General design method for diversity antenna arrays

Keijo Nikoskinen, Juha Juntunen
Helsinki University of Technology, Institute of Radio Communications,
Electromagnetics Laboratory,
P.O.Box 3000, FIN-02015 HUT, Finland
phone: +358 9 451 2263, fax: +358 9 451 2267
e-mail: Keijo.Nikoskinen@hut.fi Juha.Juntunen@hut.fi

Abstract

Diversity reception is a widely used technique in radio communications to alleviate signal fading due to complex propagation environments such as downtown areas in large cities. This study concentrates on the design problem of an antenna array which can be used in a base station of a radio communication system to provide diversity. A design method for antenna arrays is introduced, which results in exactly the same power pattern but dissimilar phase patterns for the array. Radio signal reception using different phase pattern provides possibility to reduce destructive interference of incoming plane waves while the unchanging power pattern quarantees the fulfilment of original cell and network planning. The developed theory is rather general and can be applied for linear, planar and 3-dimensional array design. The well-known space diversity technique is shown to be a simple specific solution of the introduced method.

1 Introduction

There exist many techniques which can be utilized in order to reduce fading problem in mobile communication systems. This paper is focused on design method of diversity arrays that can be used as base station antennas in mobile telecommunication networks. Since the diversity is a property of a group of antenna elements rather than a single antenna element one can easily list the parameters allowing the existence of diversity reception: amplitude and phase excitations, physical locations and polarizations of the antenna elements. In the following analysis we neglect the polarization of the antenna elements and furthermore polarization diversity, because its implementation is quite straightforward procedure and does not seem to provide interesting prospects for further generalizations. Instead, the emphasis of the presented analysis is on phase diversity properties of antenna arrays. For every imaginable array geometry of two or more antenna elements, there are excitations which correspond to exactly the same amplitude

2 Theory

Let us study diversity properties of two similar antenna elements. In general the far-field radiation due to a two-element antenna array can be presented in the following form

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_0(\mathbf{r}) f_{\mathrm{AF}}(\theta) \tag{1}$$

where $\mathbf{E}_0(\mathbf{r})$ is the radiated electric field arising from the element located at the origin whereas $f_{\mathrm{AF}}(\theta)$ denotes the array factor of two similar antennas. It does not affect the polarization of the radiated field whereas it may have a great effect on the amplitude and phase properties of the array. For two-element arrays the array factor can be written as

$$f_{\mathrm{AF}}(\theta) = 1 + I_1 e^{j(kd_1 \cos\theta + \delta_1)} \tag{2}$$

where the first term is due to the antenna element at the origin and the second term corresponds to the other element whose excitation is determined by the current ratio I_1 and the phase difference coefficient δ_1 and is situated at a distance d_1 from the origin. k denotes the free space wave-number

$$k = \frac{2\pi}{\lambda_0} = \omega\sqrt{\epsilon_0 \mu_0} \tag{3}$$

The array factor has three freely choosable parameters which can be used when designing the radiation properties of the array. The current and phase differences are electrically tunable and the tuning can be adaptively implemented with a digital signal processor. The element separation d_1 is, in practice, a fixed constant, which however can be considered as a free parameter at the design stage of the array.

2.1 Radiation properties of a two-element array

The radiation pattern of the array is given by

$$|f_{\mathrm{AF}}(\theta)| = \sqrt{1 + 2I_1 \cos(kd_1 \cos\theta + \delta_1) + I_1^2} \tag{4}$$

which is proportional to electric field. The power-normalized pattern or the directivity function of the array can be expressed as

However, if two or more plane waves are received simultaneously the phase pattern of an antenna together with the power pattern determine how the complex sum of the incoming waves is formed. Two extreme cases are either a constructive or destructive combination of the incoming waves. Mobile telecommunication networks in densely built urban cities form a radio channel where base station antennas may receive hundreds of plane waves simultaneously due to the multipath propagation of radio waves. Furthermore, the base station reception and transmission should be nominally insensitive to the location of a mobile terminal which implies that the radiation pattern of a BS antenna should be relatively omnidirectional in the horizontal plane. This emphasizes the effect of the phase properties of an BS antenna in reception, but not in a strict deterministic way. The radio channel is changing temporarily due to dynamic variations in the overall path between the receiving and transmitting radio terminals. In practice, this fluctuation of the radio channel can not be completely compensated by changing the phase properties of a receiving BS antenna, since it would require arbitrarily tuneable phase pattern of the antenna, which cannot be implemented with an array of finite number of elements. However, if any changes in the phase-pattern of a BS antenna can be made, one has possibilities to compensate temporal variations of the radio channel by choosing between the multiple choices for the phase pattern. While keeping the radiation pattern of BS antenna constant its varying phase pattern can be used as a resource to achieve diversity reception to reduce fading effects of narrow bandwidth radio channels. Naturally, the radiation pattern could also be changed in order to achieve diversity but from the cellular network point of view this might cause problems, since the coverage areas of the base stations would also fluctuate in time. Diversity produced by changing the phase pattern is unconstrained from this drawback.

The technique for simultaneous reception of a mobile terminal transmission with different phase patterns is called *phase diversity* to distinguish it from other diversity schemes such as e.g. space diversity in which two relatively distant antennas are used to simultaneously receive two uplink signals whose fast fading components are dissimilar. The key issue here is to find antenna configurations whose phase properties could be controlled without any alteration in its power pattern. Since a single antenna has well-defined amplitude and phase properties, at least two similar antennas are needed for phase diversity reception. Let us study the normalized power pattern of a two-element array (5). If one substitutes the coefficient I_1 as

$$I_1 \rightarrow \frac{1}{I_1} \tag{7}$$

the shape of the radiation pattern remains exactly the same. Virtually this means simply that the real current coefficients of the antenna element are interchanged. However, when doing this, the phase pattern of the array is transformed into

$$\ldots \left(\frac{\sin(kd_1 \cos\theta + \delta_1)}{\ldots} \right) \tag{8}$$

2.2 Space diversity

Let us study two-element phase diversity in the specific case, where the ratio of the current coefficients tends to infinity. For the radiation and phase patterns one obtains

$$\lim_{I_1 \to 0} D(\theta) = 1, \quad \lim_{I_1 \to 0} \arg(f_{\mathrm{AF}}(\theta)) = 0 \tag{9}$$

and

$$\lim_{I_1 \to \infty} D(\theta) = 1, \quad \lim_{I_1 \to \infty} \arg(f_{\mathrm{AF}}(\theta)) = kd_1 \cos\theta + \delta_1 \tag{10}$$

Physically the limit $I_1 \to 0$ means that the element at the distance d_1 from the origin is switched off and the element at the origin is receiving alone. Its radiation and phase patterns are omnidirectional ones. The second case i.e. $I_1 \to \infty$ means that the element at the origin is switched off and the other element is receiving. Likewise in the previous situation its radiation pattern is omnidirectional. However, its phase properties with respect to the element at the origin are quite different due to the physical distance, d_1, from the phase center at the origin. These observations lead directly to the well-known space-diversity scheme, in which two antennas are separately used in reception to eliminate fading dips of radio signal. It is thus nothing but a special case of the phase diversity technique, where different phase patterns are produced by separate locations of antennas.

3 General diversity arrays

In the previous section mainly the phase diversity properties of a two-element antenna array were discussed. The element radiation properties were neglected since array properties are independent of element characteristics. However, if the elements themselves are arrays having diversity properties i.e. a diversity array is embedded into a diversity array, one can find easily controllable antenna arrays whose diversity properties are far more versatile than that of a two-element array. One can easily construct linear, planar or full 3D-arrays whose phase properties can be changed in a relatively simple fashion. The element spacing needs not to be constant as is shown in the next section.

3.1 4-element linear diversity array

The array factor of a four-element diversity array consisting of two subarrays each having two elements can be written as result in exactly the same normalized radiation pattern. These are found by selecting I_1 from $\{a_1, a_1^{-1}\}$ and I_2 from $\{a_2, a_2^{-1}\}$ where a_1 and a_2 are assumed to be positive and greater than one i.e. $a_1, a_2 > 1$ without losing generality.

Hence, the normalized radiation pattern can be expressed as

$$D(\theta) = \frac{1}{A}(1 + 2I_1 \cos(kd_1 \cos\theta + \delta_1) + I_1^2)(1 + 2I_2 \cos(kd_2 \cos\theta + \delta_2) + I_2^2) \qquad (12)$$

where the normalization constant A is

$$A = (1 + I_1^2)(1 + I_2^2) + \frac{2I_1(1 + I_2^2)\cos\delta_1 \sin(kd_1)}{kd_1} + \frac{2I_2(1 + I_1^2)\cos\delta_2 \sin(kd_2)}{kd_2} +$$

$$\frac{2I_1 I_2 \cos(\delta_1 - \delta_2)\sin[k(d_1 - d_2)]}{k(d_1 - d_2)} + \frac{2I_1 I_2 \cos(\delta_1 + \delta_2)\sin[k(d_1 + d_2)]}{k(d_1 + d_2)} \qquad (13)$$

From the equation above it can be easily seen that the radiation pattern remains the same if either or both current excitation values I_1 or I_2 are inverted. The corresponding phase patterns are found from the equation

$$\arg(f_{\mathrm{AF}}(\theta)) =$$

$$\tan^{-1}\left(\frac{I_1 \sin(kd_1 \cos\theta + \delta_1) + I_2 \sin(kd_2 \cos\theta + \delta_2) + I_1 I_2 \sin(k(d_1 + d_2)\cos\theta + \delta_1 + \delta_2)}{1 + I_1 \cos(kd_1 \cos\theta + \delta_1) + I_2 \cos(kd_2 \cos\theta + \delta_2) + I_1 I_2 \cos(k(d_1 + d_2)\cos\theta + \delta_1 + \delta_2)}\right) \qquad (14)$$

by selecting values of I_1 and I_2 as explained above. The result contains two, three or four element space diversity as specific cases if the extreme cases of excitations $I_1 \to 0$ or ∞ and $I_2 \to 0$ or ∞ are investigated.

Figures 8 and 9 show the radiation and phase patterns of four-element linear diversity array, whose parameters are arbitrarily set to values $I_1 = 3$, $\delta_1 = 0$, $d_1 = 1.3\lambda$, $I_2 = 5$, $\delta_2 = 0$ and $d_2 = 0.5\lambda$.

3.2 2^N-element linear diversity array

In general a linear 2^N-element diversity array can be described by the array factor

$$f_{\mathrm{AF}}(\theta) = \prod^{N}(1 + I_n e^{j(kd_n \cos\theta + \delta_n)}), \qquad (15)$$

$$\mathbf{I} = \{I_1, I_2, ...I_N\}, \quad \text{where } I_n = a_n \text{ or } I_n = a_n^{-1} \text{ for all } n \tag{17}$$

In the general case there are 2^N different excitation vectors $\mathbf{I}_n$ for the array.

By simple expansion of the array factor it becomes obvious that it is realizable with a linear array, whose

- current excitations are: $\{1, I_1, I_2, ..., I_N, \underset{n<m\leq N}{I_n I_m}, \underset{n<m<\ell\leq N}{I_n I_m I_\ell}, ..., I_1 I_2 ... I_N\}$
- phases are: $\{0, \delta_1, \delta_2, ..., \delta_N, \underset{n<m\leq N}{\delta_n + \delta_m}, ..., \underset{n<m<\ell\leq N}{\delta_n + \delta_m + \delta_\ell}, ..., \delta_1 + \delta_2 + ...\delta_N\}$
- antenna element distances from the origin are:
  $\{0, d_1, d_2, ..., d_N, \underset{n<m\leq N}{d_n + d_m}, ..., \underset{n<m<\ell\leq N}{d_n + d_m + d_\ell}, ..., d_1 + d_2 + ...d_N\}$

3.3 Planar diversity array

Even more general approach for a diversity array can be presented, if the array elements are allowed to lie in a two-dimensional plane instead of the one-dimensional line discussed before. Two vectors are needed to determine a plane in three-dimensional space. Hence let us therefore define two unit vectors, $\mathbf{u}_1$ and $\mathbf{u}_2$, which specify the plane of a planar array. If diversity array elements may be placed freely to this plane, the radiation properties of an 2^N-element array can be described with the array factor

$$f_{\mathrm{AF}}(\mathbf{u}_r) = \prod_{n=1}^{N} (1 + I_n e^{j(k\mathbf{u}_r \cdot \rho_n + \delta_n)}), \tag{18}$$

which indicates that the true locations of the diversity array elements are given by sum combinations of vectors $\rho_n = \rho_{1n}\mathbf{u}_1 + \rho_{2n}\mathbf{u}_2$. Instead of a single angle as before, the array factor is now a function of unit vector $\mathbf{u}_r$, which points towards the observation point. In fact by expanding of the array factor it can be seen how it corresponds to an array, whose

- current and phase excitations are determined in the same way as in case of 2^N-element linear array
- antenna element locations are specified by:
  $\{0, \mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N, \underset{n<m\leq N}{\mathbf{r}_n + \mathbf{r}_m}, ..., \underset{n<m<\ell\leq N}{\mathbf{r}_n + \mathbf{r}_m + \mathbf{r}_\ell}, ..., \mathbf{r}_1 + \mathbf{r}_2 + ...\mathbf{r}_N\}$

Without losing much generality of the approach, one may limit the element placement to a correspond to the same radiation pattern but dissimilar phase patterns. These phase diversity excitations are attained by choosing M and L- component amplitude vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ so that

$$\mathbf{a}_1 = \{a_{11}, a_{12}, ...a_{1M}\}, \ \mathbf{a}_2 = \{a_{21}, a_{22}, ...a_{2L}\}, \quad \text{where } a_{1n}, a_{2n} > 1, \text{ for all n.} \tag{20}$$

After the values of the base vectors are known, the corresponding current excitation vectors are defined in the similar way as before such that

$$\mathbf{I}_1 = \{I_{11}, I_{12}, ...I_{1M}\}, \ \mathbf{I}_2 = \{I_{21}, I_{22}, ...I_{2L}\}, \quad \text{where } I_{mn} = a_{mn} \text{ or } I_{mn} = a_{mn}^{-1} \text{ for all m and n.} \tag{21}$$

By expansion of the separable parts of the array factor it can be observed how the grid-line locations are determined by the grid-spacing parameters d_{1m} and $d_{1\ell}$ in the similar way as it was presented for the linear array case.

3.4 3D diversity array

In general, array elements can be situated anywhere in three-dimensional space. The previously presented approach can be easily generalized to allow this by defining the geometrical space by a set of three orthonormal unit vectors: $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_3$. If diversity antenna elements can reside freely in this space, the radiation patterns of the array are obtained from the array factor

$$f_{\mathrm{AF}}(\mathbf{u}_r) = \prod_{n=1}^{N} \left[1 + I_n e^{j(k\mathbf{u}_r \cdot \mathbf{r}_n + \delta_n)}\right], \tag{22}$$

where the true antenna element locations are given in the respective way by sum combinations of vectors $\mathbf{r}_n = r_{1n}\mathbf{u}_1 + r_{2n}\mathbf{u}_2 + r_{3n}\mathbf{u}_3$ in arbitrary three-dimensional space. Analogically to the planar case, the array factor can be factorized, if the antenna elements are located in a grid with respect to some orthogonal unit vectors: $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_3$. Therefore the array factor for a 3D grid based diversity antenna of size 2^M x 2^L x 2^K $(N = M + L + K)$ reads

$$f_{\mathrm{AF}}(\mathbf{u}_r) = \prod_{m=1}^{M} \left[1 + I_{1m} e^{j(kd_{1m}\mathbf{u}_r \cdot \mathbf{u}_1 + \delta_{1m})}\right] \cdot \prod_{\ell=1}^{L} \left[1 + I_{2\ell} e^{j(kd_{2\ell}\mathbf{u}_r \cdot \mathbf{u}_2 + \delta_{2\ell}]}\right] \cdot \prod_{k=1}^{K} \left[1 + I_{3k} e^{j(kd_{3k}\mathbf{u}_r \cdot \mathbf{u}_3 + \delta_{3k}]}\right],$$

where the grid is defined by the distance paremeters d_{1m}, $d_{2\ell}$ and d_{3k}. The array has $3(M+L+K)$ arbitrary parameters, which can be used to yield up to 2^{M+L+K} phase diversity excitations. The phase diversity excitations can be obtained by choosing M, L and K- component base vectors $\mathbf{a}_1$, $\mathbf{a}_2$ and $\mathbf{a}_3$, which will be of the form

$$\mathbf{a}_1 = \{a_{11}, a_{12}, ...a_{1M}\}, \ \mathbf{a}_2 = \{a_{21}, a_{22}, ...a_{2L}\}, \ \mathbf{a}_3 = \{a_{31}, a_{32}, ...a_{3K}\},$$

to 2^N radiation patterns that are exactly the same while the corresponding phase patterns are dissimilar. The array has $2N+1$ freely choosable parameters - N current coefficients, N phase constants and the common element spacing d. If the element separation is allowed to vary, there are at most $3N$ free parameters while the element number is increased to 2^N.

The theory of linear diversity arrays was shown to be easily generalized for two and three dimensional arrays whose array factors can be factorized similarly as in the one-dimensional arrays.

The most natural application of this theory is in mobile telecommunications where diversity reception is needed especially in micro-cell and indoor environments. The use of diversity arrays provides possibility for realizing a simple but versatile means to alleviate problems arising from signal interference due to multipath propagation. However, this diversity scheme does not disturb the conventional network planning utilizing fixed radiation patterns. The widely used space diversity technique was shown to be a specific case of a two-element phase diversity.

Acknowledgment

This study was partially supported by Nokia Foundation.

References

[1] R.G. Vaughan, J.B. Andersen, "Antenna Diversity in Mobile Communications," *IEEE Trans. Veh. Technol.,* vol. VT-36, no. 4, pp. 149 – 172, 1987.

[2] P. Eggers, J. Toftgård, A. Oprea, "Antenna Systems for Base Station Diversity in Urban Small and Micro Cells," *IEEE J. Select. Areas Commun.,* vol. 11, no. 7, pp. 1046 – 1056, 1993.

[3] A.M.D. Turkmani, A.A. Arowojolu, P.A. Jefford, C.J. Kellett, "An Experimental Evaluation of the Performance of Two-Branch Space and Polarization Diversity Schemes," *IEEE Trans. Veh. Technol.,* vol. 44, no. 2, pp. 318 – 326, 1995.

[4] J.J.A. Lempiäinen, K.I. Nikoskinen, J.O. Juntunen, "Multistate Phase Diversity Microcell Antenna," *Electronics Letters,* vol. 33., no. 6, pp. 438 – 440, 1997.

[5] J.O. Juntunen, K.I. Nikoskinen, K. Heiska, "Binomial Array as a Multistate Phase Diversity Antenna," *Helsinki Univ. Technol., Electromagnetics Lab. Rept. 255*, 1997. Submitted to *IEEE Trans. Veh. Technol.*

[6] D. Parsons, *The Mobile Radio Channel,* Pentech Press, 1992.

Figure captions

- **Figure 1.** A normalized field radiation pattern (linear scale) of a two-element array with parameters $I_1 = 4$, $\delta_1 = 0$ and $d_1 = 1.2\lambda$.
- **Figure 2.** Cosine of the phase patterns as function of θ corresponding to excitation in Figure 1.
- **Figure 3.** A normalized field radiation pattern of a four-element linear diversity array defined by parameters $I_1 = 3$, $\delta_1 = 0$, $d_1 = 1.3\lambda$, $I_2 = 5$, $\delta_2 = 0$ and $d_2 = 0.5\lambda$
- **Figure 4.** Cosine of the phase patterns as function of θ corresponding to excitation in Figure 3.

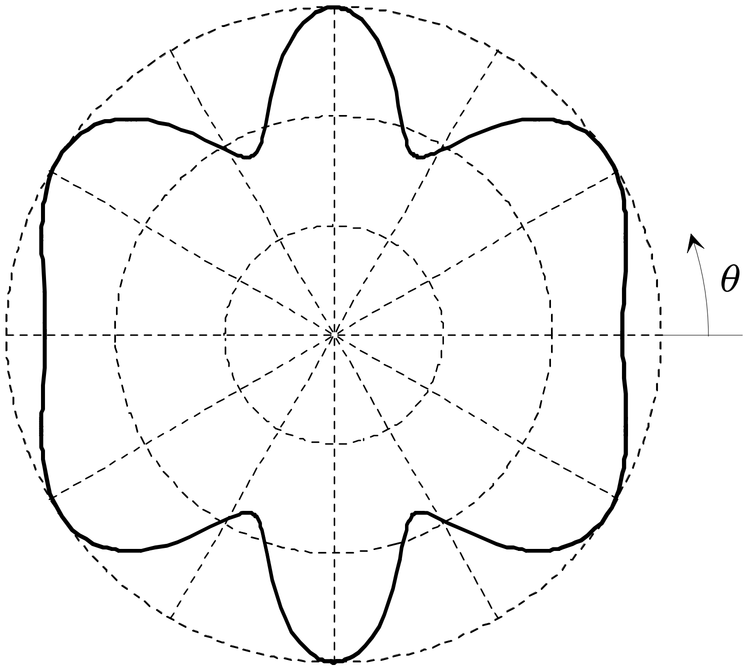
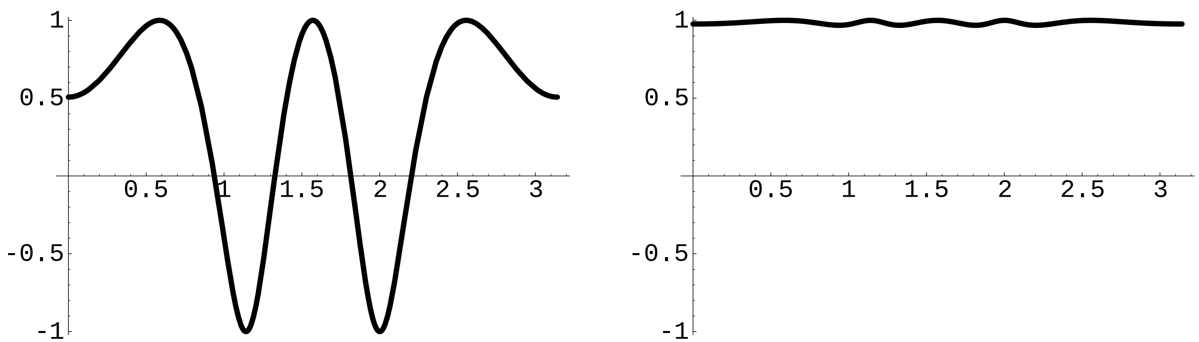


Figure 1.



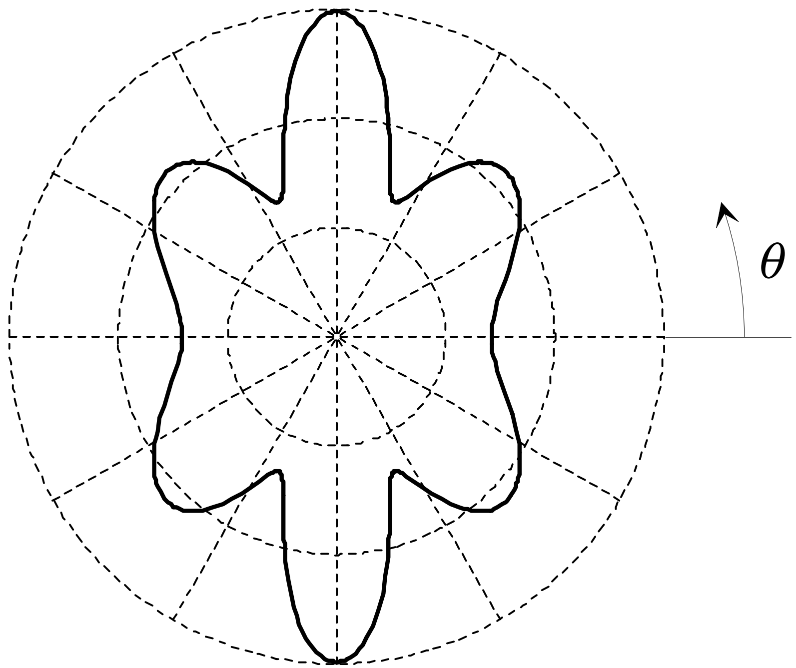


Figure 3.