges of 11, 16, 22, 24, 32, 44.1, 48, 64, 88.2, 96 and 192 kHz. Apart from the described devices, the Adobe Audition software was used in the experiment. This tool was developed by the following group of authors: Mat Chavez, Ron Day, Shawn Deyell, Paul Ellis, Steve Fazio, Peter Green, David Johantson, Bryse Joansson, Janson Levine, Todd Orler, Chris Robinson, John Russ, Hart Shafer, Nariman Sodeifi and Shenzhin Zhang.

Figure 12.: Waveterminal 192M breakout box and M Appeal sound card (Source: www.proaudio_1892.com/html)

The Adobe Audition software supports the afore-mentioned devices and also allows for the sampling frequencies (11, 16, 22, 24, 32, 44.1, 48, 64, 88.2, 96 and 192 kHz) to be modified during audio recording. In addition, the word length can be changed, to include 16, 20, 24 and 32 bits. In the experiment ten 175 mm 45-rpm POLYDOR gramophone records (or 'singles') were used. This choice of analogue audio media is accounted for by the higher quality of analogue signal recording. A 60-second two-channel audio sample was taken from each medium. The same audio sample was recorded at various sampling frequencies and word lengths.

For each recorded audio the sample dynamic, frequency range and file size were measured. In total, 400 samples were obtained, which were subsequently measured[3]. By comparing the size of audio recording samples obtained in the experiment, comparative tables were created showing the relation between the sampling frequency, word length and mean values of audio recording dynamic, as well as the relation between the sampling frequency, word length and size of the files obtained in the experiment.

3 Research results

Table 2: Relation between sampling frequency, word length and dynamic of audio recording

SAMPLIN G FREQUE NCY	MEAN VALUES OF AUDIO RECORDING DYNAMIC (L+R) IN Db FOR VARIOUS WORD LENGTHS				FREQUENCY RANGE IN Hz		DIFFE RENCE S BETWE EN NEIGH BOURI NG SAMPL ING FREQU ENCIE
	16 BITS	20 BITS	24 BITS	32 BITS			
11 kHz	- 76.013 939671	- 76.013 939671	- 51.416 160738	- 51.416 160738	10.7 66	550 1.73 3	
16 kHz	- 60.939 004471	- 60.696 59283	- 60.696 59283	- 60.916 31213	15.6 25	798 4.37 5	5 kHz
22 kHz	- 51.336 37086	- 51.336 37086	- 51.336 37086	- 51.336 37086	21.5 33	110 03.4 66	16 kHz
32 kHz	- 66.579 61853	- 66.673 29849	- 66.673 31242	- 85.186 36921	31.2 5	159 68.7 5	10 kHz
44.1 kHz	- 55.938 50481	- 55.884 43586	- 55.884 43586	- 55.884 43586	43.0 66	220 06.9 33	12.1 kHz
48 kHz	- 61.738 03703	- 61.738 03703	- 61.738 03703	- 61.738 03703	46.8 75	239 53.1 25	3.9 kHz
64 kHz	- 96.658 97049	- 97.346 02009	- 97.366 75997	- 97.195 61493	62.5	319 37.5	16 kHz
88.2 kHz	- 94.081 98255	- 93.903 94214	- 95.756 03588	- 95.756 03582	86.1 32	440 13.8 67	24.2 kHz
96 kHz	- 63.009 28222	- 63.009 28222	- 88.372 84628	- 88.483 46344	93.7 5	479 06.2 5	7.8 kHz
192 kHz	- 96.137 84124	- 62.993 55953	- 97.947 04073	- 97.947 10386	187. 5	958 12.5	96 kHz

[3] ((10 (ten) sampling frequency x 4 (four) word lengths = 40 (forty) samples. 40 (forty) samples x 10 (ten) audio media = 400 (four hundred) samples.))

Table 2 shows the relation between the sampling frequency, word length and mean values of the audio recording dynamic of the left and right channel. By increasing the sampling frequency, the frequency range of the measured signal is increased from 10 Hz to 96 kHz, while the mean value of the dynamic of the left and right channel of the audio recording ranges between 50 and 98 dB. At the sampling frequency of 44.1 kHz and 16-bit word length (CD quality) the mean value of the dynamic is 56 dB, with the frequency range between 10 Hz and 22 kHz. At considerably higher sampling frequencies (96 kHz and 192 kHz), an increase in the mean value of the dynamic and frequency range is evident.

The right-hand column in Table 2 shows differences between neighbouring sampling frequencies. At a sampling frequency increased by 4.63, that is, 8.7 times the highest frequency in the signal being sampled (20 kHz, according to the Nyquist theorem (**$f_s > 2 \cdot f_{max}$**)), that is, at sampling frequencies of 96 kHz and 192 kHz, a wider frequency range and larger dynamic of an audio recording are obtained. At the highest sampling frequency (192 kHz), the frequency range is between 10 Hz and 96 kHz**.**

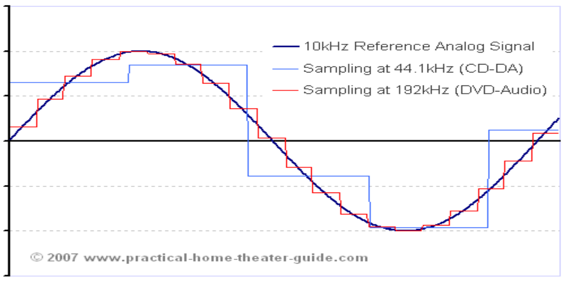


Figure 13: Signal frequency 10 Hz, sampled with a frequency Fs = 44.1kHz, and frequency Fs = 192kHz, (Source: http://www.practical-home-theater-guide.com/DVD-audio.html, Accesed 12th July 2009.)

These results are further supported by frequency analysis for particular characteristic groups (various frequencies combined with various word lengths) by means of the Adobe Audition software. Each instance of the frequency analysis of the sample contains 1024 pieces of data, that is, 512 measurements for each audio channel[4] Figures 14 to 16 show examples of the frequency analysis of the audio signal at the sampling frequencies of 11 kHz, 44.1 kHz, 96 kHz and 192 kHz and 32-bit word length:

- sampling of the signal at the frequency of 11 kHz enables a frequency range of up to 5 kHz

[4]Frequency analysis of an audio sample by means of the Adobe Audition software contains 1024 pieces of data, that is, 512 frequency measurements for each audio channel. Initial frequencies of the observed audio samples shown in in Table 3 are therefore differentiated in the range between 5 kHz and 96 kHz.

and a dynamic of 22 dB (-38 dB to -60 dB, Figure 14),

- sampling of the signal at the frequency of 44.1 kHz enables a frequency range of 22 kHz and a dynamic of 52 dB (-26 dB to -78 dB, Figure 15),
- sampling of the signal at a frequency of 192 kHz enables a frequency range of up to 96 kHz and a dynamic of 76 dB (-24 dB to -100 dB, Figure 16), with the highest useful signal frequency being that of 40 kHz.

Table 3: Relation between sampling frequency, word length and file size obtained.

SAMPLING FREQUENCY	RECORDING TIME	NUMBER OF CHANNELS	WORD LENGTH	FILE SIZE
11 kHz	60 s	2	16 bita	2,65 MB
			20 bita	3,85 MB
			24 bita	3,85 MB
			32 bita	5,12 MB
16 kHz	60 s	2	16 bita	3,81 MB
			20 bita	5,73 MB
			24 bita	5,73 MB
			32 bita	7,62 MB
22 kHz	60 s	2	16 bita	5,21 MB
			20 bita	7,83 MB
			24 bita	7,83 MB
			32 bita	10,4 MB
32 kHz	60 s	2	16 bita	7,62 MB
			20 bita	11,4 MB
			24 bita	11,4 MB
			32 bita	15,2 MB
44.1 kHz	60 s	2	16 bita	10,5 MB
			20 bita	15,7 MB
			24 bita	15,7 MB
			32 bita	21,0 MB
48 kHz	60 s	2	16 bita	11,4 MB
			20 bita	17,1 MB
			24 bita	17,1 MB
			32 bita	22,8 MB
64 kHz	*60 s*	2	16 bita	15,2 MB
			20 bita	22,8 MB
			24 bita	22,8 MB
			32 bita	30,5 MB
88,2 kHz	*60 s*	2	16 bita	20,1 MB
			20 bita	31,5 MB
			24 bita	31,5 MB
			32 bita	42,0 MB
96 kHz	*60 s*	2	16 bita	22,8 MB
			20 bita	34,3 MB
			24 bita	34,3 MB
			32 bita	45,7 MB
192 kHz	*60 s*	2	16 bita	45,7 MB
			20 bita	68,6 MB
			24 bita	68,6 MB
			32 bita	91,5 MB

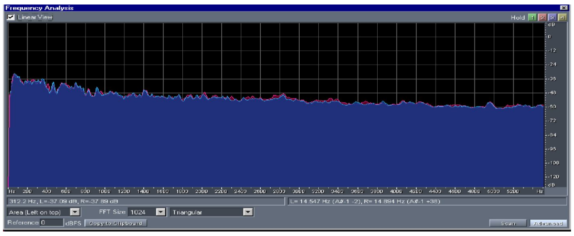


Figure 14: Frequency analysis of a 32-bit audio signal at the sampling frequency of 11 kHz obtained by Adobe Audition software.

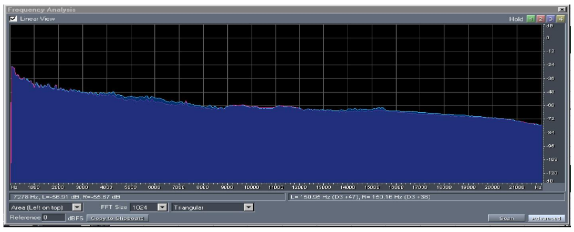


Figure 15: Frequency analysis of a 32-bit audio signal at the sampling frequency of 44.1 kHz obtained by Adobe Audition software.

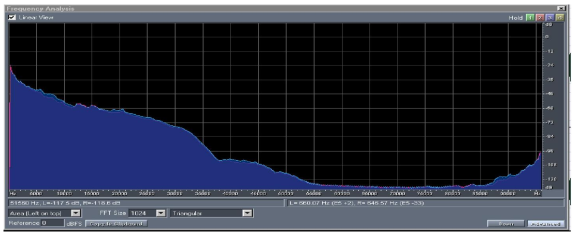


Figure 16: Frequency analysis of a 32-bit audio signal at the sampling frequency of 192 kHz obtained by Adobe Audition software.

4 Conclusion

Parameters which determine the quality of an audio recording depend on the audio storage and reproduction technology. In analogue reproduction and recording technology these parameters are the dynamic, tone pitch, tone colour and transients, whereas in digital technology they are the sampling frequency and the number of digits.

By analyzing the obtained results it can be concluded that, both in the analogue and the digital audio recording technology, for a higher audio recording quality more space on a storage medium is needed [Jarmić T. "Aspekti zvuka u odnosu na medije i multimedijske sadržaje na digitalnom mnogo-strukom disku (DVD)", Sveučilište u Zagrebu, Fakultet organizacije i informatike, Master's thesis, Varaždin 2003.], which is expressed by various characteristics depending on the technology applied. In case of the analogue technology, this is achieved through record groove width or magnetic tape length, whereas in the digital technology it is expressed by file size. Although different in nature, audio recording techniques have certain features in common, including the following:

- sampling of the signal at the frequency of 11 kHz enables a frequency range of up to 5 kHz and a dynamic of 22 dB (-38 dB to -60 dB, Figure 14),
- sampling of the signal at the frequency of 44.1 kHz enables a frequency range of 22 kHz and a dynamic of 52 dB (-26 dB to -78 dB, Figure 15),
- sampling of the signal at a frequency of 192 kHz enables a frequency range of up to 96 kHz and a dynamic of 76 dB (-24 dB to -100 dB, Figure 16), with the highest useful signal frequency being that of 40 kHz.

In the development of CD and DVD major companies set out to improve the quality of audio recording in a number of ways. As a result, HDCD (or high definition compatible digital) was created for CDs, in which the sampling frequency of 44.1 kHz and 20-bit word length are used due to a higher dynamic. Later, SACD (or super audio CD) was developed, which can be reproduced on CD and DVD players at the quality comparable to HDCD.

As a disc format from the DVD family, DVD audio is significant as a medium for high-fidelity audio recording and storage primarily owing to its large capacity, easy handling and storage. The capacity of a DVD is an important issue since on different disc formats (DVD-5 to DVD-9) 120 to 215 minutes of high-fidelity audio recording, and approximately 82 to 146 hours of audio recording in the WMA and the MP3 format, at the transmission rate of 128 kb/s, can be stored.

Different producers will have different points of view regarding audio formats and methods of audio recording and reproduction, which results in a number of different standards and methods for audio encoding and reproduction. For high-fidelity audio recording on DVD discs, a unique standard needs to be introduced, specifying the upper border of the sampling frequency, word length and compression method. Such a standard would enable all the discs from the DVD family to be used for audio recording and reproduction in new generation DVD devices.

The analysis of the data obtained in experiments described in Section 2 showed that by increasing the sampling frequency, the frequency range of the measured signal from 10 Hz to 96 kHz is also increased, while the mean value of the dynamic of the right and left channel of the audio recording is between 50 and 98 dB. At the sampling frequency of 44.1 kHz and 16-bit word length (CD quality) the mean value of dynamic is 56 dB, with the frequency range between 10 Hz and 22 kHz. At considerably higher sampling frequencies (96 kHz and 192 kHz), an increase in the mean value of the dynamic and frequency range is evident. In addition, the audio file size depends on the quality of the recording and ranges between 2.66 MB and 91.5 MB. The analysis showed that the file size for 20- and 24-bit word length is identical, with the larger dynamic of the audio recording in case of the 24-bit word length, which is the reason why producers use the 24-bit word length at the sampling frequency of 96 and 192 kHz.

Table 4: Indicators of the distribution of sampling frequency, word length and the resulting file size in WAV format

Varijable	Opisna statistika Broj pokusa	Sredina	Minimum	Maksimum	Std. devijacija
Frekvencija uzorkovanja	40	61,33000	11,00000	192,0000	52,10971
Duljina riječi	40	23,00000	16,00000	32,0000	5,99145
Veličina datoteke	40	21,86125	2,65000	91,5000	19,84414

(Source: STATISTICA 6 software package, Advanced linear / Non-linear regression models module)

Analysis of the sound depending on the size of the file records of sampling frequency and length of words used, showed a high correlation as evidenced by the following table.

Table 5: The dependence of the size of audio files records of sampling frequency and length of words in the WAV format

N=40	Vrijednosti regresijske analize R= ,97171956 R2= ,94423890 Izglađeni R2= ,94122479 F(2,37)=313,27 p<0,0000 Std.pogreška procjene: 4,8109 Beta	Std.pogreška. of Beta	B	Std. pogreška of B	t(37)	p-razina
Ishodišna vrijednost			-19,3370	3,185313	-6,07068	0,000001
Frekvencija uzorkovanja	0,938155	0,038821	0,3573	0,014784	24,16628	0,000000
Duljina riječi	0,253188	0,038821	0,8386	0,128578	6,52196	0,000000

(Source: STATISTICA 6 software package, Advanced linear / Non-linear regression models module)

The dependence of the audio file size upon the sampling frequency and word length was confirmed by a regression analysis of the data obtained in experiments. Consequently, the following multiple correlation model was established:

$$\text{audio file size } y = -19{,}337 + 0{,}938x_1 + 0{,}253x_2$$

where y is the audio file size in MB, x_1 the sampling frequency in Hz, and x_2 word length in bits.

On the basis of the derived multiple correlation model confirmed by means of variance analysis, chi-square test and test of convergence between the values obtained by measurement and those derived by the model, the file size values were obtained for the pre-set sampling frequency value of 288 kHz and word lengths of 16, 20, 24 and 32 bits (Table 6). The 288 kHz sampling frequency increases the frequency range of an audio recording to 144 kHz and encompasses the sixth harmonic of the upper border frequency $\mathbf{f_g}$ ($\mathbf{f_g}$ = 20 kHz). At this sampling frequency and word lengths of 16, 20, 24 and 32 bits, sizes of audio files vary insignificantly (between 96.97 MB and 110.39 MB for a minute of recording), whereas the dynamic is largest at the 32-bit word length.

Table 6: Values of audio file sizes at a pre-set sampling frequency of 288 kHz.

FREKVENCIJA UZORKOVANJA	VRIJEME SNIMANJA	BROJ KANALA	DULJINA RIJEČI	VELIČINA DATOTEKE
288 kHz	60 s	2	16 bita	96,97 MB
			20 bita	100,33 MB
			24 bita	103,68 MB
			32 bita	110,39 MB

(Source: STATISTICA 6 software package, Advanced linear / Non-linear regression models module)

In this way the standard for high-quality digital audio recording was defined – it has to include the sampling frequency of 288 kHz and the minimum 32-bit word length. These values would be sufficient to meet the basic requirement of the high-fidelity analogue audio recording – frequency range between 20 Hz and 20 kHz, encompassing the sixth harmonic of the upper border frequency.

To ensure the lossless and faithful signal transmission through a digital channel or a system for high-fidelity recording and reproduction, the frequency of signal sampling fs needs to be at least twice as high as the multiple of the upper border frequency of the signal fg:

$$f_s \geq 2 \cdot \lambda \cdot f_g,$$

where λ of the multiple fg is such that λ·fg encompasses the sixth harmonic of the border frequency, that is:

$$f_s \geq 2 \cdot 6 \cdot f_g.$$

In line with the afore-mentioned statement, the following standard for minimum requirements in storage and reproduction of high-fidelity audio recording, obtained by digital technology, is established:

Table 7: Minimum requirements for high-fidelity digital audio recording on audio DVDs.

FREKVENCIJA UZORKOVANJA	DULJINA RIJEČI	VELIČINA DATOTEKE	KANAL1	KANAL2
288 kHz	32 bita	110,4 MB	MLP	

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