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Analysis and Comparison of the Fade Phenomenon in the SFN DAB+ Network With Two and Three Transmitters

Ryszard J. Zielinski

Abstract—**Single Frequency Networks (SFN) of transmitters are currently used in television and digital broadcasting to effectively cover large areas using minimal spectral resources and using transmitters with much lower power than if the same area were covered using one transmitter. It is therefore a very ecological solution. In this way, much better reception conditions are obtained in large city areas, as the signal reaches the receiving antenna from different directions, reducing the risk of shading. However, in this type of network one should take into account the loss of signal caused by signal interference. Using the appropriate propagation model, it is possible, with appropriate assumptions, to check how the operation of the third transmitter affects the distribution and size of the deepest fades in relation to the network in which there are two transmitters.**

Keywords—**single-frequency network, fades, DAB+**

I. INTRODUCTION

SINGLE Frequency Networks (SFNs) cover large areas using transmitters with much smaller powers compared to one transmitter serving the same area. In addition, in many cases reaching the desired signal to the receiver from several directions reduces the phenomenon of shading by various types of propagation obstacles [9]. For this reason, such solutions are used in digital broadcasting [1, 2]. This is made possible by a radio interface using Orthogonal Frequency Division Multiplexing (OFDM) channel. As part of the LokalDAB project, it was possible to check the distribution and depth of fades in a network of three transmitters that were launched in a single frequency network in Wroclaw. The article [4] presents the conditions that must be met by SFN network to ensure the correct reception of signals. In order to better understand the essence of the phenomenon, a method of determining maximum fade locations and their size for systems consisting of two transmitters was presented. These areas are concentrated along the hyperbola with a given coefficient k determining the difference of paths to the analyzed point from the transmitters [5, 8]. The main problem in calculating the depth of fades is the lack of propagation models that allow determining both the amplitude of the e-m field strength vector at the receiving point based on the magnitude of the propagation losses as well as the phase of this electric field strength vector. Therefore, assuming certain assumptions, a propagation model was presented, which is based on the propagation model over perfectly conductive plain earth [3]. The limits of applicability of this model were also determined. Using this model, the relationship enabling the calculation of the fade depth was determined and examples of results for different values of the parameter k were presented [5]. The fade thus determined is closely related to the signal of a given carrier frequency and includes only subcarriers around this frequency [8]. The analysis for two transmitters [6] has been extended for the case of three working co-phase transmitters. On the same routes, the distribution of e-m field intensity caused by interference of signals from two and three operating transmitters was determined. Due to the frequency-selective nature of the interference, the method of determining the depth of fade as a function of frequency in characteristic points of the area including two signals is presented in [8].

II. GEOMETRIC PLACES OF THE MAXIMUM FADE

The single frequency network built in Wroclaw was analyzed. This network consists of three transmitters located in the vertices of the triangle in the locations: Polish Radio (PR), Institute of Telecommunications (IL) and Wroclaw University of Science and Technology (PWr). The sides of the triangle are as follows: 6070 m (PR - PWr), 7410 m ((PWr - IL) and 8830 m (PR - IL). The distribution of network nodes is shown in Fig. 1. Perfect frequency and phase synchronization was assumed for the transmitters. With this assumption, the only element causing the lack of co-phase of the received OFDM signals from SFN DAB+ transmitters is the difference in propagation paths. It will cause that in the broadband signal will appear so-called fades on specific subcarriers. Their location in the frequency domain will depend on the magnitude of the propagation path difference causing the delay. The analysis will be carried out for two and three co-phase transmitters. The geometric locations of the maximum fading of signals from two transmitters for a given frequency can be determined using the hyperbola equation. In the case of signals from three transmitters, it is not possible to determine the locations of the maximum fades using a specific curve.

In the general case of interference of two signals, the hyperbola equation has the form (1):

$$\frac{(x-x_0)^2}{a^2}-\frac{(y-y_0)^2}{b^2}=1 \tag{1}$$

in which: x_0 and y_0 is the displacement of the centre of symmetry of hyperbolas relative to the origin of the coordinate system, a -

The Author are with Wroclaw University of Science and Technology, Poland (e-mail: ryszard.zielinski@pwr.edu.pl).

the length of the real half axis (Fig. 2), b - the length of the imaginary half axis, 2a - the difference (constant) in the length of the path of points on the hyperbola from the focal points ($|d_1-d_2| = 2a$), 2c - distance between transmitters. The distance c of each focus (transmitter) from the centre of symmetry is equal to (2):

$$c=\sqrt{a^2+b^2} \tag{2}$$

The deepest signal losses will occur if destructive interference defined by the relationship (3) occurs:

$$\Delta d_k=|d_1-d_2|=(2\cdot k+1)\cdot\frac{\lambda}{2}=(2\cdot k+1)\cdot\frac{150}{f_{[MHz]}}\ \text{[m]} \tag{3}$$

k=0, 1, 2, …

With the known distance between the transmitters (2c) and the established difference in road length (2a), it is possible to determine from the relationship (2) the imaginary axis length (b) and determine the hyperbolic equation describing a set of points with a given difference in the length of propagation paths.

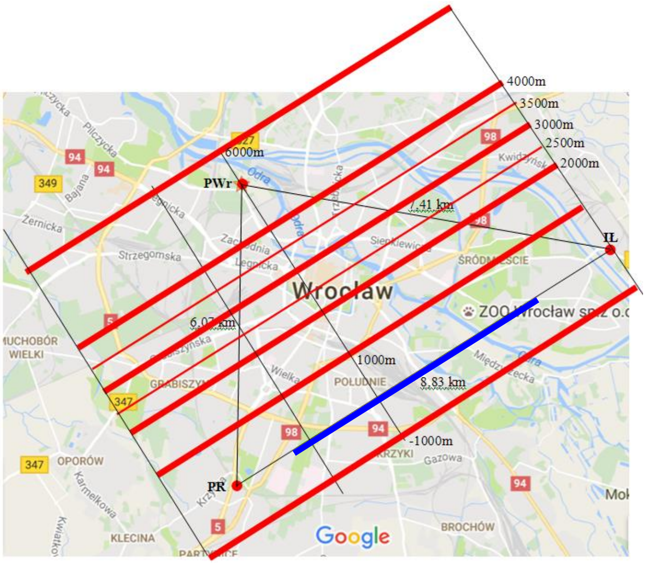


Fig. 1. Location of transmitters (PR, IL and PWr) and routes for which calculations of the electric field strength level from two and three transmitters are presented.

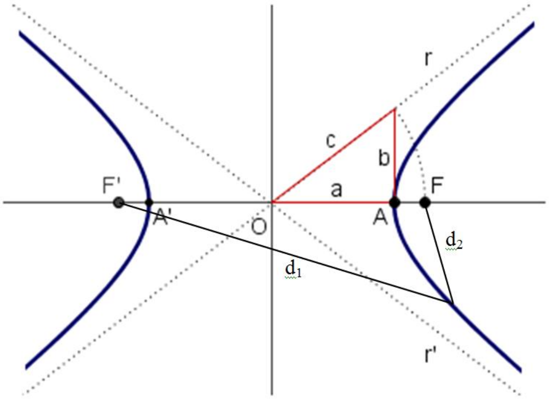


Fig. 2. Hyperbole - geometrical place of points with a constant difference in distance from points F and F' in which SFN DAB+ transmitters are located ($x_0 = 0$, $y_0 = 0$).

Analyzing the structure of the RF signal occupied by the subcarrier emitted by transmitters of the single-frequency DAB+ network in Wroclaw, according to the first transmission mode (T_U = 1 ms), we can determine the subcarrier frequency bandwidth ΔF (4):

$$\Delta F=\frac{1}{T_U}=\frac{1}{0{,}001}=1000Hz \tag{4}$$

The number of subcarriers k is 1536, therefore the bandwidth B_{DAB} of signal DAB+ is 1536 kHz and the center frequency f_{cf} 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_{sr_1} is 216.1605 MHz, and the frequencies of the other subcarriers can be determined from the relationship (5):

$$f_{sr\_n}=f_{sr\_1}+(n-1)\cdot 0.001\ \text{[MHz]}\quad n=2,\ \dots,\ 1536 \tag{5}$$

Selected fragments of the spectrum of the RF signal transmitted by DAB+ transmitters are presented in Fig. 3. From the relationship (3) it is possible to determine the difference of length of the propagation paths Δd_k at which the maximum signal loss on a given subcarrier will occur. The parameter in this case will be the number k, for which the fade will occur at the same frequency but with changing propagation path lengths differences.

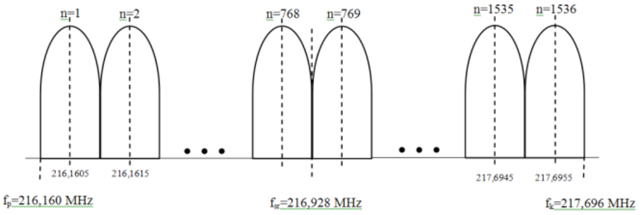


Fig. 3. OFDM signal spectrum for transmission channel 11A and transmission mode I.

For these Δd_k values will also change the position of the next hyperbola marking the geometry of points with the given Δd_k. For example, for k = 0 and for the fade occurring for the first subcarrier, the signal path difference is:

$$\Delta d_0=|d_1-d_2|=(2\cdot 0+1)\cdot\frac{\lambda}{2}=\frac{150}{f_{[MHz]}}=\frac{150}{216.1605}=0.694\ \text{[m]}$$

while for fade for the last subcarrier under the same conditions:

$$\Delta d_0=|d_1-d_2|=(2\cdot 0+1)\cdot\frac{\lambda}{2}=\frac{150}{f_{[MHz]}}=\frac{150}{217{,}6955}=0.687\ \text{[m]}$$

For k = 1 and the first subcarrier, Δd_1 = 2.082m is obtained under the same conditions, and for the last subcarrier Δd_1 = 2.067 m. For k = 100, Δd_{100} = 139.48m for the first subcarrier, and Δd_{100} = 138.50m for the last subcarrier.

The analysis shows that for the given k value, the differences in the signal path lengths slightly depend on the frequency for the selected DAB+ channel, they change with the change of the k parameter. Fig. 4 illustrates these changes for the k value varying from 1 to 1000 and for the central frequency of channel 11A equal to 216.928 MHz.

For a given difference in the length of propagation paths, the geometrical places of the occurrence of fading can be determined by calculating the hyperbola parameters in an appropriate manner. For example, for the distance between transmitters 8830m (IL-PR transmitters), frequency 216.928 MHz and for k = 1000 we get the following hyperbola parameters: distance difference from transmitters for k = 1000 equal to Δd_{1000} = 1384 m; 2a = Δd_{1000}; a = 692 m, c = 8830 m. From formula (2) b = 8803 can be determined. Therefore, the hyperbola formula can be written in the form (5):

$$y = \pm b \cdot \sqrt{\frac{x^2}{a^2} - 1} = \pm 8803 \cdot \sqrt{\frac{x^2}{692^2} - 1} \tag{5}$$

and its graph is shown in Fig. 5.

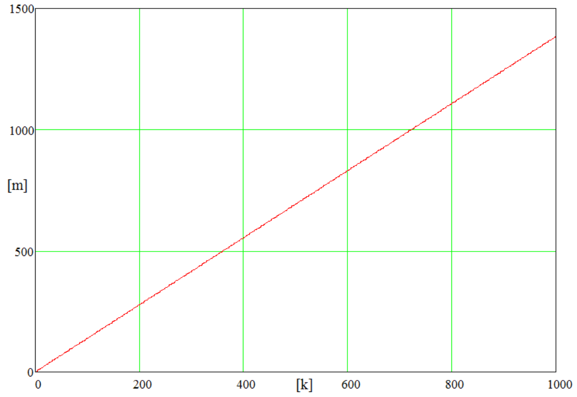


Fig. 4. Difference in propagation path length Δd_k as a function of parameter k (f = 216.928 MHz).

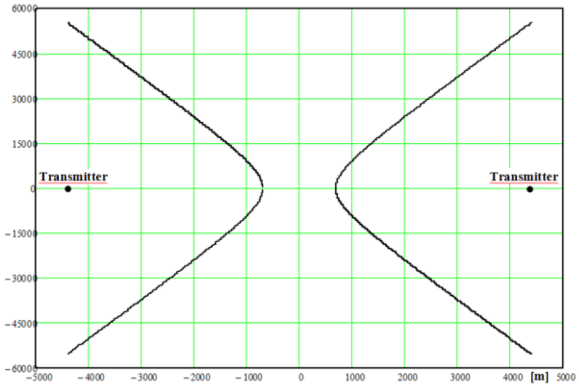


Fig. 5. Hyperbola - the geometric place of points with a constant difference in distance from the transmitters equal to 1384 m (k = 1000) spaced apart by 8830 m.

In order to better understand the shape and properties of geometric places where there is maximum attenuation of the signal level due to interference of signals with the same frequencies emitted by two DAB+ transmitters, additional calculations were carried out for the parameter values k = 200, 400, 600 and 800. For these parameter values k, Δd_k and values of basic hyperbolic parameters, i.e. a and b, were determined. The results are presented in Table I.

TABLE I
PARAMETERS DETERMINING THE SHAPE OF HYPERBOLE REPRESENTING PLACES OF GIVEN SIZE OF Δd_K

	D=2c=8830 m		
k	Δd_k	a	b
200	277	139	8829
400	554	277	8826
600	830	415	8820
800	1107	554	8813
1000	1384	692	8803

A set of hyperbole having these parameters for transmitters at a distance of 8830m is shown in Fig. 6.

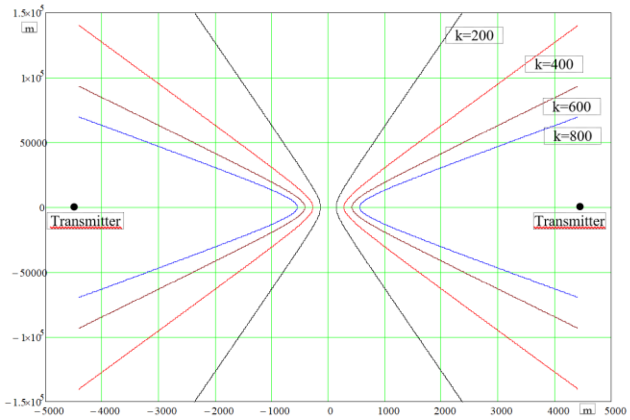


Fig. 6. Hyperbolic complex - the geometric place of points with a constant difference in distance from transmitters 8830 m apart for k = 200, 400, 600 and 800.

III. FADES IN THE SFN DAB+ NETWORK WITH TWO TRANSMITTERS

In the case of interference from signals from two transmitters, it should be expected that the deepest fades will occur in places located on hyperbole meeting the condition determined by formula (3). The more uniform the field strengths of the two interfering waves, the greater the fading is expected. The deepest fades will occur in places where the e-m field strength levels are the same from two transmitters and the phases of the RF signals opposite. In the case of interference of three signals from three transmitters, the field strengths at the analyzed point must be summed vectorially. First, interference of two signals will be considered.

A. Propagation model

For the theoretical estimation of the depth of fades, a model of flat reflective ground (plane perfectly conductive earth), can be used (Fig. 6).

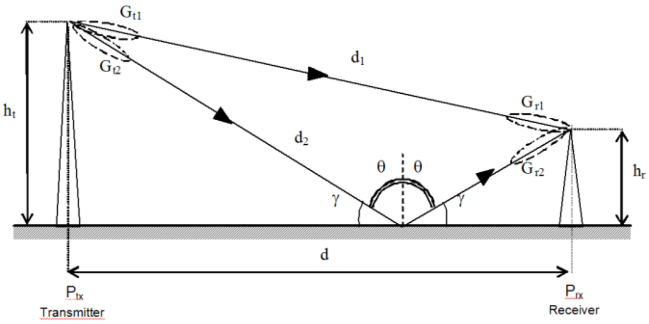


Fig. 6. Model for the analysis of double-ray propagation over a plain surface of the earth

Loss of signal power due to propagation expressed as the ratio of received power P_{rx} to transmitted P_{tx}, i.e. L = P_{rx}/P_{tx} can be determined from the relationship (6):

$$L = \left(\frac{\lambda}{4\pi}\right)^2 \left| \sqrt{G_{t1}G_{r1}} \frac{e^{j\phi_1}}{d_1} + R\sqrt{G_{t2}G_{r2}} \frac{e^{j\phi_2}}{d_2} \right|^2 \tag{6}$$

with: λ - signal wavelength, R - complex reflection coefficient (for perfectly conductive earth R=-1), G_{ti} - gain of the transmitting antenna in the direction of the path i, G_{ri} - gain of the receiving antenna in the direction of the path i, d_i – length of path i, ϕ_i - phase of the incoming signal along the path i (relative to the transmitter), i - path index, i = 1 direct path, i = 2 path with reflection.

The phase shift of the signal relative to the transmitter resulting from the length of propagation paths is determined from the relationship (7):

for direct path: $$\phi_1 = \frac{-2\pi d_1}{\lambda} = \frac{-2\pi f d_1}{c}$$

(7)

for path with reflection: $$\phi_2 = \frac{-2\pi d_2}{\lambda} = \frac{-2\pi f d_2}{c}$$

Distances d_1 and d_2 can be determined if the distance between the transmitter and receiver d is known, and the height of the transmitting antenna h_t and receiving h_r is known. In addition, it was assumed that altitude above sea level the places where both antennas are located are the same.

$$d_1 = \sqrt{(h_t - h_r)^2 + d^2} \qquad d_2 = \sqrt{(h_t + h_r)^2 + d^2} \tag{8}$$

Substituting formulas (7) and (8) to formulae (6) we get an exact formula for propagation losses over perfectly conductive plain earth in the form (9):

$$L(d) = 20 \cdot \log\left(\left(\frac{c}{4\pi \cdot f}\right)\left|\frac{e^{-\frac{2\cdot\pi\cdot j\cdot f}{c}\cdot\sqrt{(h_t-h_r)^2+d^2}}}{\cdot\sqrt{(h_t-h_r)^2+d^2}} - \frac{e^{-\frac{2\cdot\pi\cdot j\cdot f}{c}\cdot\sqrt{(h_t+h_r)^2+d^2}}}{\cdot\sqrt{(h_t+h_r)^2+d^2}}\right|\right) \text{[dB]} \tag{9}$$

The formula (9) takes into account the reflection coefficient $R=1e^{-\pi}=-1$, which does not change the amplitude of the reflected signal, but only shifts its phase by 180°. An example graph of propagation losses L as a function of distance d is presented in Fig. 7.

Analyzing the obtained results of propagation losses, it is clearly seen that near the transmitter there are deep signal losses due to interference of the direct and reflected waves from the ground. For the frequency and height of suspension of the transmitting antenna under consideration, the number of fades as a function of distance from the transmitter for mobile reception is definitely smaller than for stationary reception. From a certain distance from the transmitter, the phenomenon of local fades ceases to occur, while propagation losses increase with distance at a rate of 40dB/dec (proportional to d^4). It can be shown [3] that within these distances, propagation losses are described by the simplified relationship (10):

$$L(d) = 10 \cdot \log\left(\frac{h_t^2 \cdot h_r^2}{d^4}\right) \text{[dB]} \tag{10}$$

Fig. 7 clearly shows that in both cases the approximate pattern can be used only from a certain distance from the transmitter. This distance can be determined by imposing a condition determining the permissible error δ resulting from the use of the simplified formula (11):

$$\delta(d) = L(d)_{approximate} - L(d)_{exact} \le \varepsilon \tag{11}$$

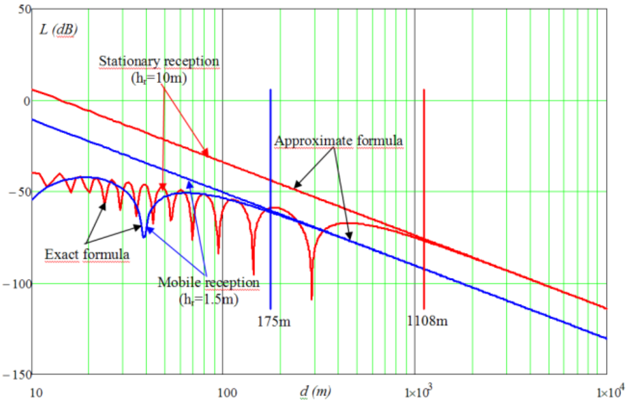


Fig. 7. Propagation losses in a double-ray propagation model as a function of distance from a DAB+ transmitter operating at 216.928 MHz with a transmitting antenna at h_t = 20m and receiving antenna at h_r = 10m (stationary reception) and h_r = 1.5m - comparison results from the exact formula and the approximate formula

In the analyzed cases it can be assumed that the sufficient accuracy of the approximation is the error δ(d) not exceeding 1 dB. Then the approximate formula can be used from a distance from the transmitter equal to 1108 m at a receiver height of 10 m and 175 m at a receiver height of 1.5 m. These distances are marked in figure 7 by vertical lines. Assuming a more critical assumption of an error δ(d) of no more than 0.1 dB, we will receive the distances: 3467 m and 551 m respectively.

IV. FADES IN THE SFN DAB+ NETWORK WITH TWO TRANSMITTERS

This chapter presents the distribution of the electric field strength level on specific routes, which takes into account the interference of two waves. For this purpose, the same propagation model and the same assumptions as previously introduced will be used. The SFN network built in Wrocław as part of the LocalDAB project, which consists of three transmitters, will be analyzed. Therefore, the analyzed situation assumes switching off one transmitter, e.g. due to loss of synchronization with the other two transmitters. The same suspension height of the transmission antennas was assumed to be 20 m and a propagation model over perfectly conductive plane earth. The analysis will be carried out for the receiving antenna placed at a height of 10 m (DVB+ stationary receiver). The location of SFN network transmitters, the distance between them and the routes on which the analysis was carried out is presented in Fig. 1. It was assumed that the only working transmitters are transmitters PR (location Polish Radio) and IL (location Communication Institute). A similar picture of the distribution of fading can be obtained for the other two combinations of working transmitters.

In order to determine the e-m field strength level from two co-phase transmitters operating in a single frequency network, it is convenient to assume the XY coordinate system in which one of the transmitters, e.g. PR (Polish Radio) is located at its beginning at (x1,y1) = (0,0), the second IL (Institute of Communications) lies on the X axis at the point with the coordinates (x2,y2) = (8830,0), the location of the third transmitter is irrelevant in this case.

For given x y coordinates of the observation point, we can determine distances from two DAB+ transmitters. They amount to:

$$d_1(x,y) = \sqrt{(x-x_1)^2 + (y-y_1)^2} = \sqrt{x^2+y^2}$$
$$d_2(x,y) = \sqrt{(x-x_2)^2 + (y-y_2)^2} = \sqrt{(x-8830)^2 + y^2} \qquad (12)$$

Only the area in which a simplified two-ray propagation model over perfectly conductive plane earth can be used (this area is limited by the minimum distance from the transmitter, which is 1108 m for stationary receivers). Therefore, the analysis was carried out for routes whose distances are not less than 1000 m from working transmitters. Using the relationship (13), we can determine the amplitude of the e-m field strength (vector module) coming from the working transmitter for stationary reception conditions.

$$E_{dB\left[\frac{v}{m}\right]} = 10\cdot\log 480 + 20\cdot\log\frac{\pi}{\lambda} + EIRP_{dB[W]} + 10\cdot\log\left(\frac{h_t^{\,2}\cdot h_r^{\,2}}{d^4}\right) \qquad (13)$$

In the case of our DAB+ signal emission, we can assume the following assumptions: EIRP = 200 W = 23 dBW, f = 216.928 MHz, i.e. λ = 1.383 m, h_t = 20 m, h_r = 10 m - stationary reception. Formula (13) after entering the values of individual parameters for stationary reception takes the form:

$$E_{dB\left[\frac{v}{m}\right]} = 102.96 - 40\log(d) \qquad (14)$$

with d in the formulas expressed in meters.

The e-m field strength phase remains to be determined. It depends on the length of propagation path. Since the area we are interested in lies in the range of distances in which we can apply a simplified relationship for the two-ray propagation model (the length of the direct ray is almost equal to the length of the reflected ray path), therefore we take the length of the direct ray as the path length.

Taking into account the previously assumed suspension height of the transmitting antenna and receiving antenna for stationary reception, we will get the length of propagation paths from the analysed transmitters ($dp_{1,2}$) expressed by the relationship:

$$dp_1(x,y) = \sqrt{d_1^{\,2}(x,y) + (20-10)^2} = \sqrt{d_1^{\,2}(x,y) + 100}$$
$$dp_2(x,y) = \sqrt{d_2^{\,2}(x,y) + 100} \qquad (15)$$

Taking into account the formulas: (12), (14) and (15), we can determine the resultant field strength at (x, y) as the sum of two field strength vectors (vertical polarization), expressed by the relationship:

$$E_T(x,y))_{dB\left[\frac{\mu V}{m}\right]} = 20\cdot\log\left(\left|10^{\frac{E_1(x,y)}{20}}\cdot e^{j\varphi_1(x,y)} + 10^{\frac{E_2(x,y)}{20}}\cdot e^{j\varphi_2(x,y)}\right|\right) \qquad (16)$$

however, we use the following formulas for stationary reception:

$$E_i(x,y) = 222{,}96 - 40\log(d_i(x,y)) \quad [\mathrm{dB}_{(\mu V/m)}]$$
$$\phi_i(x,y) = \frac{-2\cdot\pi}{\lambda}\cdot dp_i(x,y) \quad \text{i=1, 2} \qquad (17)$$

V. FADES IN THE SFN DAB+ NETWORK WITH THREE TRANSMITTERS

In the SFN DAB+ network, in which coverage is obtained by receiving three signals from three co-phase transmitters, the nature of the occurring fades is worth analysing in an area where the amplitudes of the received signals are similar. The condition of full loss of signal at the receiving location can be written using the following formula:

$$\bar{E}_1 + \bar{E}_2 + \bar{E}_3 = E_1\cdot e^{j\phi_1} + E_2\cdot e^{j\phi_2} + E_3\cdot e^{j\phi_3} = 0 \qquad (18)$$

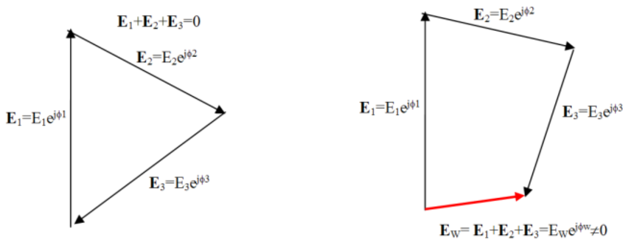
wherein:

$\bar{E}_i$ - vector of electric field strength from the i-th transmitter (i = 1, 2, 3),

E_i - amplitude of the electric field strength vector from the i-th transmitter (i = 1, 2, 3),

ϕ_i - phase of the electric field strength vector from the i-th transmitter (i = 1, 2, 3).

This relationship can be illustrated in Fig. 8.



a) b)

Fig. 8. Interference of three signals at the reception point leading to a complete signal loss a) and partial signal loss b).

As you can see, there may be complete signal loss, partial signal loss or signal amplification at the receiving point. Maximum signal amplification will occur when three signals of equal amplitudes have identical phases. Then the resulting signal amplitude E_w = 3E and the received signal power will be 9.5 dB higher than the power received from one transmitter. The area in which both strong signal losses and high signal amplifications may occur will be located in the centre of the triangle, at the vertices of which transmitters with the same emission parameters are located. This area has been symbolically marked in Fig. 9.

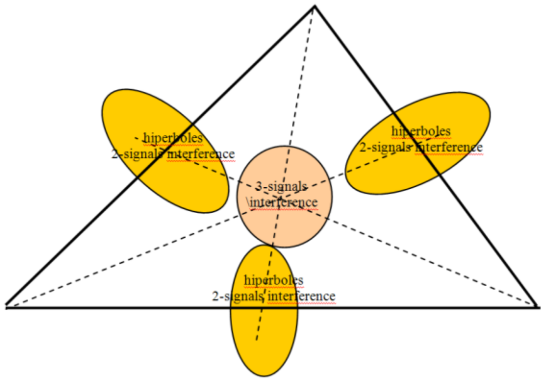


Fig. 9. Interference areas of two (hyperbolas) and three signals

The analysis was carried out for a network of three DAB+ transmitters located in Wrocław (Fig. 1). In order to determine the e-m field strength level from three co-phase transmitters operating in a single frequency network, the same XY coordinate system was used as for the interference of two signals. The third PWr transmitter due to the given distance from the PR and IL nodes will have the coordinates (x3, y3) = (3392.17; 5033.44). For the given value of x and y of the observation point, we can determine the distance d3(x, y) from the third DAB+ station:

$$d_3(x,y) = \sqrt{(x-3392{,}17)^2 + (y-5033{,}44)^2} \qquad (19)$$

Using the relationship (17), we can determine the amplitude of the e-m field strength (vector module) from each of the three transmitters for stationary reception conditions. The remaining phase of field strength e-m from the third transmitter remains to be determined, which we determine from the relationship:

$$dp_3(x,y) = \sqrt{d_3^{\,2}(x,y) + 100} \qquad (20)$$

Considering the formula (17) we can determine the resultant field strength in point (x,y) as the sum of three field strength vectors, expressed by the relationship:

$$E_T(x,y))_{dB\left[\frac{\mu V}{m}\right]} = 20\cdot\log\left(\left|10^{\frac{E_1(x,y)}{20}}\cdot e^{j\varphi_1(x,y)} + 10^{\frac{E_2(x,y)}{20}}\cdot e^{j\varphi_2(x,y)} + 10^{\frac{E_3(x,y)}{20}}\cdot e^{j\varphi_3(x,y)}\right|\right) \qquad (21)$$

where the e-m field strength is determined from the formula (17) for i=1, 2, 3.

VI. RESULTS OF ANALYSIS OF FADE LEVELS IN THE SFN DAB+ NETWORK WITH TWO AND THREE TRANSMITTERS AT STATIONARY RECEPTION

It may be very interesting to analyse the level of the resultant signal level on selected routes presented in Fig. 1 in the event that one of the transmitters will be switched off, e.g. due to loss of synchronization. Particularly interesting may be the comparative analysis of fades when the most distant transmitter is not working. This analysis can indicate to what extent the third transmitter affects the level of interference loss caused by the interference of two dominant and comparable signals.

The result of the analysis for stationary reception is presented in Fig. 10. It shows the value of the electric field strength in dB(μV/m) for the route between transmitters 1 and 2 within the range of 1000 m from transmitter 1 (Polish Radio - PR) up to a distance of approx. 1030 m from transmitter 2 (Institute of Communications - IL) (Fig. 1). As you can see, in the presence of two signals (blue graph) the strongest signal interference effects can be observed halfway between the transmitters 1 and 2. Their level exceeds 40 dB. It can also be seen that at smaller distances from transmitters 1 and 2, one signal becomes dominant and the size of fades decreases significantly. The signal from the third transmitter causes a significant widening of the area of significant fading, the level of deep fading is similar but they occur less often and are not concentrated in one place, as is the case in a network consisting of two transmitters. In addition, outside the area of significant fading, fading in the network of three transmitters is greater.

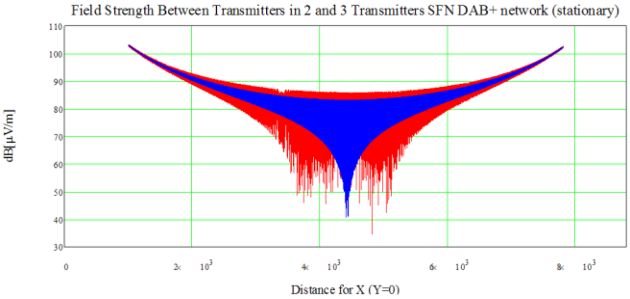


Fig. 10. Distribution of electric field strength between the transmitter 1 (Polish Radio) and 2 (Institute of Communications) in the SFN DAB+ network (Y = 0 m) during the operation of two and three transmitters (stationary reception). The route is marked in Fig. 1; analysis for Δx = 0.05 m.

Fig. 11 shows the distribution of the electric field strength (stationary reception) on the route shifted by 1000 m towards transmitter 3 (PWr), which is marked with a bold red line in Fig. 1. In this case, fades from two transmitters in several places slightly exceed the value of 40 dB. In this case, when approaching one of these transmitters, the amount of fade decreases significantly - one signal dominates. In this case, the area of significant fades is also much wider in the network of three transmitters working (it is about 2500 m) than in the network consisting of two working transmitters (about 200 m). The fade level in a narrow area, close to places with small level of power imbalance of two interfering signals, is higher for a network with two working transmitters and exceeds 50 dB. In a much wider area of the network with three working transmitters, the level of loss does not exceed 40 dB with rarely occurring places where it is larger. Outside the area of significant fade, as before, the fade in a network with two transmitters in operation is smaller than in a network with three transmitters in operation.

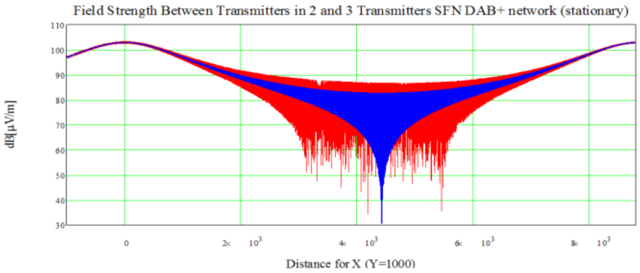


Fig. 11. Distribution of electric field strength along the route marked in Fig. 1, (Y = 1000 m) in the SFN DAB+ network consisting of two and three transmitters (stationary reception); analysis for Δx = 0.05 m.

The analysis of the electric field strength distribution on the route with Y = 2000 m (Fig. 12) for three working transmitters clearly shows two areas of increased fades. These areas are caused by the interference of signals from the transmitters (PR) and (PWr) - the area on the left side of the drawing and the transmitters (IL) and (PWr) - the area on the right side of the drawing. Signal levels in these areas are beginning to be comparable, hence the size of the fades increases and reaches 50 dB. In the central area of the triangle defined by the locations of three transmitters, corresponding to the centre of Wroclaw, the size of fading is limited to 20 dB. When the PWr transmitter is turned off, we observe a deep fade in the middle of the route by more than 50 dB.

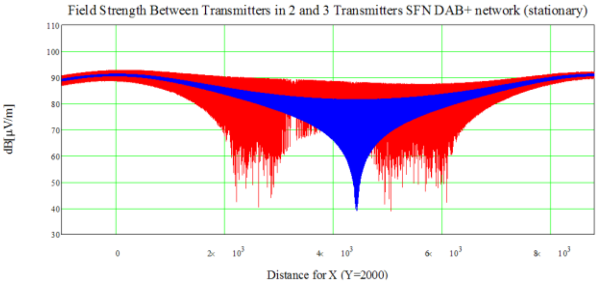


Fig. 12. Electric field strength level from two and three transmitters for a route with Y = 2000 m (stationary reception); analysis for Δx = 0.05 m.

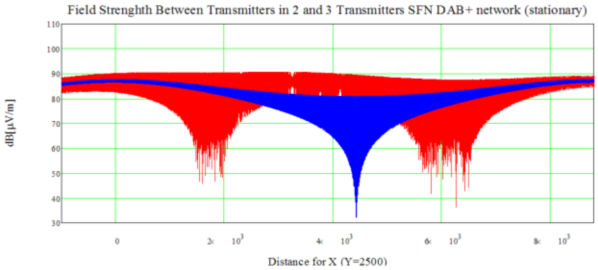


Fig. 13. Electric field strength level from two and three transmitters for a route with Y = 2500 m (stationary reception); analysis for Δx = 0.05 m).

The course of the electric field strength along the route running through the centre of the area delimited by the vertices of the triangle is shown in Figure 13. In this case, the trends described earlier are even stronger. In the middle area of the route in the network with three working transmitters, the level of loss decreases to about 10 dB, while in the case of two working transmitters it reaches in the narrow area to about 50 dB. It is also clear that the fade increases in areas near the line connecting the transmitters (PR) with (PWr) and (IL) with (PWr). It is caused by the dominant influence of signals from these transmitters and the weakening influence of the third transmitter due to the increasing distance to it.

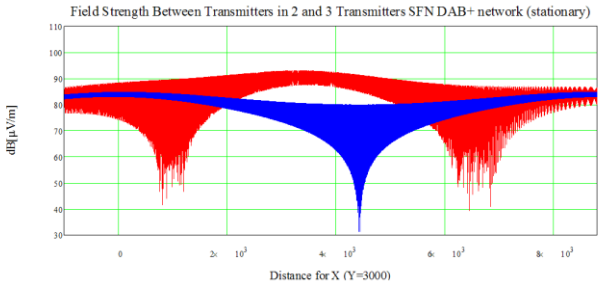


Fig. 14. Electric field strength level from three transmitters for a route with Y = 3000 m (stationary reception); analysis for Δx = 0.05m.

Further shifting towards the transmitter (PWr), i.e. for Y = 3000 m (Fig. 14) causes that the influence of this transmitter becomes dominant. Therefore, the level of fading in the central part of the triangle is further reduced to about 6 dB. When only two transmitters (PR and IL) are working, the loss level is about 50 dB. During the work of three transmitters, the dominant influence of the PWr transmitter in the central area begins to be noticed. For values near X = 1000 m and X = 6400 m, there is strong interference signal loss due to comparable levels of interfering signals from PR and PWr (X = 1000 m) and IL and PWr (X = 6400 m) transmitters. Their value reaches up to 50 dB. The comparable sizes of the two interfering signals are a consequence of comparable distances from these transmitters. The impact of the third signal on the depth of fading is very small due to the much greater distance to the analysed area.

Similar effects can be seen on the route at Y = 3500 m (Fig. 15). As before, the fading reaches 50 dB at the ends of the route and is caused by the same reasons. Because this route in its central part runs closer to the PWr transmitter than the route for Y = 3000m, therefore the influence of the signal from this transmitter (PWr) becomes clearly visible, which reduces the level of interference loss to values below 5 dB.

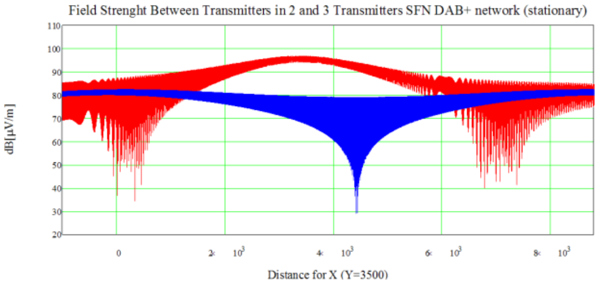


Fig. 15. Electric field strength level from three transmitters for a route with Y = 3500 m (stationary reception); analysis for Δx = 0.05m.

Further closer the analysed route to the PWr transmitter (Y = 4000 m) increases the dominant influence of the signal from this transmitter, which results in a further reduction of occurring losses (Fig. 16) in the middle section of the analysed route to about 2 dB. For this route, the central area is located near the PWr transmitter. The signal from this transmitter dominates. This causes that the level of interference fade is very small and does not exceed 2 dB. However, in the area to the left and right of the signal level graph there are very strong interference of two signals. On the left, signals from PWr and PR transmitters and on the right, from PWr and IL transmitters. One can also see a very strong interference exceeding 55 dB for X = 7900 m caused by equal distance from the PWr and IL transmitters, therefore also almost equal levels of interfering signals with insignificant influence of the third signal from the PR transmitter due to its significant distance from the analysed area. When the PWr transmitter is turned off, the deepest fades occur in the middle of the route and reach up to 60 dB, and their area of occurrence is very small.

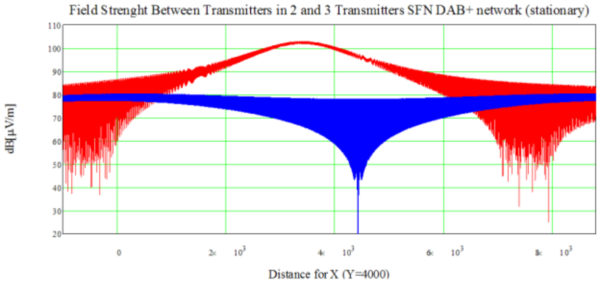


Fig. 16. Electric field strength level from three transmitters for a route with Y = 4000 m (stationary reception); analysis for Δx = 0.05m.

The electric field strength waveforms located outside the area of the triangle delimited by three vertices corresponding to the locations of the DAB+ co-phase transmitters can also be very interesting. The electric field strength was determined for two routes, one 1000 m (Y = -1000 m) below the line connecting the transmitters of the Polish Radio (PR) and the Institute of Communications (IL) and the other 1000 m away (Y = 6000 m) from the transmitter of the Wroclaw University of Technology (PWr). These routes are marked in Fig. 1.

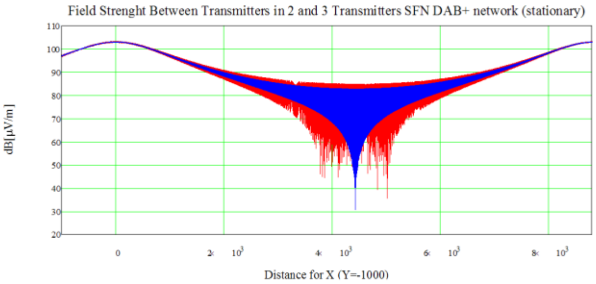


Fig. 17. Electric field strength level from two (blue) and three (red) transmitters for a route with Y = -1000 m (stationary reception); analysis for Δx = 0.05m.

For the route at a distance of Y = -1000 m (Fig. 17), as was to be expected, the area of strong interference occurs in the middle of the graph, in which two signals from PR and IL transmitters of comparable level interfere with a small, due to the distance, influence of the third signal from the PWr transmitter. Fade sizes reach up to 50 dB. At the ends of the route under consideration, one signal from the nearest transmitter begins to dominate and the amount of fading decreases to the value of few decibels.

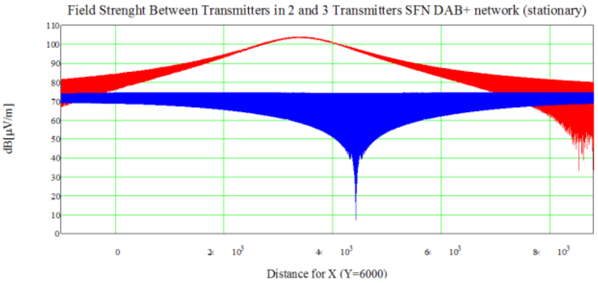


Fig. 18. Electric field strength level from two (blue) and three (red) transmitters for a route with Y = 6000 m (stationary reception); analysis for Δx = 0.05m.

We observe other situations for the route at a distance of Y = 6000 m (Fig. 18). In this case, only one signal from the nearest PWr transmitter dominates in the middle of the route. Signals from the other two transmitters are much weaker. In this area, the fades fall to below 1 dB. At the beginning and at the end of the analysed route (Fig. 18) interfering two strongest signals coming from the PWr and PR transmitters (beginning of the route) and the PWr and IL transmitters (end of the route), due to the leveling of signal levels associated with the equalizing distances from these transmitters, cause a significant increase in fading to values well above 10 dB.

VII. CONCLUSIONS

The interference analysis of three signals from DAB+ transmitters located in the vertices of the triangle shows strong fading in areas where the distance to two transmitters is comparable and the third is far away. This effect could have been expected. On the other hand, a fairly strong reduction in the size of the fades in the area of interference of three comparable signals in terms of signal level, thus the area located at similar distances from the three transmitters, is a surprising result of the analysis. In the case of Wrocław, this area coincides with the city centre.

The results of comparative analysis of fades occurring in a network with two and three transmitters show that the appearance of a third operating transmitter in a synchronized single-frequency network causes a decrease in the level of fading, in particular clearly visible in the area of the centre of the triangle designated by the vertices where the transmitters were located. The nature of the fades, their level and their locations are different in the network of two transmitters compared to the network of three transmitters located at the vertices of the triangle. Similar analyses can be made by calculating along routes parallel to the lines connecting the transmitters (PR) and (PWr) or (IL) and (PWr). The results obtained and the trends occurring in the distribution of fades will be the same.

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