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The Effects of Mutual Coupling on Performance of a Wideband Smart Antenna with Non-Uniform Components

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1. Introduction

With the rapid growth of various wireless services and applications calling for high data rate transmission there is a demand for developing robust wideband wireless technology. In order to counter count adverse phenomena such as multi-path signal propagation and interference, which become more pronounced in wideband systems, smart antennas can be employed as a remedy. So far, most of investigations have been devoted to narrowband smart antennas. Extending the smart antenna concept to wideband systems requires new research efforts. In the literature, three main concepts of wideband smart antenna system have been introduced, which include: space-time signal processing, space-frequency signal processing and fully spatial processing or space-only signal processing [1-3]. The advantages of the last wideband smart antenna concept are due to low complexity and low costs of practical realization. In [4-6], the authors proposed a wideband smart antenna using Non-Uniform Components (NUC). The investigations concerned the situation in which the mutual coupling between the array elements was neglected. In the present paper, we extend our considerations of the NUC wideband smart antenna system when the effect of mutual coupling between antenna elements is included. In particular, we investigate the mutual coupling effect on the radiation pattern and the signal-to-noise ratio (SNR). Comparisons are performed against a conventional uniform array antenna.

The reminder of this paper is organized as follows. In Section 2, the configuration of a NUC wideband smart antenna is briefly described. In section 3, suitable expressions are derived to investigate the effect of mutual coupling on the conventional and NUC arrays radiation pattern and the SNR of a received signal. Section 4 presents results of computer simulations. Section 5 provides the discussion of these results. Section 6 concludes the paper.

2. Wideband Smart Antenna using Non-Uniform Components

The core concept of a wideband smart antenna with Non-Uniform Components (NUC) relies on the use of array sets serving sub-bands in a wide frequency band (from f_l to f_h). This band is divided into R sub-bands with center frequencies given by a set ($f_0, f_1, \ldots, f_{R-1}$), where f_{R-1} is lower than f_{R-2}. As seen in Fig. 1, the NUC array is formed in one-dimension (1-D) by (N-1)R+1 elements, where N denotes a number of sub-arrays, R denotes a number of elements in each sub-array (which is called an array set), d_0 is the inter-element spacing in the array set of highest frequency, and Δx is the parameter related to the designed frequency band specified by the lowest frequency and the highest frequency [6]. As observed in Fig. 1, antenna elements are identified by two indices (n ,r), where $0 \le n \le N-1$ and $0 \le r \le R-1$. The inter-element spacing (d_r) in the r-th array set is chosen as half-wavelength of the designed frequency f_r from the set ($f_0, f_1, \ldots, f_{R-1}$).

Fig. 2 shows the 1-D NUC antenna array including signal weights and a summing network. In order to perform a fully spatial signal processing, the signal weights are chosen according to the scheme described in [6]. This scheme neglects mutual coupling between the NUC array elements. Fig. 3 shows the radiation pattern of the NUC array consisting of 14 sub-arrays and 10 array sets. The array operates in the frequency band from 1.61 to 2.69 GHz (WCDMA BlueTooth-band). In the presented simulation results it has been assumed that the array is formed by broadband antenna elements (each producing isotropic and frequency independent radiation pattern in azimuth) for which mutual coupling effects are neglected. We observe no noticeable variation in the gains of the antenna for the specified frequency band. As seen in Fig.3, the main beam of the antenna points to the desired direction of 30˚ throughout the entire frequency band.

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3. Mutual Coupling Effect on Wideband NUC Antenna Performance

To include the mutual coupling effect into the operation of the NUC wideband array antenna, we consider as an example a non-uniform linear array of M=(N-1)R+1 dipoles. By including the mutual coupling effect, the signals received by the individual elements of the array can be expressed in frequency domain by the following expression:

$$\mathbf{S}(f) = S_d \mathbf{C}(f)\mathbf{a}(\phi_d) + \mathbf{n}(f) \tag{1}$$

where S_d is an incoming signal, $\mathbf{n}(f)$ is a M×1 noise vector, $\mathbf{C}(f)$ is a M×M coupling matrix and $\mathbf{a}(\phi)$ is a M×1 steering vector of the source coming from ϕ as given by $\mathbf{a}(\phi)=\exp[-jn\pi(\lambda_r/\lambda)\sin\phi]$. For the NUC wideband array, n and r are given by $<(M+1)/R>$ and $\{M/R\}-1$, respectively, where $<\cdot>$ and $\{\cdot\}$ denote the round towards minus infinity and the remainder after division, respectively. In the beamforming process, the optimum weight vector ($\mathbf{w}$) is applied to receive the maximum power from the ϕ direction. Therefore, including these weights the output signal of the array can be expressed as

$$y(f) = S_d \mathbf{w}\,\mathbf{C}(f)\mathbf{a}(\phi) + \mathbf{w}\,\mathbf{n}(f) \tag{2}$$

An expression for $\mathbf{w}$ for the NUC array has already been introduced in [6] and thus it is not repeated here. $\mathbf{C}(f)$ represents the coupling matrix as given by

$$\mathbf{C} = (Z_A + Z_T)(\mathbf{Z} + Z_T \mathbf{I}_M)^{-1} \tag{3}$$

where Z_A is the element's impedance in isolation, Z_T is the impedance of the measurement equipment at each element, $\mathbf{Z}$ is the mutual impedance matrix which results from the Schelkunoff and Friis formulas [7] and $\mathbf{I}_M$ is the identity matrix. Here, Z_T is chosen as the complex conjugate of Z_A to obtain an impedance match for maximum power transfer. The mutual coupling coefficients defined in (3) can be obtained from measurements or computer simulations (here we obtain them from computer simulations). Using expression (3) and a suitable definition, the signal-to-noise ratio (SNR) for a received signal can be derived and is given by

$$SNR = \frac{E\,[|S_d \mathbf{w}\,\mathbf{C}(f)\mathbf{a}(\phi)|^2]}{E\,[|\mathbf{w}\,\mathbf{n}(f)|^2]} \tag{4}$$

where E[·] is the expectation over bandwidth.

4. Simulation Results

In this paper, computer simulation results are presented to illustrate the influence of mutual coupling on performance of conventional (linear uniform) and NUC wideband array antennas. The parameters of interest include radiation pattern and signal-to-noise ratio (SNR). The assumed frequency band is defined by the center frequency of 2.4 GHz with the span of 1 GHz. For the NUC array, the half-wavelength dipoles are assumed to resonate at the center frequency of each sub-band.

Fig.4 shows the directional pattern of a conventional array consisting of 5 dipoles (spaced by half-wavelength), whose beam is to be pointed at 30° from broadside direction at 2.4GHz. In this case, the dipoles are assumed to be identical and resonating at 2.4GHz. The presented results concern two cases, one without mutual coupling and the other with mutual coupling included in simulations. Fig.5 shows analogous results for the radiation pattern of an NUC wideband array antenna (R=3, N =5), obtained at 2.4 GHz for comparison purposes. As seen in Fig.4, for the conventional array of 5 dipoles, the mutual coupling affects the array beamforming ability. For example, the first side lobe level becomes comparable with the main lobe. This effect is less pronounced in the NUC array, as the sidelobes are only slightly affected by mutual coupling.

Fig. 6 and 7 show the results for SNR of the investigated antenna arrays. In simulations,

AWG (Additive White Gaussian) noise has been assumed and for SNR at center frequency (of 2.4 GHz) excluding mutual coupling effects, it was set at 0 dB. As seen in Fig. 6, without mutual coupling, SNR is decreased when the frequency bandwidth of the incoming signals is increased, except for the case of the NUC wideband smart antenna. The SNR of the conventional array decreases drastically when the signal bandwidth is increased from 0 to 1 GHz. The SNR of the NUC array antenna only slightly decreases throughout the designed frequency band. Fig. 7 shows the change of average SNR (dB/Hz) with respect to signal bandwidth. It can be noticed (the dashed line) that SNR is increased as the signal bandwidth is increased. The mutual coupling effect has larger impact for a larger bandwidth. When compared with the conventional array for the NUC array, the average SNR is increased only slightly when the bandwidth becomes large.

5. Conclusion

In this paper, the effect of mutual coupling between elements on performances of conventional and Non-Uniform Component (NUC) array antennas when they operate over a wide frequency band has been investigated. The parameters of concern have been a radiation pattern and a SNR. The investigations have been carried out via computer simulations. It has been shown that the mutual coupling considerably affects a conventional array in terms of its beam forming ability and SNR. The NUC wideband array antenna is less prone to the adverse effects of mutual coupling.

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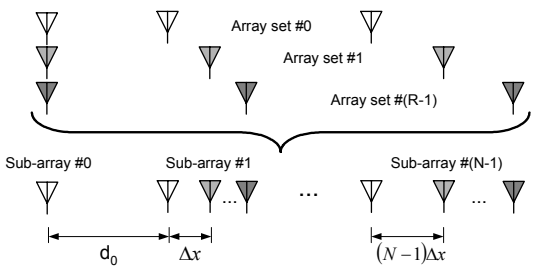

Fig. 1. NUC array antenna configuration.

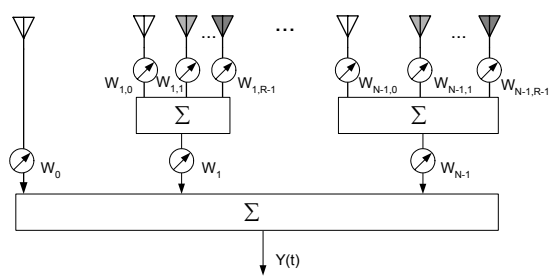

Fig. 2. NUC array including weighting and summing network.

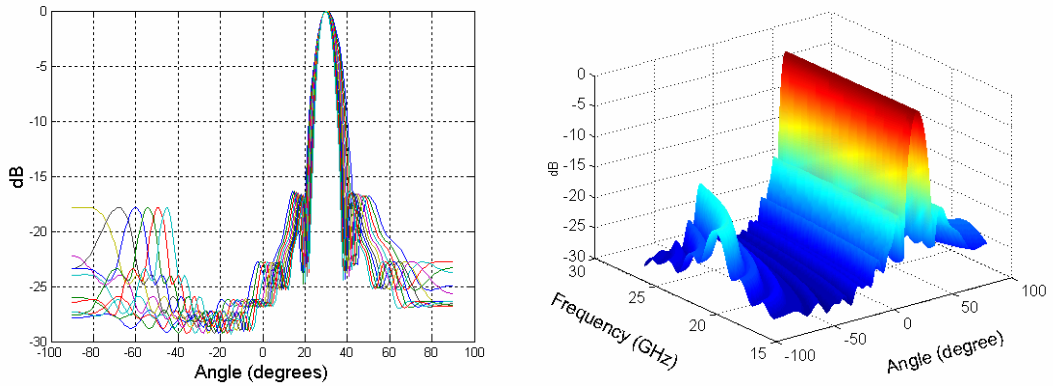

Fig. 3. Radiation pattern of the NUC array for frequencies from 1.61 to 2.69 GHz with 14 sub-arrays and 10 array sets. Mutual coupling effects being neglected.

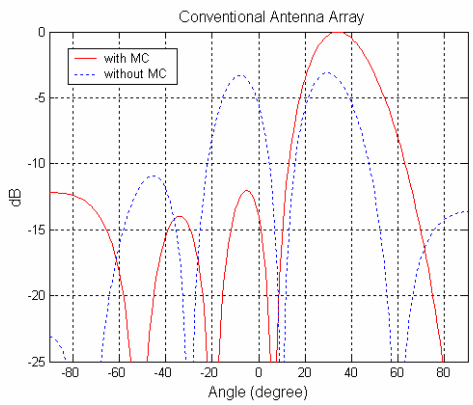

Fig. 4. Radiation pattern of a uniform array composed of 5 dipoles at 2.4 GHz.

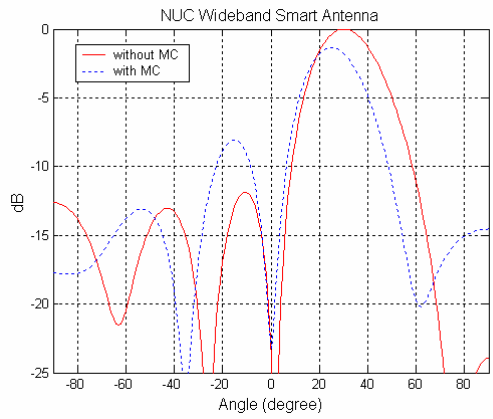

Fig. 5. Radiation pattern of a NUC array (half-wavelength dipoles: R=3, N=5) at 2.4 GHz.

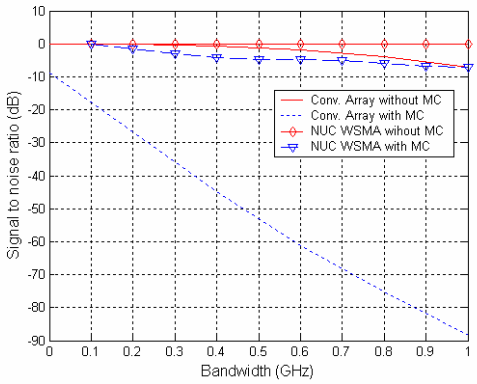

Fig. 6. The effect of mutual coupling (MC) on Signal-to-Noise ratio (dB) of a wideband smart antenna (WSMA) using conventional (Conv.) and NUC array technique for frequency of 2.4 GHz.

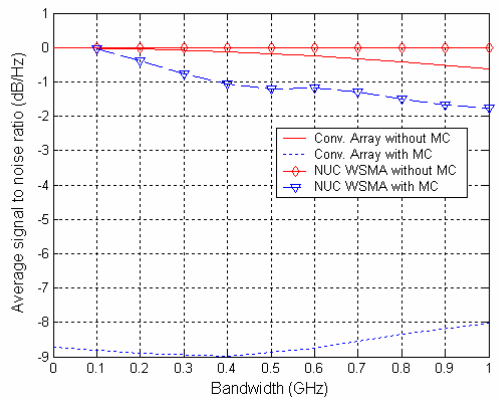

Fig. 7. The effect of mutual coupling (MC) on average signal-to-noise ratio (dB) of a wideband smart antenna (WSMA) using conventional (Conv.) and NUC array technique at frequency of 2.4 GHz.