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THE INFLUENCE OF PROPAGATION ENVIRONMENT ON THE ACCURACY OF EMISSION SOURCE BEARING

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Abstract

This paper focuses on the radio *direction finding* (DF) in multipath environments. Based on the measurement results presented in the open literature, the authors analyse the influence of environment transmission properties on the spread of the signal reception angle. Parameters that define these properties are rms delay and angle spreads. For these parameters, the mutual relationship is determined. This relationship is the basis for assessment of the required number of bearings that minimize the influence of the environment on the accuracy of DF procedure. In the presented analysis, the statistical properties of the signal reception angle are approximated by the normal distribution. The number of bearings versus the rms delay spread is presented as the main objective of this paper. In addition, a methodology of the bearings' spatial averaging that provides better estimation of the reception angle is shown.

Keywords: DF, methodology of bearing measurement, bearing accuracy, measurements in multipath environment, power azimuth spectrum.

1. Introduction

During execution of a radio *direction finding* (DF) procedure, the main causes of errors are:

– errors of the used DF method;
– practical implementation of the DF method;
– environmental interference – natural and industrial;
– movement of signal sources;
– phenomena associated with multipath propagation of radio waves in real environments.

In urban areas, the most important reason that limits use of the DF procedure is the multipath propagation of radio waves. In these cases, the radio DFs are performed in *non-line-of-sight* (NLOS) propagation conditions. This greatly enhances the impact of the multipath propagation phenomenon on the angular power spread of the received signals, which is a major cause of errors in procedures determining the direction of the electromagnetic wave source. Assessment of these errors is the basis for determining the error ellipse of the source location [1, 2]. Therefore, the problem of minimizing the environmental impact has a significant importance on the accuracy of DF procedures. In practice, many techniques are used to minimize errors of these procedures. To estimate the directions of the reception wave, the super-resolution techniques such as MUSIC [3–5], CLEAN [6], ESPRIT [7], SAGE [8], SPACE [9] are adopted. The complex procedures of digital signal processing (DSP) make it possible to obtain a high-resolution measurement of the *angle of arrival* (AOA). In addition to DSP techniques, the methods based on the antenna adaptive beamforming are used [4, 5, 10]. However, these techniques do not provide for elimination of multipath components of the wave which significantly impede determination of the direction to the source. Under these conditions, the

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spatial averaging the bearings is necessary in order to eliminate scattered components. This fact is described in [11].

This paper is devoted to assessment of the bearing error as a function of the propagation environment type whose properties are characterized by parameters defined on the basis of the radio channel *impulse response* (IR). The aim of this paper is evaluation of the required number of bearings that will provide the desired accuracy of the bearing in the multipath propagation conditions. In this case, for statistical representation of propagation conditions, the position change of the *direction-finder* (DFR) is always required. For a wide range of propagation environments, measurement results in the open literature are the basis for AOA analysis presented in this paper.

The results obtained by the authors are the basis for development of a methodology to determine successive locations, where bearings are used. It provides significant reduction in the influence of multipath propagation for radio DF errors.

The paper is organized as follows. Section 2 presents the rms delay spread as a fundamental criterion for the classification of propagation environment types. Use of the Gaussian *probability density function* (PDF) as the approximating PDF of AOA is shown in Section 3. Analysis of the number and methodology of space measurements is presented in Section 4. In conclusion, the practical possibility of quantitative evaluation of the bearing error in a multipath environment is emphasized as a result of the presented analysis.

2. Transmission properties of propagation environments

In terms of the radio signal transmission properties, the radio channel IR parameters are the basis for the propagation environment classification. The rms delay spread, σ_τ, is the fundamental criterion for the classification of propagation environment types [12]. This parameter is defined as the square root of the second-order moment of the *power delay spectrum* (PDS), P_τ, according to the relation:

$$\sigma_\tau = \sqrt{\frac{\int_0^\infty \tau^2 P(\tau)\,\mathrm{d}\tau}{\int_0^\infty P(\tau)\,\mathrm{d}\tau} - \left(\frac{\int_0^\infty \tau\, P(\tau)\,\mathrm{d}\tau}{\int_0^\infty P(\tau)\,\mathrm{d}\tau}\right)^2}\,. \tag{1}$$

This parameter can be interpreted as a multipath phenomenon intensity measure that is determined based on the time domain.

An example of propagation environment classification due to their transmission properties is standard COST 207 [13]. In this case, four propagation environment types: the *rural area* (RA), the typical *urban area* (TU), the *bad urban area* (BU), and the *hilly terrain* (HT) are distinguished. Each type has a different PDS represented by a discrete set of time delays and the corresponding powers. For individual types of the propagation environments, the criteria values of σ_τ are presented in Table 1.

Table 1. Classification of the radio propagation environments [13].

Type of the environment	RA	TU	BU	HT
Average σ_τ [µs]	0.1	1.0	2.5	5.0

The presented values are the measurement ranges that determine the classification of the environment types.

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The power azimuth spectrum (PAS) describes the reception directions of the received signal components. This characteristic represents the relationship between the power, $P(\theta)$, and AOA, θ, of the received signals. In this case, the reference direction ($\theta = 0$) is the direction determined by the locations of the signal source (transmitter, TX) and the receiver (RX). The measuring methodology of PAS is based on use of the antenna system that is capable of producing a spatially tuneable, narrow radiation pattern in the reception point. On the basis of PAS there is defined a parameter that represents a quantitative measure of the spatial dispersion of the received signal power. It is the azimuth angle spread, σ_θ, that is defined by the relationship, the form of which is similar to (1), namely:

$$\sigma_\theta = \sqrt{\frac{\int_{-180^\circ}^{180^\circ} \theta^2 P(\theta)\,\mathrm{d}\theta}{\int_{-180^\circ}^{180^\circ} P(\theta)\,\mathrm{d}\theta} - \left(\frac{\int_{-180^\circ}^{180^\circ} \theta P(\theta)\,\mathrm{d}\theta}{\int_{-180^\circ}^{180^\circ} P(\theta)\,\mathrm{d}\theta}\right)^2}. \tag{2}$$

This parameter can also be interpreted as an intensity measure of the multipath phenomenon. However, in contrast to σ_τ, this parameter is defined on the basis of the received signal spatial characteristic.

The above-stated parameters, σ_τ and σ_θ, are the basis for the intensity assessment of the multipath phenomena as a function of the propagation environment nature. Hence, for each environment, the error of the bearing is associated with σ_θ that has a specific value for each type of environment.

The assessment of the propagation environment's influence on the bearing errors is based on the measurement results of PAS and PDS that are presented in [14–17]. The described measurement scenarios and the empirical results have been obtained for different propagation environments. In [14, 15], the presented results were performed in RA near Bristol. The measurement results that are shown in [16] and [17] were made in Stockholm (Sweden), Aarhus, and Aalborg (Denmark). These environments are TUs. In all scenarios, the measurements were performed at the frequency of 1.8 GHz using broadband test signals. The signal sources used TXs with omnidirectional antennas that were installed on the vehicles (mobile stations – MS). The measurement RXs had a linear antenna array consisting of the half-wave dipole antennas. In the analysed publications, the presented PAS and PDS are the averaged measurement results that were obtained on different routes. For each measurement scenario, the average distances, D, between the route and RX antenna location are presented in Table 2. In this table, σ_τ and σ_θ are determined from the measurements of PDS and PAS, respectively. The remaining parameters are described in Section 3.

The obtained values of parameters are used for the linear approximation of the relationship between σ_τ and σ_θ. The base for this approximation is the least-squares method [18]. In this case, numerical calculation gives the following solution:

$$\sigma_\theta\left[^\circ\right] = 15.95 \cdot \sigma_\tau\left[\mu\mathrm{s}\right] + 0.94. \tag{3}$$

In [16], between these parameters, an analogous relationship is determined as a statistical analysis result of all partial measurements. In this case, the regression line is described by:

$$\sigma_\theta\left[^\circ\right] = 17.37 \cdot \sigma_\tau\left[\mu\mathrm{s}\right] + 2.08. \tag{4}$$

The graphs of (3) and (4) are shown in Fig. 1.

Table 2. The temporal and spatial power dissipation of the received signals for analysed measurement scenarios.

Measurement scenario	**Pedersen et al. [15] Fig. 1 (Bristol)**	**Pedersen et al. [16] Fig. 4 (Aarhus)**	**Pedersen et al. [16] Fig. 4 (Stockholm)**	**Mogensen et al. [17] Fig. 3 (Aalborg)**
Environment	RA	TU	TU	TU
D [m]	5000	1500	1500	2100
σ_τ [µs]	0.10	0.29	0.59	1.13
σ_θ [˚]	1.84	6.79	9.79	19.01
σ_G [˚]	1.06	4.19	7.95	5.93
$w = \sigma_G / \sigma_\theta$ [1]	0.58	0.62	0.81	0.31

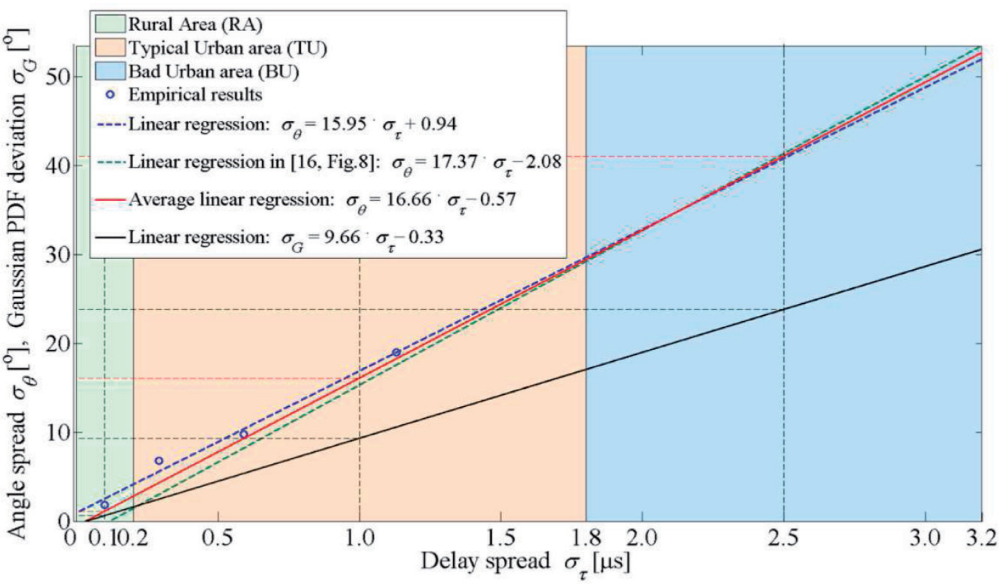

Fig. 1. The angle spread versus the rms delay spread for different propagation environments.

By averaging (3) and (4), the linear equation is obtained:

$$\sigma_\theta\left[{}^\circ\right] = 16.66 \cdot \sigma_\tau\left[\mu\mathrm{s}\right] + 0.57. \quad (5)$$

The above equations show a clear relationship between the received signal power dispersion in time and space domains. The (5) is taken into account for further analysis.

3. Approximation of measurement data

The empirical results and analysis of PAS measurements in different propagation environments are shown in [16]. One of the presented problems is verification of the Gaussian distribution hypothesis for AOA of the received signal. The obtained results of the statistical analysis show that for a confidence level larger than 0.83, this hypothesis is rejected. In practice, this result provides the basis for the use of the Gaussian PDF as the approximating PDF of AOA. A goodness-of-fit of the Gaussian PDF to the empirical dataset is the minimum of *least-squares error* (LSE), δ. This measure is defined as:

$$\delta = \frac{1}{K}\sum_{k=1}^{K}\left[f_m(\theta_k) - f_G(\theta_k)\right]^2 , \tag{6}$$

where: $f_m(\theta_k)$ (k = 1,..., K) denotes the normalized values from the empirical dataset, K refers to the cardinality of the set of measurement data, and $f_G(\theta_k)$ represents the values for the Gaussian PDF. For different propagation environments, the graphical comparisons of the measurement results and the Gaussian PDFs are shown in Fig. 2.

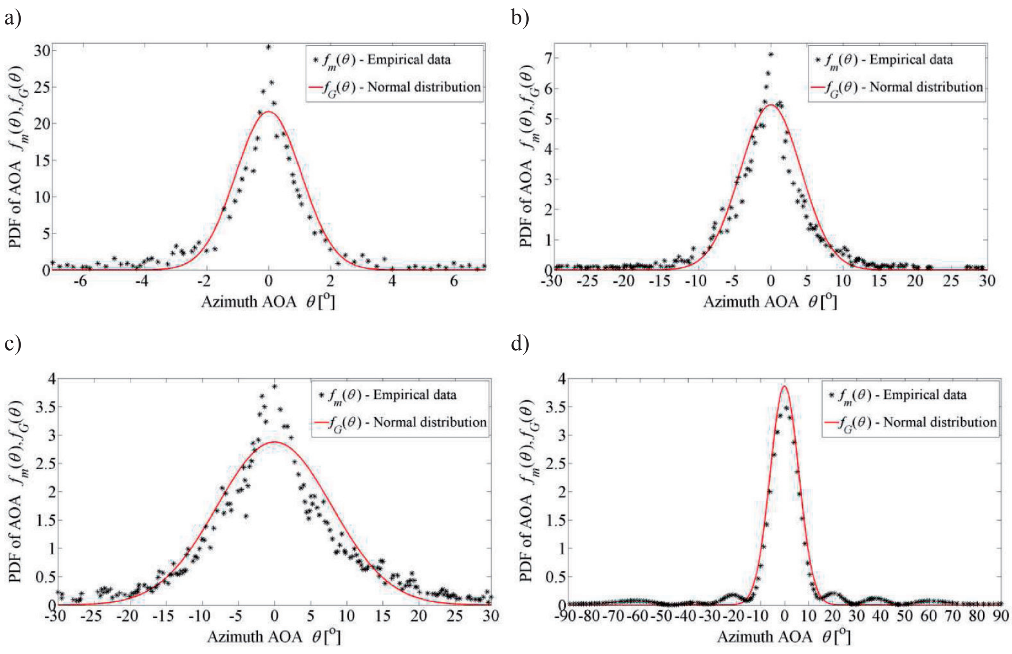

Fig. 2. The measurement results and approximating Gaussian PDFs for different scenarios: a) [15] Bristol; b) [16] Aarhus; c) [16] Stockholm; d) [17] Aalborg.

Approximation of measurements consists in selection of a Gaussian PDF deviation, σ_G, that will provide the minimum of LSE. For the analysed measurement scenario, the values of σ_G and σ_θ obtained from measurements are included in Table 2.

These data show that the analysed parameters are proportional. The averaged proportionality coefficient is $w_{\text{avg}} \cong 0.58$. On the basis of this coefficient and (5), the relationship between the propagation environment properties and the parameter that defines the approximating PDF of AOA is:

$$\sigma_G\left[^\circ\right] \cong w_{\text{avg}}\sigma_\theta = 9.66\cdot\sigma_\tau\left[\mu\text{s}\right]-0.33\,. \tag{7}$$

This relationship enables to assess the intensity of the received signal angular dispersion according to the transmission properties of the propagation environment.

4. Influence of the environment on the number of spatial measurements

The bearing θ_0 is the angle between the direction towards the emission source and the reference direction, usually the north direction. In real conditions, the bearing, $\tilde{\theta}$, is burdened with errors that arise from the finite accuracy of DFR and impact of the propagation environment:

$$\tilde{\theta} = \theta_0 + \Delta_0 + \Delta_e = \theta_0 + \tilde{\Delta}\,, \tag{8}$$

where: Δ_0 is a random variable that represents the DFR accuracy, Δ_e is a random variable that maps the errors related to the propagation environment, whereas $\tilde{\Delta} = \Delta_0 + \Delta_e$ is a random variable that represents the resultant error.

The basic model that reproduces the statistical properties of DFR is the Gaussian PDF [1, 2]. The rms DFR accuracy, σ_0, is one of the technical parameters of DFRs. Depending on the class of DFR, the σ_0 value is in the range from 0.2° to 5°. For description of AOA of signals to RX, use of the Gaussian PDF is shown in Section 3. In practice, Δ_0 and Δ_e are independent and the normal distribution describes their statistical properties. Thus, $\tilde{\Delta}$ is also a normal random variable where the standard deviation is $\tilde{\sigma} = \sigma_0 + \sigma_G$. This means that on the basis of N spatial measurements, the estimated bearing, $\tilde{\theta}$, is [19]:

$$\tilde{\theta} = \theta_0 + \frac{\tilde{\sigma}}{\sqrt{N}}z\,, \tag{9}$$

where: z is a normalized random variable with the normal distribution.

For specified errors of the first and second kind, the acceptance of a hypothesis that the bearing is θ_0 is related to the determination of $\tilde{\theta}$ variation interval. The boundaries of this interval are the basis for determining the desirable number of spatial measurements. For the error of the first kind, the lower bound of the interval is $\theta_0 + z_{1-\alpha/2}\tilde{\sigma}/\sqrt{N}$, where α is the significance level, and $z_{1-\alpha/2}$ is $\alpha/2$ order quantile of the normal distribution. If the discreteness of the bearing is Δ_θ, the upper bound for the error of the second kind is $\theta_0 + z_\beta\tilde{\sigma}/\sqrt{N} - \Delta_\theta$, where β is the probability of the second kind of error, and z_β is $1-\beta$ order quantile of the normal distribution. The lower and upper boundaries are equal, so:

$$\theta_0 + \frac{\tilde{\sigma}}{\sqrt{N}}z_{1-\alpha/2} = \theta_0 + \frac{\tilde{\sigma}}{\sqrt{N}}z_\beta - \Delta_\theta\,. \tag{10}$$

Because $z_{1-\alpha/2} = -z_{\alpha/2}$, from (10) we have:

$$z_{\alpha/2} = -z_\beta + \frac{\sqrt{N}}{\tilde{\sigma}}\Delta_\theta\,. \tag{11}$$

Hence, the desirable number of space measurements that provide errors of the first and second kind equal to α and β, respectively, is:

$$N = \left\lfloor \frac{\tilde{\sigma}^2 \left(z_{\alpha/2} + z_\beta \right)^2}{\Delta_\theta^2} \right\rfloor = \left\lfloor \frac{\left(\sigma_0 + 9.66 \cdot \sigma_\tau - 0.33\right)^2 \left(z_{\alpha/2} + z_\beta \right)^2}{\Delta_\theta^2} \right\rfloor . \tag{12}$$

For $\alpha = 0.1$, $\beta = 0.1$, $\Delta_\theta = 1.0^{\circ}$, and different σ_0, the desirable number of space measurements versus σ_τ is presented in Fig. 3.

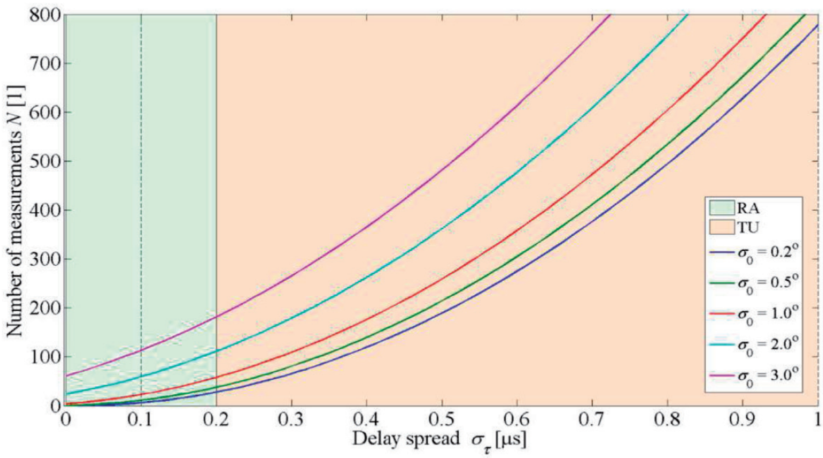

Fig. 3. The desirable number of space measurements versus σ_τ for $\alpha = 0.1$, $\beta = 0.1$, $\Delta_\theta = 1.0^{\circ}$, and different σ_0.

Analysis of the influence of the environment on the bearing accuracy is based on the measurement data that are obtained for statistically independent propagation conditions. This means that each measurement should be made in a different DFR position. The distance, d, between successive RX positions that determine the statistical independence of received signals, is presented in [20] as the so-called *Lee criterion*. This distance depends on the wavelength of the carrier, λ_0, and is $d = 40\lambda_0$. The average bearing that is obtained on the basis of successive measurements determines the direction of DFR movement. A method of determining the successive DFR positions is presented in Fig. 4.

Spatial structures that occur in the real measurement environment limit execution of a large number of bearings for different DFR positions. Thus, to minimize the error, increasing the number of bearings is conditioned by the spatial structure of the environment. In practice, this improving accuracy of bearing can only be used in poorly urbanized areas, such as RA and TU with small σ_τ . For typical parameters of RA and TU, the dispersion of bearing estimator, σ_B, versus the number of measurements is shown in Fig. 5. The parameter σ_B is defined as:

$$\sigma_B = \frac{\tilde{\sigma}}{\sqrt{N}} z_{\alpha/2} = \frac{\sigma_0 + 9.66 \cdot \sigma_\tau - 0.33}{\sqrt{N}} z_{\alpha/2} \, . \tag{13}$$

In Fig. 5, the number of measurements is selected for the RA and TU environments and for the probabilities of the first kind of errors that are equal to $\alpha = 0.1$. For the RA ($\sigma_\tau = 0.1$ μs), the dispersion of bearing equal to 2.69° is reduced to 0.85° for $N = 10$, whereas for the

TU (σ_τ = 0.1 μs), the dispersion decreases from 16.99º to 5.37º. This shows that the bearing accuracy significantly increases with *N*. However, the spatial structures that occur in the TUs limit the number of permissible DFR positions. In this case, the presented graphs are the basis for assessment of the bearing estimator dispersion.

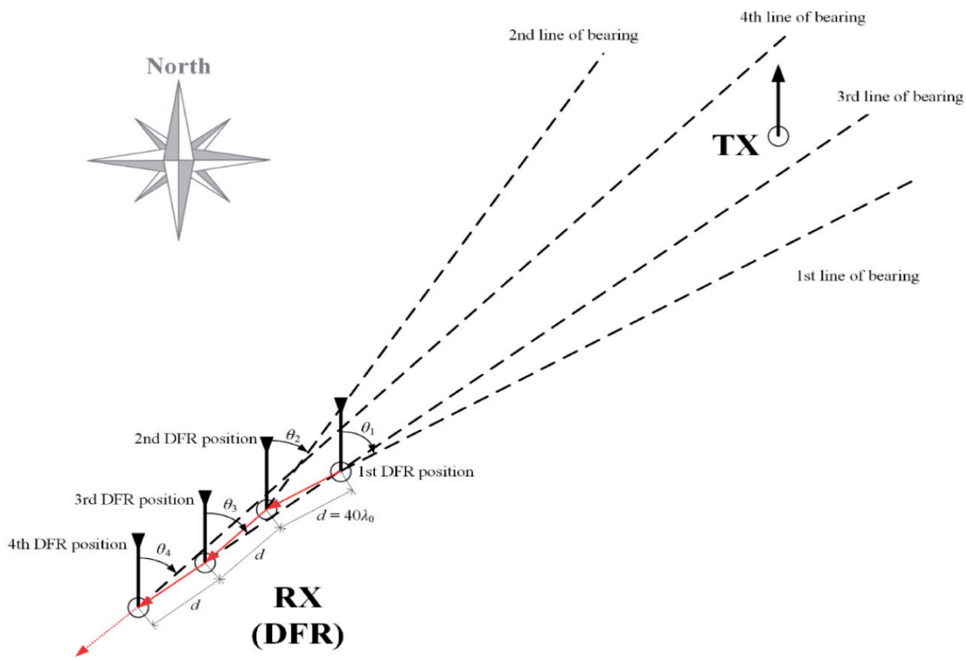

Fig. 4. A method of determining the successive DFR positions.

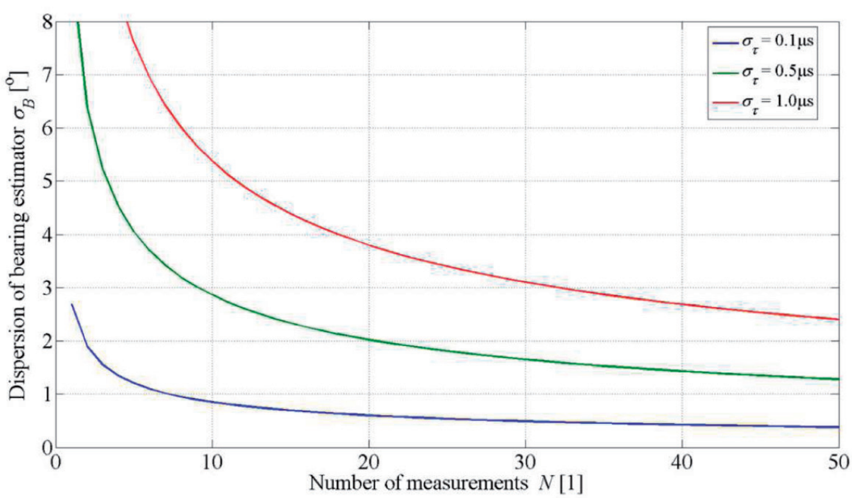

Fig. 5. The dispersion of bearing estimator versus the number of space measurements for α = 0.1, σ_0 = 1.0, and different σ_τ.

5. Conclusion

In this paper, the influence of the propagation environment on the accuracy of the bearing is presented. Evaluation of the environment transmission properties is based on σ_τ, whereas σ_θ describes the spatial properties of the received signals. The relationship between these parameters is obtained based on the measurement results that are presented in the open literature. This relationship shows that the bearing errors significantly increase with increasing urbanization degree of the propagation environment. The spread of the error can be reduced by the bearing estimation based on measurement results obtained for statistically different DFR positions. For the specified precision of bearing, the required number of DFR positions versus σ_τ is presented. Additionally, for typical σ_τ values that define the RA and TU environments, the effect of N on the dispersion of the bearing estimator is shown. In conclusion, it should be noted that the presented results can be applied in practice, as they give a possibility of quantitative evaluation of the bearing error in a multipath environment.

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