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Digital Transformation of Terrestrial Radio: An Analysis of Simulcasted Broadcasts in FM and DAB+ for a Smart and Successful Switchover

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Featured Application: An analysis of terrestrial broadcasts involve simulcasted audio signals in both analog FM (Frequency Modulation) and digital DAB+ (Digital Audio Broadcasting plus) techniques, including different profiles of radio programs as well as type of transmitted content. The results of the carried-out experiments may be a valuable source of information for both private and public broadcasters around the world and not to mention various third parties interested in the digitization process, including content, service and network providers, and of course policy makers and professionals involved in the electronic media market.

Abstract: The process of digitizing radio is far from over. It is an important interdisciplinary aspect, involving Big Data and AI (Artificial Intelligence) when it comes to classifying and handling content, and an organizational challenge in the Industry 4.0 concept. There exist several methods for delivering audio signals, including terrestrial broadcasting and internet streaming. Among them, the DAB+ (Digital Audio Broadcasting plus) system is one of the leading standards of terrestrial digital radio transmission. Compared with analog FM (frequency modulation) radio, it is more bandwidth efficient and offers greater possibilities when it comes to delivering content and forming an ensemble and multiplex. Currently, many countries worldwide, particularly European States, are still making adjustments in order to perform an efficient switchover from analog FM to digital DAB+ radio. This paper presents the current situation of the digital radio market as well as the results of a subjective quality evaluation study and questionnaire concerning broadcasting in both digital and analog techniques. It involves radio programs, transmitting both speech and music signals, simulcasted in DAB+ and FM standards. It also presents the development of the national multiplex. The results of this study may help both researchers and scientists as well as policy makers and professionals active in the field of broadcasting and electronic media and not to mention the consumption of multimedia content.

Keywords: audio; broadcasting; coding; compression; DAB+ (Digital Audio Broadcasting plus); digital transformation; signal processing; switchover; radio transmission

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1. Introduction

Radio is one of the most user friendly and privacy-respecting electronic media. Terrestrially broadcasted content is consumed by people around the world. It provides information in the form of audio signals. With the spoken word, we can exchange ideas and share knowledge among individuals with different backgrounds. With music, we can express ourselves as well as inspire and shape the taste of others. As we know, a single receiver gathers more than only one individual. Radio is consumed at home, at work, and on the move. It has been a valuable part of our lives for more than a century.

The exponential growth of computing power, including both desktop as well as mobile devices, along with more affordable storage media brings new possibilities for content processing. Big Data, cloud-based services, crowdsourcing, etc., all affect the

broadcasting industry. Whether we are talking about terrestrial or online radio transmission, they all require efficient and reliable technologies. The most up-to-date technologies include interdisciplinary fields such as deep learning, machine learning, and AI (artificial intelligence) [1–5]. Nowadays, digitization becomes very important, and with the advent of the Industry 4.0 concept, even terrestrial radio transmission will have to face a digital transformation. In this case, we refer to it as a switchover that is most often related with the migration from analog FM (frequency modulation) to digital DAB+ (Digital Audio Broadcasting plus) radio.

This challenge brings together computer scientists, electrical engineers, sound engineers, and specialists from the field of medical healthcare, psychology, and various arts. Since simulcasting involves a simultaneous transmission of the same audio content, it automatically causes excessive consumption or even a waste of resources being either hardware, energy, or human resources. That is why it is important to study how the quality of radio programs is perceived by end users and whether the time has come for an efficient migration to digital technology.

The paper is organized as follows: Section 2 presents the current situation of the digital radio market, including the availability as well as penetration of the DAB+ standard. Section 3 describes the state of the art and advancements in both subjective and objective studies of digital and analog broadcasting carried out by scientists from all around the world. Section 4 shows the multiplex configuration of the analyzed DAB+ ensemble, including adjustments in number of available services, their profile, type of transmitted audio content, and assigned resources, namely bitrate. Section 5 is focused on the results of a subjective quality evaluation of simulcasted analog FM and digital DAB+ broadcasts compared to an earlier study of the same ensemble including its previous configuration. Section 6 deliberates on the results of a questionnaire and is focused on parameters and factors necessary for a successful switchover. Section 7 discusses results before and after modifying the analyzed multiplex ensemble. Section 8 concludes and summarizes the paper, pointing out possible future studies and directions for further research.

2. Digital Radio Market

The DAB+ system, successor of the Eureka 147 DAB project, is one of the leading broadcasting standards. It provides high-quality digital terrestrial services for both fixed and portable devices, including fast-moving objects, e.g., trains or cars up to 200 km/h. It can operate in either MFN (Multiple Frequency Network) or SFN (Single Frequency Network) mode [6,7]. This standard also enables stable reception conditions in case of highly populated dense urban areas [8,9].

The DAB/DAB+ system can be manufactured and/or utilized by any interested third party. Moreover, as a digital broadcasting system, it is more bandwidth (spectrum) efficient, and offers several advantages over traditional analog systems, e.g., higher sound quality compared to FM radio, of course, at the appropriate bitrate.

This multimedia content distribution standard is highly supported by the WorldDAB forum, which provides various information on its development [10]. Table 1 describes the percentage of population covered by the digital signal in the top five European countries.

Table 1. Network coverage of DAB+ (as a percentage of population).

Country	Percentage (%)
Denmark	99.9
Norway	99.7
Switzerland	99.5
Germany	98
UK	97.3

As shown, the leaders in digitizing radio reached almost full coverage, considering the number of inhabitants in particular countries. One must note, however, that this does not

mean that each and every citizen consumes this digital content. The household penetration of DAB/DAB+ receivers among the top five European markets is described in Table 2.

Table 2. Household penetration of DAB+ receivers.

Country	Percentage (%)
Norway	100
UK	67
Denmark	34
Germany	25
Netherlands	24

It should be mentioned that most devices are hybrid ones enabling the consumption of analog FM and digital DAB/DAB+ radio as well as a number of internet streaming services, not to mention Bluetooth compatibility with wireless devices such as smartphones, tablets, or headphones.

One should take into account that the car industry has a profound impact on the popularity and number of sold consumer devices. On the other hand, many people listen to radio while driving to work or home. Table 3 describes the percentage of new cars sold with integrated DAB/DAB+ radio among the top five European countries.

Table 3. Cars with DAB+ radio compatibility.

Country	Percentage (%)
Norway	100
Switzerland	99
UK	94
Italy	90
Belgium	59

Potentially, each newly bought car most often has DAB/DAB+ compatibilities built in. It only requires a license and/or additional configuration.

A service may be viewed as popular or valuable only if it fulfills the needs and expectations of end users and whether it matches the taste of each target group and/or individual. Table 4 describes the popularity of DAB/DAB+ among the top five European radio markets.

Table 4. Number of national stations in FM and DAB+.

Country	No. of FM Stations	No. of DAB+ Stations
Norway	0	32
Switzerland	54	70
Belgium	29	55
UK	6	50
Italy	21	50

As shown, Norway performed a total switchover from analog to digital radio, whereas other countries are trying to establish balance between FM and DAB/DAB+ radio. It is worth mentioning that Switzerland will not resign from analog broadcasting in order to distribute content to serve the local community in particular cantons.

In case of DAB+, all services are grouped in the so-called ensemble. The number of offered services, including traditional radio programs as well as additional data services, related with allocated resources (bitrate) can be easily arranged. Thanks to this, the ensemble can be flexibly reconfigured in order to test the best settings that will meet user demands. Other countries from outside the European Union are also making investments

in this digital content distribution standard. Table 5 describes the top five emerging DAB/DAB+ markets around the world.

Table 5. Emerging worldwide digital radio markets and their coverage.

Country	Percentage (%)
Azerbaijan	30
Turkey	30
Thailand	14
Algeria	7
Ukraine	7

Nowadays, since numerous broadcasters simulcast the same content in FM and DAB+, transmitting in the analog format, related with objective listener judgments, becomes a reference or starting point for designing digital services. Moreover, digital broadcasting is more resistant to interference [11].

3. Related Work

In a recent paper [12], a group of Italian authors presented a study on the quality of demodulated FM broadcasting. The subjective judgements involved a set of audio signals comprising different types of content and/or genre of music that included classical and modern/pop music as well as the spoken word. The obtained results, in a five-step MOS (Mean Opinion Score) scale, were linked with different SIR (Signal-to-Interference Ratio) and QoS (Quality of Service) characteristics. As pointed out, their findings on technical and subjective FM signal quality issues may be interesting sources of information during the switchover from analog to digital radio.

A similar study concerning the current broadcasting market in the Czech Republic, along with DAB+ network coverage measurements and planning, is available in [13]. The author provides information about the implementation process from testing to regular broadcasting. He discusses different parameters and settings related with frequency allocation and the transmitter itself, as well as results of studies considering the efficiency of different variants of the AAC (Advanced Audio Coding) algorithm. This paper provides valuable data to both national and private broadcasters that would like to participate in the digitalization process.

Another recently published study [14] describes both objective PESQ (Perceptual Evaluation of Speech Quality) and subjective MOS results, including the CCR (Comparison Category Rating) variant, of speech and music recordings transmitted in real-time via DAB+ radio. The authors discuss the process of quality assessments, including the overall audio quality as well as timbre with relation to utilized bitrate ranging from 24 to 128 kbps. The obtained results, involving the regional multiplex in Wroclaw (Southern Poland), are compared with other studies related with the Gdansk (Northern Poland) multiplex. Former studies on DAB+ performed by this group of authors may be found in [15–20].

In 2018, a group of Czech researchers investigated the audio quality of speech and music signals, including mono and stereo, in both DAB and DAB+ using the PEAQ (Perceptual Evaluation of Audio Quality) algorithm [21,22]. In this case, the audio samples were coded in MP2 (bitrates ranging from 56 to 320 kbps), which is utilized in DAB, as well as AAC (bitrates ranging from 24 to 256 kbps), which is utilized in DAB+. Their analysis showed a break point for each codec where objective scores did not increase significantly with increasing bitrate. Furthermore, the minimum required bitrate necessary to fulfill the broadcast quality criterion was used. Additional findings from the Czech Republic including the influence of bitrate on subjective quality perception in the broadcasting chain as well as the matter of coexistence between broadcasting of satellite television and digital radio may be found in [23,24].

A subjective and objective study, concerning the comparison of real-time simulcasted FM and DAB+ radio programs in Poland, along with AAC-processed speech and music

signal samples (bitrates ranging from 64 to 160 kbps, with a step of 32 kbps), is described in [25]. In this work, the authors analyzed whether the quality of DAB+ surpasses the quality of FM radio. The subjective quality assessment was performed using the MOS scale, whereas the objective part was carried out using the ViSQOLAudio (Virtual Speech Quality Objective Listener Audio) metric [26,27]. Both subjective and objective quality metrics provided scores in the five-step variant. As a result, the authors noted a need for higher bitrates in the case of particular audio content, e.g., with a clear stereo separation between the channels. Furthermore, DAB+ proved to be an efficient replacement for traditional FM radio.

Later on in 2017, a study concerning the difference in DAB and DAB+ broadcasting was carried out [28]. What is worth mentioning is that the author utilized his own multiplex that was particularly designed and launched in three different configurations for the purpose of this test. In each of the three described scenarios, the ensemble consisted of both MP2 and AAC-processed signal samples, offering the same content and available to the listener in the form of six radio programs. In this scenario, these were three programs simulcasted in DAB and DAB+, respectively. The utilized signal samples were categorized into three groups, speech and singing, musical instruments, and music genres, and processed in two bitrates, which is 64 and 128 kbps. This study clearly showed the superiority of DAB+, as this standard obtained higher grades when transmitting the same type of content compared to DAB.

A previous study conducted in Sweden, concerning the audio quality of FM and DAB+ terrestrial systems, is described in [29]. This examination consisted of two parts. The first one involved audio content coded and broadcasted at bitrates between 96 and 192 kbps, whereas the second one involved signal samples processed at bitrates from 48 to 192 kbps, with a comparison to FM analog broadcasting. In this case, the quality was evaluated with the 100-step MUSHRA (Multiple Stimuli with Hidden Reference and Anchor) metric. According to this study, DAB+ offered comparable or similar quality relative to FM for bitrates of approximately 192 kbps. In particular cases, this bitrate was ranked even higher compared to analog radio.

In 2015, an international group of authors investigated the impact of different audio codecs utilized in a number of terrestrial broadcasting as well as internet streaming services [30]. The perceived audio quality was investigated for a number of codecs, including: MP2, Opus, MP3, Ogg Vorbis, and AAC. The bitrate ranged from 24 to 320 kbps depending on the particular codec. Studies involved both subjective and objective metrics, including PEAQ and POLQA (Perceptual Objective Listening Quality Assessment) algorithms. The study provides a good introduction to currently utilized commercial services, including the pros and cons of different popular audio codecs.

It is worth mentioning that when it comes to designing and evaluating digital broadcasting systems, the process of frequency allotment, resource allocation, and ensemble configuration is still a widely discussed topic [31,32]. Advances in audio quality assessment are discussed in [33–41]. Until now, only Norway performed the so-called switchover, leaving analog FM radio behind. Currently, this is the only country that went fully digital with DAB+. The results of previous studies concerning subjective and objective tests, including both laboratory and real-time operating conditions along with the evaluation of AAC-processed speech and music samples, provide a good introduction to the state of the art regarding popular codecs and formats.

The main contributions of this paper are as follows:

- It provides an overview of the current situation of the digital radio market.
- It provides a throughout analysis of previously published works on DAB/DAB+ of research groups from all around the world.
- It describes and discusses modifications of a selected DAB+ multiplex ensemble (number of available services, their profile, type of audio content, assigned bitrate, etc.).

- It presents results of a subjective quality evaluation study of broadcasts simulcasted in analog FM and digital DAB+ radio, including a comparison of the same ensemble before and after modifications.
- It shows the results of a questionnaire considering factors that seem most important for a typical user and that are necessary for a successful switchover from the analog to digital domain.

At the end, this paper points out possible future studies and directions for further research that could speed out the entire digitization process.

4. Multiplex Configuration

The investigated DAB+ multiplex in Gdansk, a regional version of the national Polish multiplex, operates on channel 5B (176.64 MHz) and transmission mode I. Each service utilizes EEP 3-A error correction and has a coding efficiency of 1/2. The configuration of the analyzed ensemble is described in Table 6. At that time, the multiplex offered 12 services, among which 10 included audio programs (transmitting speech and/or music signals), whereas two were only data services. Additional information on transmission, frame structure, error correction coding, and related signal measurements in the DAB+ radio system may be found in [42,43].

Table 6. Evaluated DAB+ multiplex ensemble.

No.	Profile	Codec	Bitrate (kbps) Previous	Bitrate (kbps) Current
1	Talk 1	AAC-LC	112	112
2	Arts	AAC-LC	128	128
3	Talk 2	AAC-LC	112	112
4	Pop Music	AAC-LC	112	128
5	Informative EN	AAC-LC	64	64
6	Informative PL	HE-AAC v1	64	64
7	Classical Music	AAC-LC	128	128
8	Children	HE-AAC v1	72	72
9	Regional PL	AAC-LC	104	112
10	Regional EN	HE-AAC v1	-	72
11	Data	-	16	16
12	Journaline	-	16	16

As shown, the bitrate did change when it comes to some programs. In the case of the Pop Music radio channel, the bitrate raised from 112 to 128 kbps. On the other hand, in case of the Regional Polish radio channel, it was also raised, in this case from 104 to 112 kbps. It should be also mentioned that there was an additional program initially broadcasting Electronic (and later on Pop) music with a bitrate of 96 kbps. However, over time between 2018 and 2019, it was shot down.

The profile of each radio program was obtained from the information displayed on the radio receiver. Of course, there exist numerous methods for, e.g., MGR (Music Genera Recognition). Further information on managing and labelling music datasets, audio signal feature extraction and MIR (Music Information Retrieval) is available in [44–46]. On the other hand, additional audio datasets, including speech and music content, along with links to other resources and online repositories may be found in [47–49].

In order to evaluate and determine the quality of each radio program simulcasted in analog FM and digital DAB+ standards a subjective study has been carried out.

5. Quality Evaluation Study

This quality study, considering simulcasted DAB+ and FM radio programs, was performed on a representative group of 45 individuals. It should be mentioned that currently six services are available both in digital and analog terrestrial radio. However,

the reception quality of the Informative PL program, recently introduced to FM radio, was not always stable. That is why it was omitted from the study.

The subjective judgement of five simulcasted radio programs, available at stable reception conditions, was realized according to [50–52]. Is should be clearly stated that the quality assessment was performed in an indoor environment with a high-quality radio receiver and headphones.

First, listeners were asked to rate the overall quality of each real-time DAB+ transmitted radio program over a period of approximately 10–20 s, separated by a 5 s interval, in a five-step MOS ACR (Absolute Category Rating) scale with no reference signal available from one (bad quality) to five (excellent quality). Next, this examination was performed for real-time FM broadcasted programs. Similarly as in case of DAB+, each radio program was presented over a period of approximately 10–20 s, separated by a 5-s interval. As previously, listeners were also asked to provide a score representing the overall quality in a five-step MOS scale, with no reference signal. In both cases, that is, FM and DAB+ signal quality evaluation, participants were not informed about the name nor profile and neither bitrate (in case of DAB+) of the currently assessed broadcast. Radio programs were presented in a randomized manner and labelled as Program 1–5. The results considering the quality of simulcasted DAB+ and FM radio programs are shown in Figure 1.

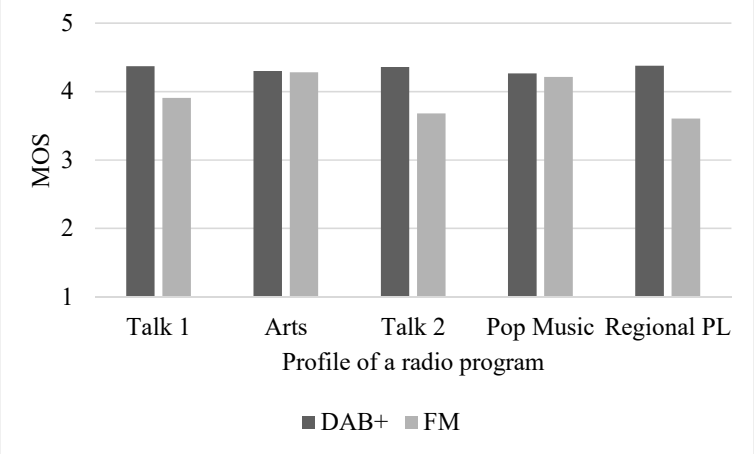

Figure 1. Subjective quality evaluation of simulcasted radio programs.

According to obtained results, all scores favor the digital system. The observed difference ranges from 0.02 (Arts—broadcasted in DAB+ at 128 kbps) and 0.05 (Pop Music—broadcasted in DAB+ at 128 kbps) to 0.77 (Regional PL—broadcasted in DAB+ at 112 kbps). Moreover, a comparison has been performed by considering the results published in 2017 [25], including the same group of radio programs as well as the same number of individuals, namely 45, participating in the listening study. The results are shown in Figure 2.

As shown, the scores are quite similar, with differences ranging from 0.04 (Pop Music—bitrate changed from 112 to 128 kbps) to 0.52 (Talk 2—unchanged bitrate of 112 kbps).

It is worth mentioning that no participants had hearing disorders. Furthermore, in order to acquaint each person with the listening equipment and the purpose of the test, every individual took a training phase before starting the essential study. Of course, no one was informed about the actual bitrate of the currently assessed radio program. In the case of both DAB+ and FM, broadcasts were only labeled as Programs 1 to 5 in a randomized manner.

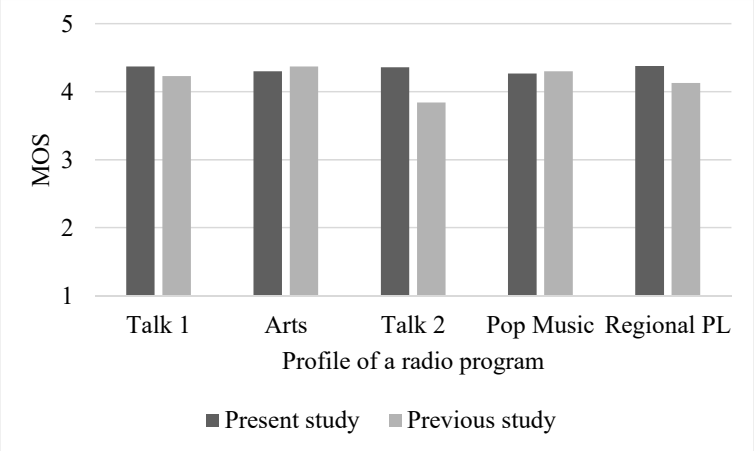

Figure 2. Comparison of subjective quality evaluation.

6. Questionnaire

After the listening study, each person was asked to fill in a questionnaire considering the current quality offered by DAB+ compared to analog FM radio, as well as their expectations and features that could help accomplish a successful switchover.

The first question was related with their overall subjective opinion about the perceived quality of DAB+ compared to FM radio. What is worth mentioning is that each individual (100% of the group) pointed out DAB+ as the superior broadcasting standard. In their opinion, digital broadcasting provided higher quality in some cases for lower and/or higher frequencies. The sound had better timbre and color and was crispier and more precise and free from interference.

Next, each individual was asked to labeled factors necessary for a successful switchover from analog FM to digital DAB+ radio in a five-step scale from 1 (least important) to 5 (most important). The results are shown in Figure 3.

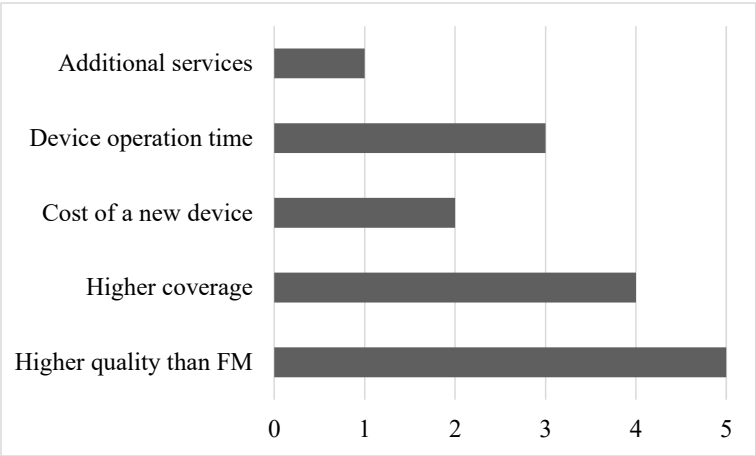

Figure 3. Factors necessary for a successful switchover from analog FM to digital DAB+ radio.

Not surprisingly, higher quality compared to FM radio was ranked as the most essential factor, followed by higher network coverage. Both device operation time and cost of a new device were viewed as less important. Surprisingly, additional services came last. This clearly shows that the biggest differentiator is audio quality itself. These few questions can be valuable guidelines for the upcoming years.

7. Discussion

The presented study describes how the ensemble configurations changed over time according to transmission requirements as well as multiplex forming mechanisms. The evaluated configuration had 12 services, including 10 regular audio broadcasts and 2 additional data services. According to available data, the target configuration should have 12 regular audio services, including 10 national and 2 regional broadcasts.

The obtained subjective results concerning the current multiplex ensemble configuration show that DAB+ proved to be superior relative to simulcasted FM programs, as described in Table 7. As observed, listeners favor the digital standard, mostly for its clarity and resistance to noise and interference. It is worth mentioning that a MOS score of above 4.0 (good to excellent quality) is considered as a requirement necessary to fulfill the so-called broadcast quality criterion.

Table 7. Difference in subjective MOS judgements of simulcasted DAB+ and FM radio programs—evaluated multiplex ensemble configuration.

Profile	DAB+ MOS Score	FM MOS Score	MOS Difference
Talk 1	4.37	3.91	0.46
Arts	4.30	4.28	0.02
Talk 2	4.36	3.68	0.68
Pop Music	4.26	4.21	0.05
Regional PL	4.38	3.61	0.77

In most cases, the differences in subjective judgement, concerning the quality of offered services in the current as well as previous study, were quite similar. A comparison of obtained results, with respect to changes in bitrate, is described in Table 8.

Table 8. Difference in subjective MOS judgements of DAB+ radio programs—previous and investigated multiplex ensemble configuration.

Profile	Bitrate (kbps) Previous Config.	Bitrate (kbps) Investigated Config.	MOS Difference
Talk 1	112	112	0.14
Arts	128	128	−0.07
Talk 2	112	112	0.52
Pop Music	112	128	−0.04
Regional PL	104	112	0.25

The biggest difference, caused by raising the bitrate from 104 to 112 kbps (Regional PL), was equal to 0.25. However, the largest observed difference, in this case not related with bitrate adjustments, was equal to 0.52 (Talk 2). This may be caused by, e.g., different types of transmitted content compared to previous studies or the change in music taste among participating individuals. The major difference, caused by raising the bitrate from 104 to 112 kbps (Regional PL), was equal to 0.25. However, the principal observed difference, in this case not related with bitrate adjustments, was equal to 0.52 (Talk 2). This may be caused by, e.g., different types of transmitted content, compared to previous studies, or the change in music taste among participating individuals.

8. Conclusions

Digital transformation is an important topic for today's researchers. The migration from the analog into the digital domain remains a challenge in a number of fields. Broadcasting, among many, is one of them. Undeniably, the DAB+ system is one of the leading standards of terrestrial digital radio transmission. Compared with analog FM radio, it offers greater possibilities of delivering high-quality content. Its main feature, related with forming the ensemble for a number of predefined audio or data services, enables flexibly

assigning bitrates and easily reconfiguring the multiplex when needed. Nowadays, many broadcasts are simulcasted in DAB+ and FM. This fact implies a direct comparison of the quality offered by both technologies carried out by listeners themselves. Currently, only one country went fully digital and performed a total switchover from analog FM to digital DAB+ radio. Other countries involved in the digitalization process are still making adjustments in order to best meet user demands.

This paper shows the development of the digital radio market, as well as a case study of a selected DAB+ multiplex ensemble, including offered radio programs, their profile, and allocated resources. It presents the results of numerous subjective and objective quality evaluation studies concerning broadcasting in both digital and analog techniques, over the past years. The results of this particular study may help both researchers and scientists, as well as policy makers and professionals from all over the world, that are involved in the digitalization process. It also provides a good background for new parties, particularly those active in the field of broadcasting and electronic media that currently may hesitate about joining the digital radio market.

Future studies may focus on new broadcasters that recently joined the commercial multiplex. It would be interesting to investigate their requirements as content providers when it comes to delivering high-quality services to the end user. Moreover, it would be surely curious to analyze an even broader range of audio signals, including different music genres and not to mention various profiles of the AAC codec itself. A survey, concerning possibilities, limitations and user expectations related with DAB+ that could help understand the radio market may be found in [53]. Further studies and analyses on the digital radio market and user expectations are described in [54,55]. On the other hand, a study focused on current trends in the consumption of multimedia content using online streaming platforms is available in [56].

Moreover, cooperation with other authors, as well as institution, would contribute to the development of guidelines and recommendations that are necessary for accelerating the digitalization process. The switchover itself requires both higher penetration and increase in the popularity of the DAB+ broadcasting standard. Undoubtedly, a broader program offer would accelerate the process. Furthermore, this would be beneficial for listeners and the entire radio market. Inspiration for future studies in computer science and related fields of study may be found in [57].

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Gdansk University of Technology.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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