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Analysis and measurements of the characteristics of fading in the DAB+ single-frequency network

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***Abstract*—In this article the measurement results and their comparison with simulation results will be shown. The obtained measurement results prove for the first time in the technical literature the real occurrence of many selective fading in the DAB + signal band. The high compliance of the measurement results of the fade characteristics with the simulation results, which were also presented in the article, indicates the possibility of predicting the areas and characteristics of fades on the basis of simulation tests. Thus, on their basis, it will be possible to determine the places where this phenomenon occurs and take it into account in the process of planning the SFN network.**

***Keywords*—Single Frequency Network (SFN); Digital Audio Broadcasting (DAB+); fade analysis; fade measurements**

I. Introduction

SINGLE-frequency networks are now widely used to build broadcasting systems ensuring coverage of large areas. This is possible thanks to the properties of the radio interface with Orthogonal Division Frequency Multiplexing (OFDM) used in these networks. The cyclic prefix (CP) used in this interface enables the correct reception of the signals coming to the receiving antenna with a different delay within the prefix length. The different signal delays may be caused by multipath propagation caused by propagation phenomena such as reflections and diffraction, as well as differences in the propagation time of the signal from the transmitters of the single frequency network. The SFN DAB+ network transmitters for which the measurements were carried out emitted a signal on the carrier frequency 216.928 MHz (DAB 11A channel) in the transmission mode I with a prefix of 246 µs. For this size of the prefix the maximum distance between SFN transmitters, due to differences in signal delay, cannot exceed 73.8 km [1]. There are many advantages to using a SFN to serve an area. The basic ones include the relatively lower power required to cover a given area compared to the power required by the MFN and much more efficient frequency management. Additionally, these types of networks provide better and more reliable reception in overlay areas due to the greater resultant power of the received signal and the incoming of these signals from different directions, reducing the shadow phenomenon. In [2] A. Mattson presents and carries out a theoretical analysis of the use of SFN, in particular in digital television. The author presented the equation (1), according to which it is possible to show a relatively lower total power necessary to cover a given area using the SFN, instead of the MFN.

$$PR(N,\alpha) := N^{\frac{\alpha}{2}-1} \tag{1}$$

wherein:

PR - is the ratio of the required MFN power to the required SFN power,

α - propagation loss factor (α = 2 - propagation in free space, α = 4 - propagation over flat perfectly conducting ground).

In the case of propagation in free space (α = 2) there is no gain, regardless of the number of transmitters N. Taking into account the propagation over a perfectly conductive flat earth (α = 4), closer to propagation models in an urban environment, we get in a network consisting of three transmitters (N = 3) PR (3,4) = 3, i.e. three times the power gain. Thus, SFN's are greener and have a much smaller carbon footprint. The use of lower power transmitters also reduces exposure of people within their range to electromagnetic fields. The increase in the coverage area of the SFN in relation to the MFN results from the summation of the power of the signals received from the transmitters of the SFN in the receiver band with a width of 1536 kHz. The phenomenon of increasing the received power in the receiver band, referred to as network gain, was presented in [3,4], while in relation to the DAB+ network in Wroclaw for unified emission parameters of transmitters using a propagation model over perfectly conductive flat ground in [5] and using propagation model ITU-R. P.1546 in [6]. In [5] and [23], the level of the resultant signal was determined by summing the signal strengths of all 1536 sub-channels with a bandwidth of 1 kHz, taking into account the phase shift.

Another advantage of the SFN network is the summation of the signal powers from the SFN transmitters. This effect should be well observed when the signals are transmitted in vertical polarization and the receiving antenna has an omnidirectional radiation pattern. Then the amplitude of the resultant electric field strength E_W acting on the antenna can be determined from the relationship (2):

$$E_W = \left|\sum_i \overline{E_i}\right| = \left|\sum_i E_i \cdot e^{j\phi_i}\right| \tag{2}$$

where: E_i is the amplitude of the electric field strength from the i-th SFN transmitter, and the phase of the field strength vector can be determined from (3):

$$\phi_i = \left(\frac{2\pi}{\lambda}\right) \cdot d_i \tag{3}$$

where λ is the wavelength and d_i is the distance from the i-th SFN transmitter. It should be expected that the phenomenon of

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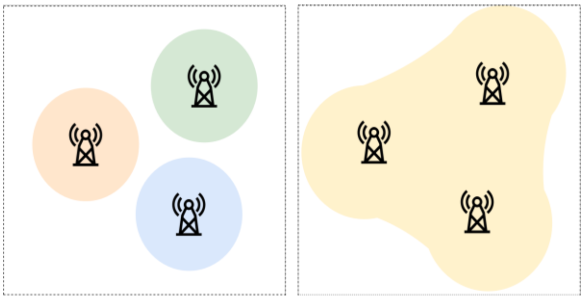
increase of the received signal level will be clearly visible in places where the field strength levels from individual SFN transmitters will be equal or not significantly different. A detailed analysis of this phenomenon is presented in [6]. In this case, the author defines the SFN gain in the form (4):

$$SFN_{Gain}=E_{SFN}-E_{MFN} \quad (4)$$

where E_{SFN} is the resultant field strength derived from the network of SFN transmitters, which can be expressed with the relationship (2), while E_{MFN} is the field strength derived from the dominant MFN network transmitter (5):

$$E_{MFN} = \max\{E_1, E_2 \dots E_N\} = \max_i\{E_i\} \quad (5)$$

Symbolically, the effect of increasing coverage is shown in Fig. 1.



a) b)

Fig. 1. Coverage obtained in the multi-frequency network (a) and in the single-frequency network (b) [7]

II. WHY DAB+ ANALYSIS AND MEASUREMENTS

The quality of signal reception in DAB+ radio is very good, which is confirmed by numerous research results [7,8,9]. DAB+ coverage areas are also very large in Australia and Europe and are constantly increasing [10]. In Poland, in 2019, signal coverage reached 56% of the country's territory. However, the further development of DAB+ digital radio is limited by the relatively high implementation costs that only nationwide broadcasters can afford. For local broadcasters, the cost of installing the system is a financial barrier. For this reason, in the years 2015 - 2017, a project called "Single Frequency Network Using the DAB+ Broadcasting Platform for the Needs of Local Broadcasters in Poland" was carried out - in short LokalDAB financed by The National Centre for Research and Development [11]. The main goal of the program was to build a SFN using low-cost solutions in the field of antenna construction, broadcasting systems, network synchronization and management, and using universal programmable devices and open source software. The SFN consisting of three transmitters was built by a consortium consisting of the Wroclaw University of Science and Technology (WUST), the National Institute of Telecommunications (NIT) and Polish Radio Wroclaw (PRW). In order to reduce costs, the broadcasting installations were placed at the consortium's premises. In February 2020, 11 programs on various topics were broadcasted in the LokalDab multiplex [12]. The LokalDAB network is an excellent research object related to the propagation and phenomena accompanying the reception of signals from several transmitters in a large city environment. Theoretical analyzes of the phenomenon of summation of power and fade in this network with the use of the propagation model over a perfectly conductive flat earth are the subject of several publications [13, 14, 15, 16]. The same heights of the transmitting antennas and their omnidirectional radiation pattern were assumed. The maximum values of fading that may occur on the channel's central frequency on routes running at several distances from transmitters, including those running through the city center, have been determined. This article presents new, original simulation and measurement results for the fading characteristics, taking into account the measured electric field strengths in previously selected places. In addition to the results of simulation, the results of fade characteristic measurements in real conditions are presented, as well as a comparative analysis. Such studies have not been published in technical literature so far.

The phenomenon of selective fading may be partially reduced in a large city environment due to rapidly changing propagation conditions, multipath propagation and transmitter synchronization requirements [17]. Those requirements are sufficient with regard to frequency synchronization. However, precise phase synchronization of the signals is not required, which is one of the key parameters in the case of fades. For this reason, the study of the characteristics of fades resulting from the operation of SFN networks in an urban environment should be investigated in places where their occurrence can be expected to the greatest extent. The analyzes carried out in [14] show that such places occur where the levels of the received signals are similar. The number of fades in the received resultant signal depends on the difference in the length of the signal propagation paths from the transmitters. A detailed description of the methodology for determining the locations of potentially large fades, taking into account the actual transmission parameters of transmitters, such as: power, antenna gain, radiation pattern and the ITU-R P.1546 propagation model is presented in [18].

The following chapters will present:

- the method of determining the fade characteristics based on the measurements of the electric field strength in the DAB + band from interfering transmitters,
- the parameters of the studied SFN network as well as the places of potentially significant fades,
- the measurement methodology and the measuring equipment,
- for selected places, the results of simulation of the fade characteristics based on the measurements of the electric field strength,
- fading characteristics measured directly with a spectrum analyzer.

Results of simulation and measurement, presented in the joint figures, will be compared. Based on the comparative analysis, conclusions and recommendations will be formulated.

III. METHODOLOGY OF DETERMINING THE FADE CHARACTERISTICS

The total electric field strength $E_{Tot}(f_{cen\_n})$ (in dB[μV/m]) at the measurement point located at distance d_i from i-th transmitter on the subcarrier central frequency f_{cen_n}, derived from two or three interfering signals (M=2 or 3 respectively) can be determined from (6):

$$E_{Tot}(f_{cen\_n}) = 20 \cdot \log\left(\left|\sum_{i=1}^{M} 10^{\frac{E_i(f_{cen\_n}, d_i)}{20}} \cdot e^{j\cdot\phi_i(f_{cen\_n}, d_i)}\right|\right) \quad (6)$$

In the DAB+ signal, the number of subcarriers K is 1536, the B_{DAB} bandwidth of the DAB+ signal is 1536 kHz and the center frequency of the LocalDAB network f_{cen_DAB} is 216.928 MHz. The DAB+ signal occupies the frequency band from f_p = 216.160 MHz to f_k = 217.696 MHz. The center frequency of the first subcarrier f_{cen_1} is 216.1605 MHz, and the frequencies of the other subcarriers can be determined from (7):

$$f_{cen\_n} = f_{cen\_1} + (n-1) \cdot 0.001 \text{ [MHz] } n=2, \dots, 1536 \quad (7)$$

If we assume that in the DAB+ signal all subcarriers are broadcast with the same power, then this should be taken into consideration by introducing the correction factor Dp with the value (8):

$$Dp = 10 \cdot \log(1536) = 31{,}86 dB \quad (8)$$

It means that each subcarrier with bandwidth equal to 1 kHz carriers only 1/1536 of the total measured power coming from the i-th transmitter E_{iB}. This E_{iB} power is measured in whole DAB+ channel with bandwidth B=1536 kHz. Therefore, the amplitude $E_i(f_{cen\_n}, d_i)$ of the subcarrier electric field strength in (6) can be determined from the relationship (9):

$$E_i(f_{cen\_n}, d_i) = E_{iB} - Dp \quad (9)$$

The phase of each subcarrier of interfering signal ϕ_i (i = 1, 2 or 3) can be determined from (10):

$$\phi_i(f_{cen\_n}, d_i) = -2 \cdot \frac{\pi \cdot f_{cen\_n}}{300} \cdot d_i \quad (10)$$

wherein the distance d_i is the distance from the point of measurement to the i-th transmitter.

IV. CHARACTERISTICS OF THE NETWORK SFN DAB+

The analysis of the fading phenomenon requires detailed data on the location of transmitters and their emission parameters. This information is necessary to determine the level of the electromagnetic field strength at selected points. The amount of information needed and its accuracy depends on the propagation model used. The more advanced the model, the greater the number of required information and its degree of detail. The requirements concerning the description of the environment in which the analyzed SFN network works are also growing. Table I presents the parameters of the SFN LokalDAB network necessary for conducting propagation analyzes, and Fig. 2 shows the location of transmitters.

TABLE I
LOCALDAB NETWORK TRANSMITTER PARAMETERS [18]

Parameter	WUST	NIT	PRW
City	Wroclaw		
Street	Dluga 67	Swojczycka 38	Karkonoska 10
Middle frequency	216.928 MHz (block 11A)		
Latitude	51°07'37'' N	51°06'55'' N	51°04'21'' N
Longitude	17°00'32'' E	17°06'48'' E	17°00'25'' E
Transmitter power	20.0 dBW	24.0 dBW	21.0 dBW
Parameter	WUST	NIT	PRW
Feeder attenuation	1.21 dB	0.87 dB	0.94 dB
Transmitting antenna gain	15.04 dBd	12.64 dBd	12.64 dBd
ERP	33.83 dBW	35.77 dBW	32.70 dBW
Polarization	Vertical		
Antenna height	36.0 m	24.0 m	16.5 m

The transmitting antennas used in the LokalDAB project have been specially designed and made with low costs. The radiation patterns of the antennas of the WUST, NIT and PRW stations are presented in Fig 3.

The procedure for selecting measuring points has been presented in [18]. Its aim was to determine the places where the phenomenon of fade will be most visible and measurable. In addition, the possibility of taking measurements in previously selected places was also taken into account. As a result, measurements were made at seven points.

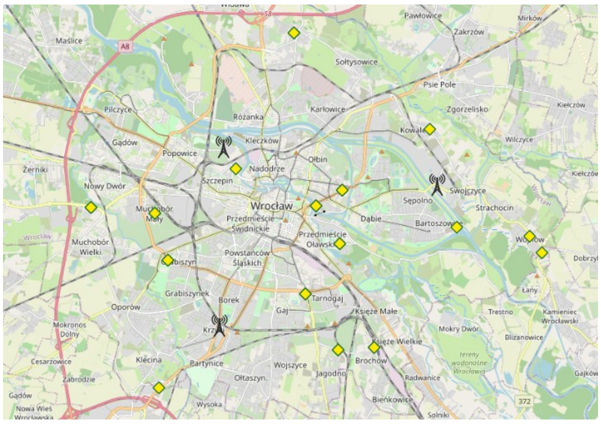
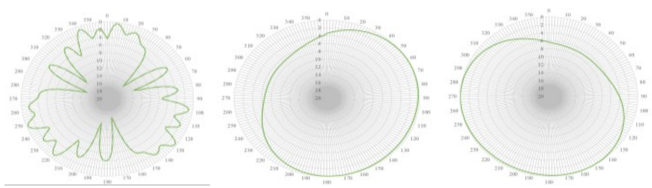


Fig. 2. Arrangement of measurement points (diamonds) and transmitting stations (transmitter symbols) in the area of Wrocław.



(a) (b) (c)

Fig. 3. Horizontal radiation pattern of antenna system at the (a) WUST, (b) NIT and (c) PRW stations [18]

V. MEASUREMENT SET-UP AND MEASUREMENT METHOD

For measurement purposes, a mobile station was built to measure both the e-m field strength in the DAB+ signal band as well as the characteristics of the occurring fades. The measuring equipment used is summarized in Table II and shown in Fig. 4 and Fig. 5.

TABLE II
LIST OF INSTRUMENTS USED DURING MEASUREMENTS

Instrument type	Model
Computer	Acer Swift 3
Spectrum analyzer	Tektronix H600 RF Hawk
Signal analyzer	Promax Ranger HD+
Directional antenna	R&S HE300 4067.6606.00 (200 – 500 MHz)
Omnidirectional antenna	-
Tripod	BOSCH Professional BT 250
Temperature and relative humidity meter	-

Fig. 4. Tripod with directional antenna, compass, temperature and humidity meter [22]

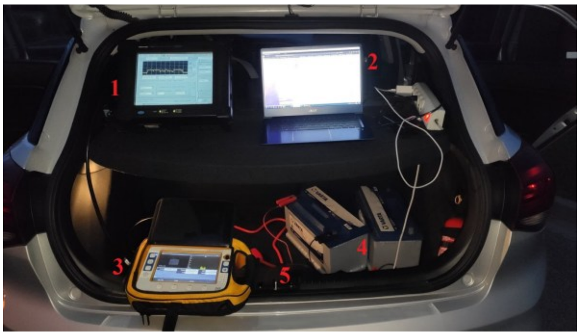


Fig. 5. Equipment of the measuring station (1 - spectrum analyzer, 2 - computer, 3 - Promax HD Ranger +, 4 - batteries, 5 - converter) [22]

During the measurements, a directional antenna from Rohde & Schwarz HE300 was used, with the antenna factor and characteristics presented in Fig. 6 and Fig. 7.

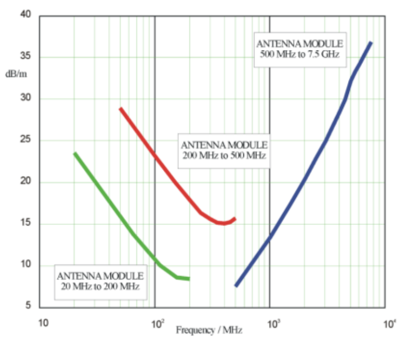


Fig. 6. Antenna factor AF of the directional antenna in active mode [21], AF(216.928 MHz)=17.5 dB/m

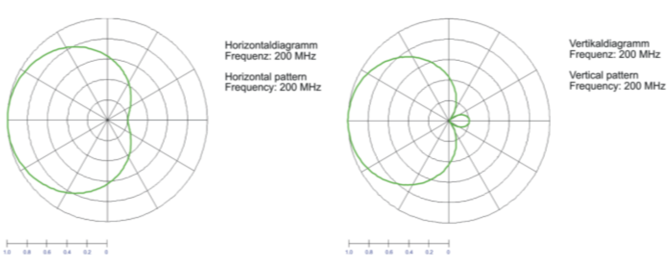


Fig. 7. Antenna radiation pattern: horizontal (left) and vertical at 200 MHz

Due to the lack of information on the omnidirectional antenna (vertical rod), it was only used to compare the shape of the spectrum and the characteristics and dynamics of fading.

The measurements were made in two stages. Stage A - measurements of the power in the channel with the use of a directional antenna, stage B - testing the occurrence of fades using an omnidirectional antenna. A spectrum analyzer was used for the measurement with the settings shown in Table III.

TABLE III
SPECTRUM ANALYZER CONFIGURATION PARAMETERS

Parameter	Power measurement in the channel	Examination of the occurrence of fades
Measure mode	Channel Power	Spectrum
Center frequency [MHz]	216.928	
Span [MHz]	2	
RBW [kHz]	1	
Chanel bandwidth [MHz]	1.536	N/A
Trace	Average value of 10 runs	
Detector	VRMS	VRMS and Peak value

Each measurement was performed at a given measuring point in five places in the area of 5 x 5 m, always keeping the minimum distance from the car of 3 m in the measuring system as shown in Fig. 8.

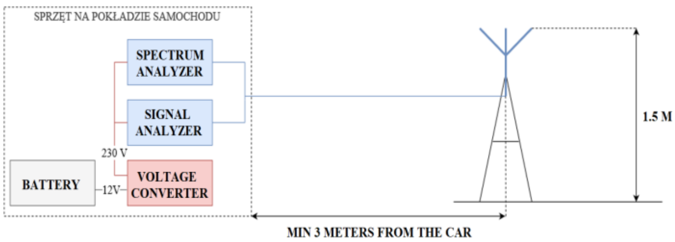


Fig. 8. Scheme of the measuring set-up

Measurements were carried out in 7 points (Table IV), Figure 2 shows the places where the measurements were taken.

TABLE IV
ELECTROMAGNETIC FIELD STRENGTH IN DB(μV/M) (MEASURED)

Measuring point	Field strength measured			
(Point No.) Street	WUST	NIT	PRW	Total
(1) Hallera	60.7	-*	57.7	62.5
(2) Konduktorska	-*	53.8	56.1	58.1
(3) Okólna	41.2	40.9	-*	44.1
(4) Grunwaldzki	51.2	59.7	-*	60.3
(5) Armii Krajowej / Bardzka	58.1	55.9	57.6	62.1
(6) Polanowicka	59.2	55.2	-*	60.6
(7) Szwajcarska	61.8	-*	58.5	63.4

*Note: The field strength measured from the weakest station at a given point was ignored during the measurement, because insufficient antenna directivity would lead to false results.

VI. RESULTS OF SIMULATION AND MEASUREMENT OF FADE CHARACTERISTICS

This chapter presents the fade characteristics calculated from the measured values of the e-m field strength and their comparison with the measured fade characteristics (Figs. 9-15).

In point 1 (Fig. 9) at Haller street, there was a strong interference of signals from the WUST and PRW transmitters. The measured e-m field strength from these transmitters differs only by 3 dB. Comparing the characteristics of the fade measured and simulated on the basis of the measured field strengths, a very great similarity can be seen. Both the number of deep fades and their nature are very similar. Also, the maximum measured fade depth of 19 dB is close to the calculated value of 20 dB.

At measurement point 2 (Fig. 10) at Konduktorska street, interfere with each other signals from transmitters NIT and PRW. The difference in levels of the measured signals is 2.3 dB. However, in this case, the picture of the measured and calculated interference differs significantly. We have 12 fading in the calculated characteristic and 14 fading in the measured characteristic. The maximum fading values are 27 dB (simulation) and 10 dB (measurement) respectively.

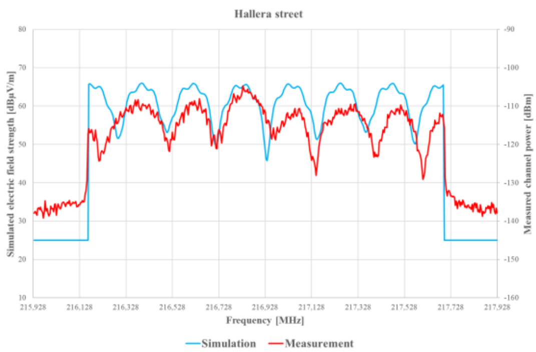


Fig. 9. Comparison of simulated (simulation based on channel power measurements) and measured fades on Hallera street. Simulated fades depth up to 20 dB, measured fades depth up to 19 dB

Fig. 10. Comparison of simulated (simulation based on channel power measurements) and measured fades on Konduktorska street. Simulated fades depth up to 27 dB, measured fades depth up to 10 dB.

At the measurement point 3 (Fig. 11) at Okolna street, signals from the WUST and NIT transmitters interfere with each other. The level difference between these signals is 0.3 dB. Both in the simulated and measured waveforms, the occurring fades are clearly visible. There are 5 deep fades in the simulated waveform and 6 in the measured waveform. The maximum fade depths are 27 dB (simulation) and 15 dB (measurement), respectively.

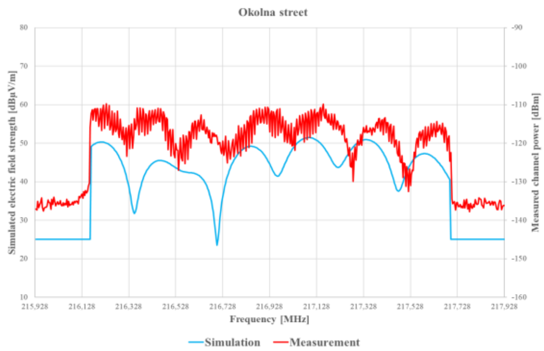


Fig. 11. Comparison of simulated (simulation based on channel power measurements) and measured fades on Okolna street. Simulated fades depth up to 27 dB, measured fades depth up to 15 dB

At the measuring point 4 (Fig. 12) at Grunwaldzka street, signals from the WUST and NIT transmitters interfere with each other. You can see clear interference. In the case of simulation, we observe 5 deep fading with a maximum depth of 10 dB, and in the case of the measured characteristic, there are 4 fading with a maximum depth of 15 dB.

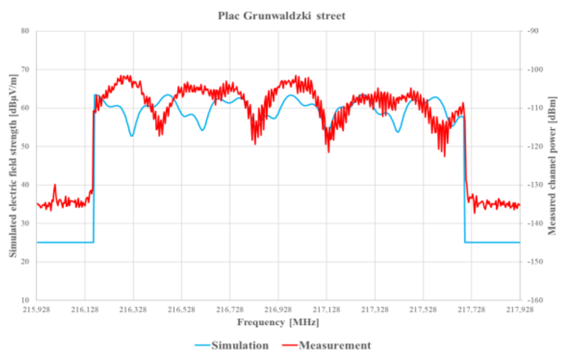


Fig. 12. Comparison of simulated (simulation based on channel power measurements) and measured fades on Plac Grunwaldzki street. Simulated fades depth up to 10 dB, measured fades depth up to 15 dB

At the measurement point 5 (Fig. 13) at Armii Krajowej street, signals from three transmitters interfere with each other. The levels of these signals differ by no more than 2.2 dB. In this case, there are 14 deep fades on the simulated waveform and 10 deep fades on the measured waveform. There is a fairly good agreement in the places where fades occurs, including the deepest ones. The maximum fade depth is 35 dB (simulation) and 18 dB (measurement).

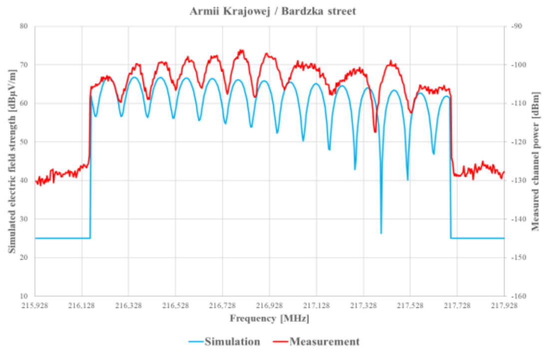


Fig. 13. Comparison of simulated (simulation based on channel power measurements) and measured fades on Armii Krajowej / Bardzka street. Simulated fades depth up to 35 dB, measured fades depth up to 18 dB

At the measuring point 6 (Fig. 14) at Polanowicka street, the signals from the WUST and NIT transmitters interfere with each other. The measured levels of these signals differ by 4 dB (in the case of simulation calculations, the difference is much larger and amounts to 11.1 dB). There are 13 fading in the simulated waveform with a maximum value of 15 dB. There are 6 deep fades and 8 of a slightly lower value in the measurement results. The maximum fade depth is 15 dB (simulation) and 20 dB (measurement).

At the measurement point 7 (Fig. 15) at Szwajcarska street signals from the transmitters WUST and PRW interfere with each other. The measured signal level difference is 3.3 dB. There are 5 distinct fades in the simulated fading characteristics. In the measured characteristic, the number of fades is 18. In the simulated characteristic, there are additional irregularities of the characteristic at the frequencies of occurrence of fades in the measured waveform. The maximum fade depth is 10 dB (simulation) and 25 dB (measurement).

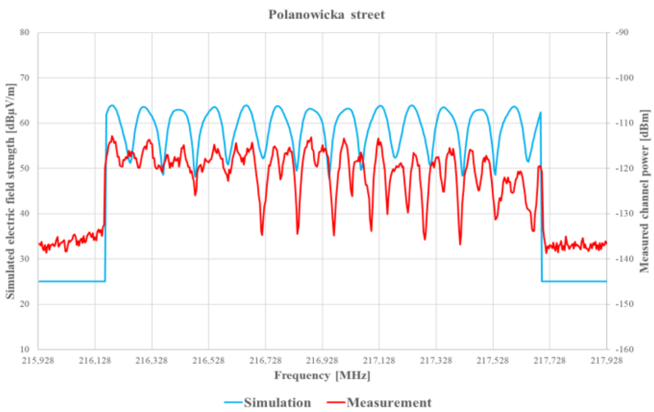


Fig. 14. Comparison of simulated (simulation based on channel power measurements) and measured fades on Polanowicka street. Simulated fades depth up to 15 dB, measured fades depth up to 20 dB

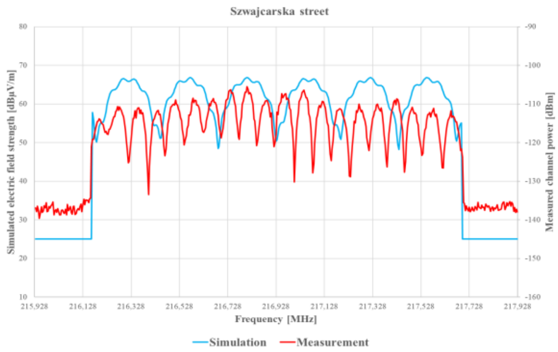


Fig. 15. Comparison of simulated (simulation based on channel power measurements) and measured fades on Szwajcarska street. Simulated fades depth up to 17 dB, measured fades depth up to 25 dB

Large differences observed in the characteristics of the simulated and measured fades may result from the influence of the multipath phenomenon on the characteristics of the fades. The determined characteristic of the fading takes into account only the signals from two or three transmitters. The characteristics measured with a spectrum analyzer also take into account the phenomenon of propagation multipath.

VII. Conclusions

The presented results of simulations and measurements of the characteristics of fades caused by the interference of signals received from transmitters of a single-frequency network allow to draw a number of conclusions.

The most important conclusion is the confirmation of the occurrence of this phenomenon. In the analyzed measuring points, fades were observed, the number and depth of which may affect the quality of the received signal. In the tested cases, the reception of the DAB+ signal was undisturbed at all measuring points. But this was due to the relatively high signal level. Limitation of SFN network coverage due to the occurrence of fading can be expected in places where the levels of received signals from transmitters still ensure correct reception but are near the lower limit. Then the phenomenon of fading may reduce the coverage in areas where the levels of the received signals are similar.

The use of the ITU-R P.1546 propagation method is effective in determining the places where deep interference of signals from the SFN network is expected. However, simulating the fading characteristics from simulated signal levels can differ significantly from the measured characteristics. The ITU-R P.1546 method does not take into account a number of elements that affect signal propagation, especially in a large city environment. The fade values obtained on the basis of the simulation may be higher or lower than the measured values. Moreover, in real conditions in the area of the receiving antenna, additional signals may appear due to multipath propagation, significantly affecting the number and depth of fades.

During the measurements, slight changes in the frequency of fade occurrences were noticed at a given measuring point. This phenomenon may be due to the limited accuracy of the synchronization of the transmitters and the slight variations in the phase of the signals. The way of synchronizing the LokalDAB network transmitters is presented in [18].

The measurement results of the signal level from the SFN transmitters are not precise due to the rather limited gain of the directional receiving antenna. Unfortunately, the transmitters could not be turned off in the network under consideration. The use of an antenna with higher gain (directivity) at the frequency of 216.928 MHz is associated with the use of a larger antenna, which may make measurements difficult.

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