Modal Diversity based on Modal Analysis for Antenna System Embedded into Television Receiver

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Abstract:

A novel approach to designing antenna systems for television receivers is proposed. The antenna system is embedded into the receiver to make the television receiver partly independent on the roof antenna system. For this purpose, it employs diversity techniques to cope with lower power ratios due to another form of propagation. For not to increase the manufacturing costs of the receiver, conducting structures inside the appliance can be exploited. It is accomplished by utilizing the method of characteristic modes (modal analysis) and using antenna elements as couplers. An example antenna is analyzed and the results are verified by the full-wave simulator.

INTRODUCTION

Terrestrial digital television broadcasting signal is assumed to be received by fixed or portable receivers. Broadcasting networks are planned with respect to the form of reception. Even if the network is planned for the fixed form of reception, there are regions where the field strength is sufficient for the portable reception. The fixed form of reception assumes the receiver to be connected to the antenna at roof level. Falling prices of television receivers make it possible to equip more rooms with a TV set than just those equipped with an antenna socket. Additional installation is a difficulty and even if present, connecting antenna input of the television receiver with the socket confines its location within the room. Using an indoor antenna instead is an aesthetical as well as technical complication too.

Integrating the antenna system into television receiver eliminates the need for connecting an external antenna. An integrated antenna system has to respect the characteristics of radio wave propagation in the radio channel where indoor reception occurs. On the other hand, not all the regions inside rooms are covered with signal of sufficient strength, so the television sets have to remain equipped with an antenna socket. Based on these facts, integrating the antenna system into the television receiver can provide an added value and competitive advantage. But nevertheless, because it cannot be utilized in all cases, the integrated antenna must not markedly increase the price of the appliance.

To fulfil all the above mentioned criteria, a novel approach to implementation of antenna system for digital television reception has been proposed. To add as little extra material as possible for not to significantly increase the volume occupied by the antenna and not to debit the manufacturing cost, multiple utilization of conductive structures is made possible. Embedding conductive structures into plastic parts (e.g. cases) is an alternative. Radiation occurs from these conductors, whereas the actual antenna elements are just coupling electromagnetic energy into them. Based on this fact, antenna elements need not possess dimensions electrically comparable to wavelength and thus, be resonant. As the conducting structures are primarily designed for other purposes than antenna system or, in the case of embedded conductors, the shape is to a great extent given by the shape of carrier, modal analysis is exploited to find the modes that can be excited. Moreover, the indoor reception suffers from a worse signal-to-noise ratio when compared to the fixed reception[1], and hence, diversity reception based on modal analysis is introduced into the proposed concept to compensate for the indoor power budget.

An approach toward integrating the antenna system into television receiver has been accomplished in [17]. A genetic algorithm is employed using a microcomputer to control a set of switching elements (relays). The antenna itself is a set of wires of varied shapes. The wires are connected in real time to maximize the signal quality at the antenna output. Nevertheless, this approach cannot provide multiple exploitation of existing conducting structures and does not provide the advantage of diversity reception.

[1] Indoor reception does not provide a line-of-sight path for propagation of electromagnetic waves. Because of multipath propagation due to reflections and no line-of-sight path employed, Rayleigh channel is an adequate model. Hence, the statistical nature of angles-of-arrival distribution prevents high-gain antennas from working effectively whereas utilizing diversity reception provides a diversity gain to the power budget.

THEORETICAL BACKGROUND

Modal Analysis

The theory of characteristic modes has been introduced in [7] and further expanded in [9]. It provides the total current excited on a conducting surface as a sum of eigenmodes. Based on the modal analysis, a clear physical insight of radiation of an arbitrary surface is obtained (as being emphasized in [10]). As the set of eigenmodes for the given structure is known, optimal location of feeding couplers can be determined. If there is more than one eigenmode in the investigated bandwidth, diversity techniques can be employed. Each eigenmode binds a radiation pattern. Diversity gain depends on the correlation of the particular radiation patterns and the aim is to find as many uncorrelated radiation patterns as possible. Effective diversity gain is influenced by the coupling efficiency which is taken into account. Thus, the form of diversity involved is the pattern diversity. As the particular patterns are derived from the eigenmodes, it is denoted as modal diversity here.[2]

Method of moments is a well-established numerical approach for obtaining the solution of antenna integral equation. The impedance matrix is found, and, based on the knowledge of excitation field, currents on the antenna structures are determined. But nevertheless, this method does not provide a clear physical insight into what currents can generally be excited on the antenna, how they can be excited and what is the frequency-dependent excitability of the particular currents. The currents excited on the antenna structure are a weighted sum of fundamental modes that relate directly to the impedance matrix of the antenna. The impedance matrix is obtained using the method of moments. The weighted coefficients depend on exciting field. The modal currents are eigensolutions of the eigenvalue equation. The eigenvalues describe the frequency dependency of eigencurrents. [7], [9]

There are applications of modal analysis for mobile-phone antennas. It has been found that as a consequence of miniaturization of mobile phones (and resultant miniaturization of their antenna systems), a substantial part of energy can be radiated from the chassis of the phones keeping the antenna element small [21]. By utilizing the modal analysis, radiation from the mobile-phone antenna systems can be optimized with respect to radiated power [1], [6], [18]. Another application of modal analysis is determination of radiation properties of antennas [4], [11].

Here, exploiting the modal analysis as a part of the proposed internal-antenna design process determines the set of characteristic modes that can be excited on the conductive structures inside the television receiver. Since the characteristic modes (characteristic currents) and their frequency dependence are known, the near field and the far field of the antenna can be evaluated. Based on the knowledge of electric field distribution in the vicinity of conducting structure, the optimal feeding location can be found.

In [1], one of the first applications of modal analysis towards mobile phone antenna design is carried out. The results of [21] saying that the chassis of the mobile phone is a substantial part of the antenna system are accepted and modal analysis is applied to the combination of antenna element and chassis to maximize the radiation efficiency of the antenna. In [6], using modal analysis, the bar-type and folder-type mobile-phone chassis structures are investigated to take the chassis into account as a radiating structure and not only in terms of an equivalent circuit. Similarly, in [18] the method of characteristic modes is employed to provide data about resonant behaviour of mobile phone chassis to optimally make use of it and place antenna coupling element.

Investigation of the behaviour of microstrip patch antenna using the analysis of characteristic modes has been done in [4]. It has been shown that this form of analysis provides a means for a quick understanding of the influence of the particular design properties on the radiation characteristics of the antenna. Another application of modal analysis is investigating the radiation properties of fractal antennas ([11]) which are cumbersome to be analyzed analytically and the straightforward numerical approach does not provide the full representation of currents that can be excited.

Using the method of characteristic modes [7], [9] for conducting bodies, a set of weighted, orthogonal modes of current distributions as well as radiation patterns in the far field can be obtained. It is based on operator equation in the form

$$\left[L(\mathbf{J}) - \mathbf{E}^{inc}\right]_t = 0 \qquad (1)$$

of tangential field components on the surface of conducting body S. Operator $L(\mathbf{J})$ describes the field strength due to the passing currents $\mathbf{J}$

$$L(\mathbf{J}) = \mathrm{j}\omega\mathbf{A}(\mathbf{J}) + \nabla\Phi(\mathbf{J}) \qquad (2)$$

where ω represents angular frequency, $\mathbf{A}$ vector potential [3] due to electric current and Φ scalar potential[4].

[2] Modal diversity has been employed in [13] where it is connected to higher modes in horn antennas.

[3] $\mathbf{A}(\mathbf{J}) = \mu \iint_S \mathbf{J}(\boldsymbol{r}')G(\boldsymbol{r},\boldsymbol{r}')dS'$, $\boldsymbol{r}$ corresponds to point of the field, $\boldsymbol{r}'$ represents point of the field source, μ is permeability.

In the physical sense, $L(\mathbf{J})$ represents the electric field strength $\mathbf{E}$ at arbitrary point in space as an impact of the current $\mathbf{J}$ on the surface S. The dimension of the operator L is the same as of impedance, and therefore follows

$$Z(\mathbf{J}) = [L(\mathbf{J})]_t. \tag{3}$$

From the reciprocity principle it follow that Z is a symmetric operator, and therefore it can be split into real Hermitian parts $Z = R + \mathrm{j}X$ where R and X are real symmetric operators. Moreover, R is positively definite[5] (all currents radiate some power).

To find the characteristic modes of a conducting body the following eigenvalue equation is to be solved

$$Z(\mathbf{J}_n) = \nu_n M(\mathbf{J}_n) \tag{4}$$

where ν are eigenvalues, $\mathbf{J}_n$ are eigenfunctions and M is a selected weighted operator. The choice of $M = R$ ensures that the eigenfunctions are real. Hence, the eigenvalue equation can be reformulated as

$$X(\mathbf{J}_n) = \lambda_n R(\mathbf{J}_n) \tag{5}$$

where $\lambda_n = -\mathrm{j}\cdot(\nu_n - 1)$.

Modal Diversity

To evaluate diversity properties of analysed structures, correlation coefficient can be employed. The received signals on two ports induce voltages in the receiver input circuits and the correlation coefficient is given as the correlation of the induced voltages. As the induced voltages directly relate to the field functions of the antenna system, the correlation coefficient can be (conditioned by uniform Rayleigh distribution) expressed as in [8] and [20]

$$\rho = \frac{\iint_{4\pi} \boldsymbol{F}_1(\theta,\varphi)\cdot \boldsymbol{F}_2^*(\theta,\varphi)\,\mathrm{d}\Omega}{\sqrt{\iint_{4\pi} \boldsymbol{F}_1(\theta,\varphi)\cdot \boldsymbol{F}_1^*(\theta,\varphi)\,\mathrm{d}\Omega \cdot \iint_{4\pi} \boldsymbol{F}_2(\theta,\varphi)\cdot \boldsymbol{F}_2^*(\theta,\varphi)\,\mathrm{d}\Omega}} \tag{6}$$

where $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ are the far-field functions of the particular multiport antenna.

It can be shown as in [2] that the envelope correlation coefficient can be obtained from the S-parameters representation of the given antenna system. No antenna diagrams are needed then and the influence of mutual couplings and input matching directly follow from the derived equation

$$\rho_e = \frac{\left|S_{11}^* S_{12} + S_{21}^* S_{22}\right|^2}{\left[1-\left(\left|S_{11}\right|^2 + \left|S_{21}\right|^2\right)\right]\left[1-\left(\left|S_{22}\right|^2 + \left|S_{12}\right|^2\right)\right]}. \tag{7}$$

The relation between particular expressions (6) and (7) of correlation coefficients can be obtained as

$$|\rho|^2 \approx \rho_e. \tag{8}$$

Again, this approximate equality (8) is valid under the condition of uniform Rayleigh field distribution. It should be emphasized here that ρ is the complex correlation coefficient whereas ρ_e describes envelope correlation coefficient. It is the reason for introducing the second power into (8).

A significant quantity for evaluating the performance of a diversity system is diversity gain (DG). It compares the signal-to-noise ratio (SNR) in the diversity system with SNR when only one radiator is employed as

$$DG\,[\mathrm{dB}] = \left\{\frac{S_c}{N_c}[\mathrm{dB}] - \frac{S_1}{N_1}[\mathrm{dB}]\right\} \tag{9}$$

where S_c/N_c is the SNR obtained by diversity reception and S_1/N_1 describes the SNR without employing the diversity reception. The ratios as well as the diversity gain can be considered to be statistical quantities and characterized by the cumulative probability function (CPF). It is usual to express the diversity gain for 1 % and 50 % (mean value) [20], [8].

There is an approximate formula to express the diversity gain for selection combining when the correlation coefficient is known as

$$DG_{app} = 10\cdot\eta_\rho \text{ with } \eta_\rho = \sqrt{1-|\rho|^2}\ ^{6} \tag{10}$$

where DG_{app} is apparent diversity gain (ADG), 10 is the maximum ADG obtained from selection combining for CPF of 1 %, η_ρ is the correlation efficiency.

Further, effective diversity gain (EDG) DG_{eff} can be expressed as

$$DG_{eff} = \eta_{tot}\cdot DG_{app} \tag{11}$$

where η_tot is the total efficiency of antenna element (including radiation and matching efficiency).

For electrically small systems, achieving a sufficiently negligible correlation between particular ports of a multiport antenna by employing only spatial diversity may not be possible. Nevertheless, as shown in [3], for angular (radiation pattern) diversity, it can be feasible for antennas separated by a fragment of wavelength.

[4] $\Phi(\mathbf{J}) = \frac{-1}{\mathrm{j}\omega\varepsilon}\iint_S \nabla\cdot\mathbf{J}(\boldsymbol{r}')G(\boldsymbol{r},\boldsymbol{r}')\mathrm{d}S'$, ε is permittivity and $G(\boldsymbol{r},\boldsymbol{r}') = \frac{\mathrm{e}^{-\mathrm{j}k|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}$ where $\boldsymbol{k}$ is wavenumber.

[5] It is condition by the fact that there is no resonant field inside the body.

[6] For correlation close to unity, ρ is multiplied by 0.99.

It is shown in [5] that to obtain a diversity gain of 7-10 dB with a 99% reliability, the correlation coefficient of particular radiators has to be below 0.7. This can be achieved for distance greater than 0.1 of wavelength. To present a more specific result, a diversity gain of 8-9 dB at the distance 0.1-0.15 of wavelength for non-line-of-sight propagation can be obtained.

Antenna Bandwidth and Matching Circuits

For electrically small antennas placed over conducting ground plane, it has been observed (as in [22]) that a substantial part of power radiated by the antenna is due to presence of the ground plane and existing coupling between the antenna element and the ground plane. If the antenna element is out of its resonance, only a small part of power is radiated by the element itself and the element performs as a coupler. It couples the power into the ground plane. The impedance bandwidth of the antenna is significantly dependent on the unloaded quality factor of the ground plane and on the position where the coupling element is placed. As is shown in [22], strong coupling between the current in the coupler and the field in the ground plane is required to obtain a large bandwidth. The coupling element should be positioned at the field maximum of the chassis wavemode.

Dual resonances are employed to obtain a greater bandwidth for a stacked patch antenna ([16]) or patch-chassis combination ([21]) utilizing optimal coupling between the radiators. The influence of the coupling between resonators is investigated. It is shown that the achievable bandwidth for an antenna system composed of two resonators is dependent on the coupling between resonators and resonant frequencies of the resonators. It is shown that even for a high-quality element out of resonance, a reasonable bandwidth can be achieved. The condition for it is a strong coupling between the resonators.

The concept of a non-resonant coupling element connected to a resonant chassis means that the antenna should be brought to resonance utilizing a matching network. There are several ways to match a complex load to given characteristic impedance, whereas a very comprehensive one is carried out in [15]. An application of matching techniques can be found in [23] where explicit formulas for obtaining the element values of the matching network are provided. A similar approach is utilized in [12]. The principle of impedance matching is based on the fact that a particular bandwidth can be set for a particular mismatch allowed for the circuit.

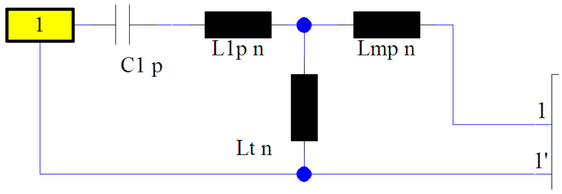

Fig. 1: Matching circuit for the embedded antenna system

APPLICATION OF MODAL ANALYSIS COMBINED WITH MODAL DIVERSITY FOR THE CONDUCTING STRUCTURES IN THE RECEIVER

Conducting structures are components of television receivers where they serve as electromagnetic shielding, ground planes or mechanical support. Conducting structures can also be realized as conformal surfaces to plastic parts. The shape is general and given by the original purpose but many structures possess dimensions comparable to wavelength. The structures can be exploited as antennas even if they had not been designed as antennas. Multiple utilization of conducting structures or inexpensive realization of conformal antennas provides the means for obtaining an integrated antenna without substantially increasing the manufacturing cost.

If based on the modal analysis of given structure, more than one mode can be excited, diversity reception can be considered.

ANTENNA ANALYSIS

For the analysis of conducting structures inside the television receiver, several scripts in MATLAB have been proposed, based on those provided by [14]. The basis functions implemented in the algorithm of method of moments are the RWG functions introduced in [19]. The impedance matrix of the structure is found and decomposed into characteristic modes by finding its eigenvalues and eigenfunctions. The eigenfunctions are the characteristic currents. The frequency dependence of particular eigenvalues can be depicted in a graph to evaluate which mode is resonant within the given bandwidth.

A measure suitable for graphic representation is characteristic angle α_n

$$\alpha_n = 180^{\circ} - \tan^{-1}(\lambda_n) \qquad (12)$$

which expresses the phase between characteristic current $\mathbf{J}_n$ and associated characteristic field $\mathbf{E}_n$. The value of 180° corresponds to zero reactive power and thus to resonance. For another representation of frequency dependence of characteristic modes, the modal significance MS_n can be defined as

$$MS_n = \left| \frac{1}{1 + j\lambda_n} \right|. \tag{13}$$

It represents the normalized amplitude of characteristic currents. As mode significance describes the frequency dependence of current amplitudes, the (e.g. 3dB) frequency bandwidth can be read from the graphic representation of it.

For the resonant modes, near field and far field are calculated. By evaluating antenna near field, it is possible to find the positions for optimal placing the coupling elements where maximal field strength occurs. By determining the particular far fields of characteristic modes, correlation coefficients are calculated to assess the diversity performance of the analyzed structure. From the knowledge of correlation coefficient, diversity gain and coupling losses are derived.

RESULTS

Analysis of a conducting structure has been carried out. The selected structure is composed of a narrow as well as a wide metal plate together to demonstrate both cases that can occur. The dimensions of the structure have been selected to correspond to the shape and size of an average rear cover of television receiver. The analyzed structure (together with some resonant characteristic modes) is depicted in Fig. 8.

First of all, nine modes closest to resonance in the given frequency band of 470-790 MHz have been selected. The resonant behaviour can be observed in Fig. 2, Fig. 3 and Fig. 4 where it can be seen that modes 1, 2, 3 and 7 are resonant within the given frequency band. These modes have been selected for the further analysis.

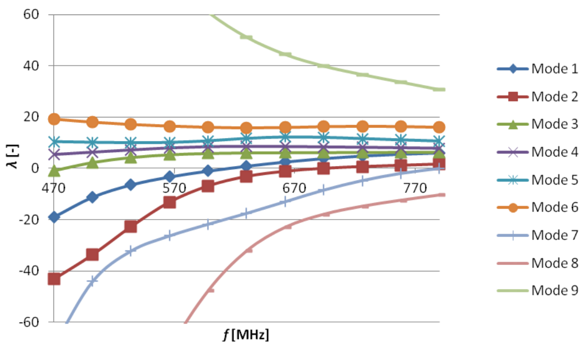

Fig. 2: Eigenvalues of particular characteristic modes depicted as a function of frequency

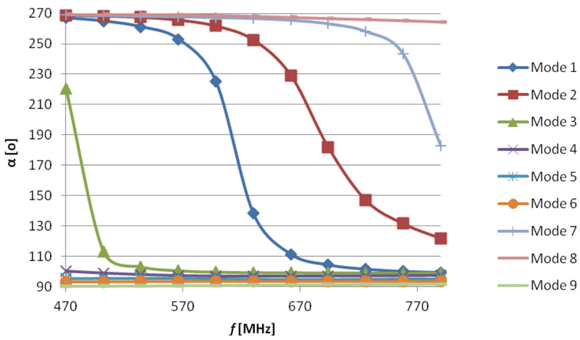

Fig. 3: Resonant behaviour of particular characteristic modes. The closer to 180° a characterictic mode is, the closer to resonance it is

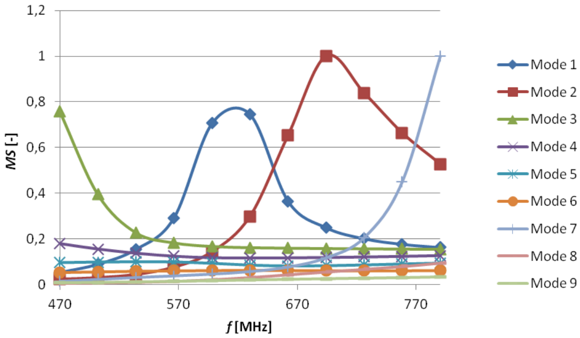

Fig. 4: Mode significance as o function of frequency for nine most significant characteristic modes

For all of the selected modes, current distribution has been obtained. Based on the surface current, near field and far field have been computed. From the calculated near field, positions of field maxima have been located. The far field data serve to evaluation of correlation coefficient.

In Tab. 1:, there are correlation coefficients evaluated for all combinations of port pairs. It can be seen that due to low values of correlation coefficients, the selected modes are suitable candidates for the diversity reception.

Tab. 1: Theoretical values of correlation coefficients for particular ports of the antenna

Port pair	***ρ_e [-]***
1-2	0.0013
1-3	0.0001
1-7	0.0028
2-3	0.0081
2-7	0.0040
3-7	0.0214

To prove the expected behaviour of antenna, a model in a full-wave electromagnetic field simulator CST Studio Suite of the given structure has been analyzed. The excitation of particular characteristic modes have been accomplished by a short antenna element (3 cm long) placed where field maxima occur.

The results of the antenna simulation using MATLAB scripts to find the characteristic modes and CST Studio Suite to evaluate whether particular modes have been excited can be seen in the following pictures. In Fig. 8, there are isolated characteristic currents obtained from the modal analysis. As juxtaposition, Fig. 9 depicts the current excited on the structure using antenna coupling elements where a field maximum occurs. It can be seen that the frequency for depicting the particular modes has been chosen to match with resonant frequencies of particular mode currents. Fig. 10 and Fig. 11 provide the two-dimensional and three-dimensional far fields of analyzed antenna structure, respectively. The former depicts field components, the latter polar diagrams. Fig. 12 is a depiction of far field pattern in Cartesian coordinates for the characteristic modes obtained from the modal analysis.

A very representative comparison is in Fig. 13. Two polar cuts of the far-field diagrams for each characteristic mode are depicted and courses for both results (from modal analysis as well as full-wave analysis) are brought into one diagram.

Finally, diversity performance of the simulated structure has been evaluated and depicted as Fig. 5, Fig. 6, and Fig. 7.

For impedance matching in the given bandwidth, matching circuit from Fig. 1 has been employed. The element values are C_1 = 0.76 pF, L_{1p} = 73 nH, L_t = 12 nH, and L_{mp} = 19 nH.

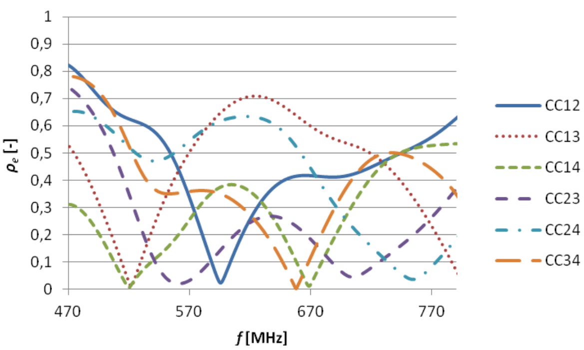

Fig. 5: Correlation coefficient as function of frequency for particular pairs of ports of the antenna

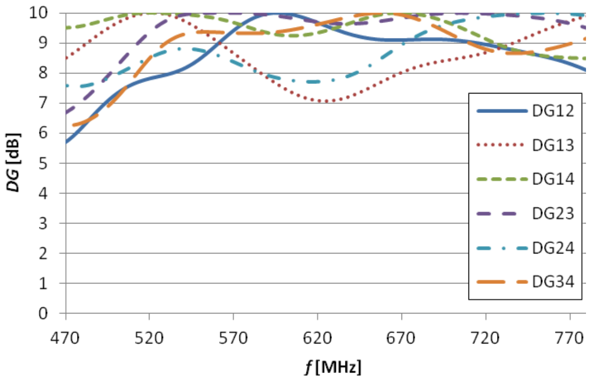

Fig. 6: Diversity gain as funcion of frequency when selection combining is employed

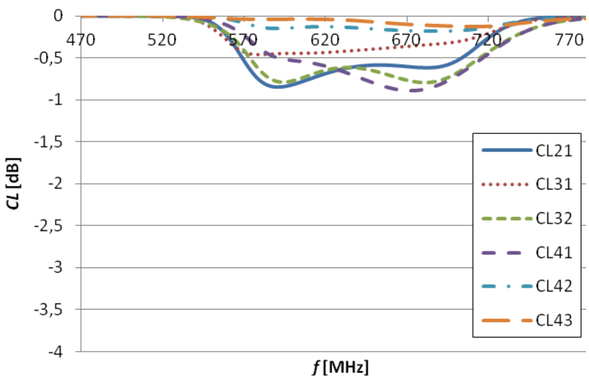

Fig. 7: Coupling losses due to coupling between particular port pairs as a function of frequency

DISCUSSION AND CONCLUSION

A novel method of antenna design has been proposed that provides the possibility of embedding the antenna system into television receiver without substantial increase of material costs during the manufacturing process but with a substantial increase of added value for the user of the appliance. To cope with unfavourable conditions during the indoor signal reception, diversity techniques are employed.

The actual antenna elements can be small compared to wavelength because their purpose above all is to couple the electromagnetic energy into electrically large conducting structure. The conducting structure can be an arbitrary electrically large structure inside the television receiver, such as shieldings, ground planes and mechanical supports. Eventually, conformal structures can be used.

By uniquely combining the method of characteristic modes with the pattern diversity technique (denoted as modal diversity in the paper), the antenna system of indoor reception is designed. The design technique starts with finding the resonant modes of given structure and the respective far-field diagrams. As a next step, correlation of far fields describes the potential of diversity reception for achieving a diversity gain. By determining near-field maxima of individual characteristic modes, optimal feed positions are found. Bandwidth optimization is carried out using impedance matching techniques.

As can be seen from the results, correlation coefficient lies below 0.7 for most port pairs and frequencies, so the proposed technique provides a means to cope with poor conditions of indoor reception modelled by Rayleigh channel.

In this paper, a novel attitude toward designing antennas for digital broadcasting receivers was proposed and a typical conductive structure was involved to demonstrate the design technique and evaluate this method by simulation. There is a future challenge of experimentally evaluating the method under real conditions and implementing it into the manufacturing process of television receivers.

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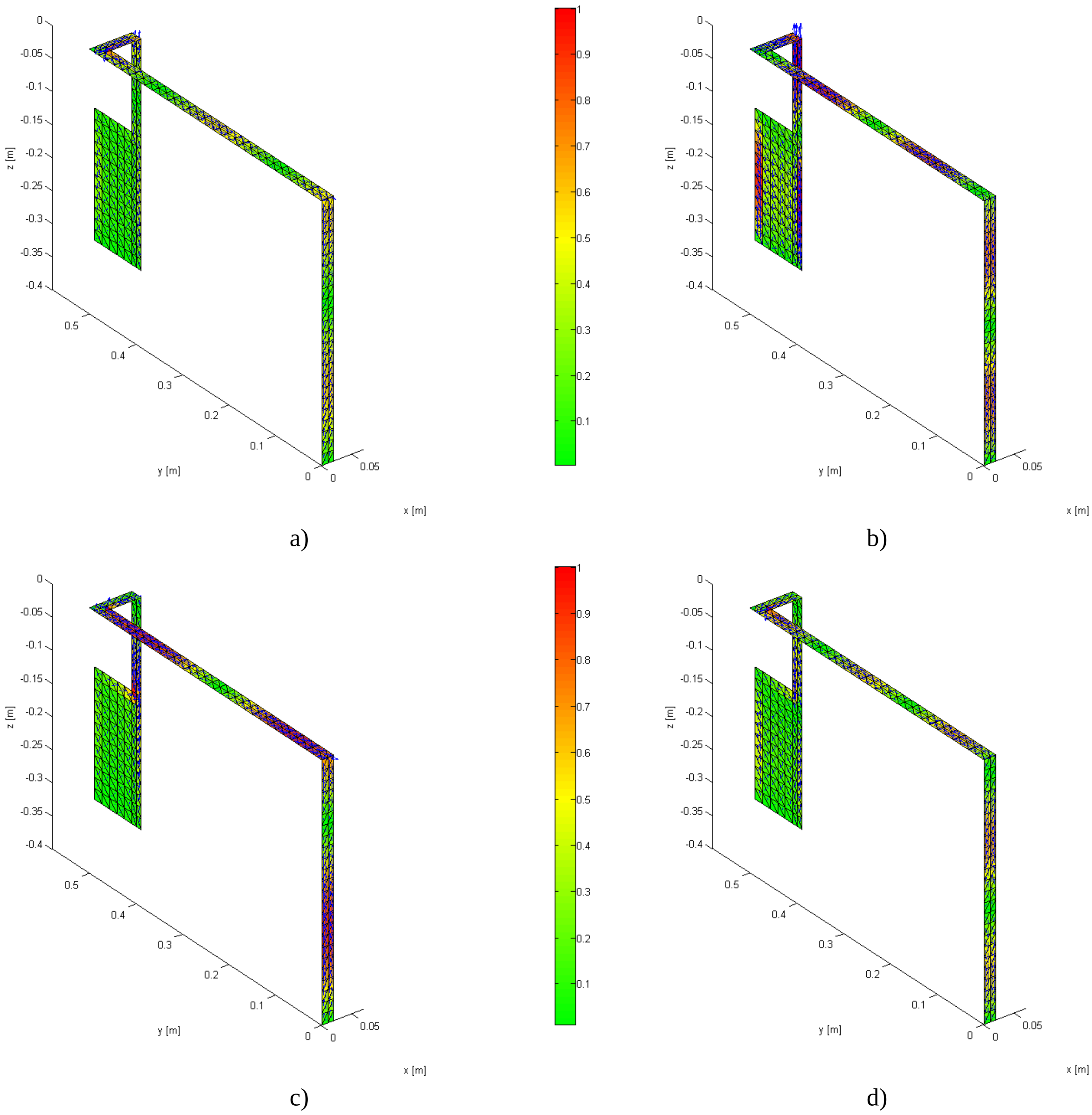


Fig. 8: Current distribution of the fundamental modes of the given structure. Only modes that are resonant within and near the frequency band 470-790 MHz are depicted. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz

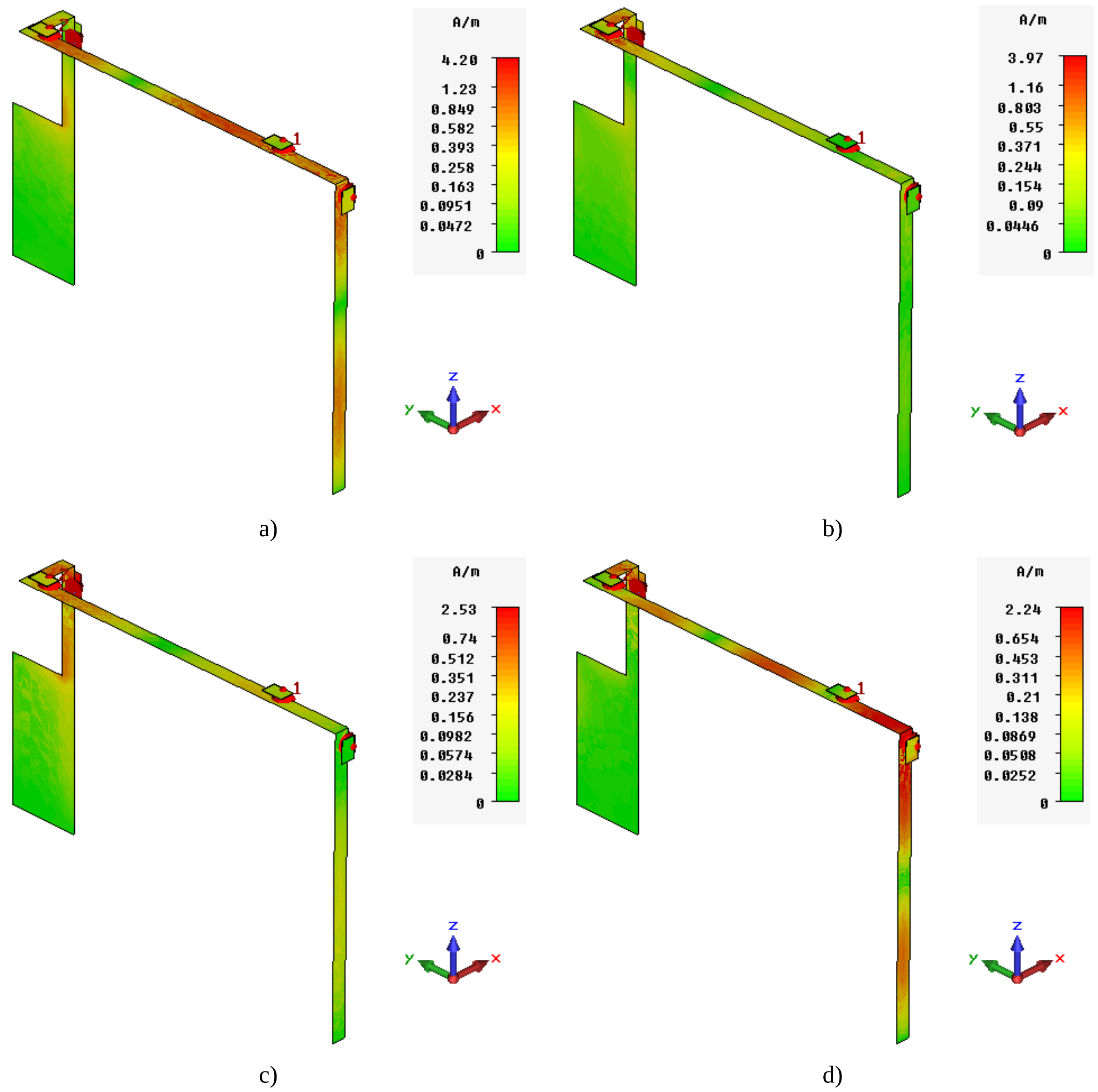
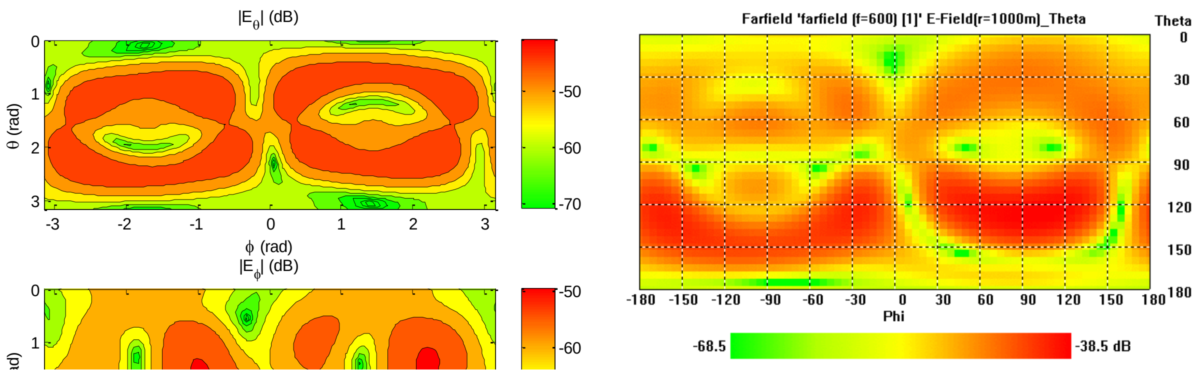
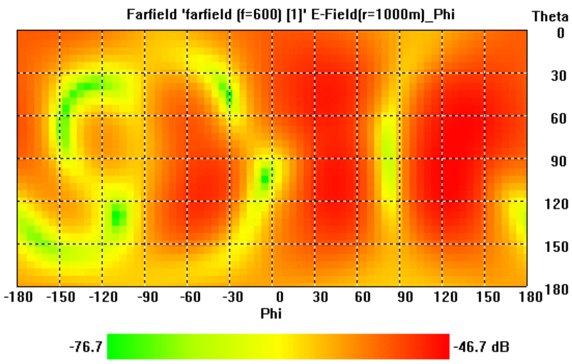
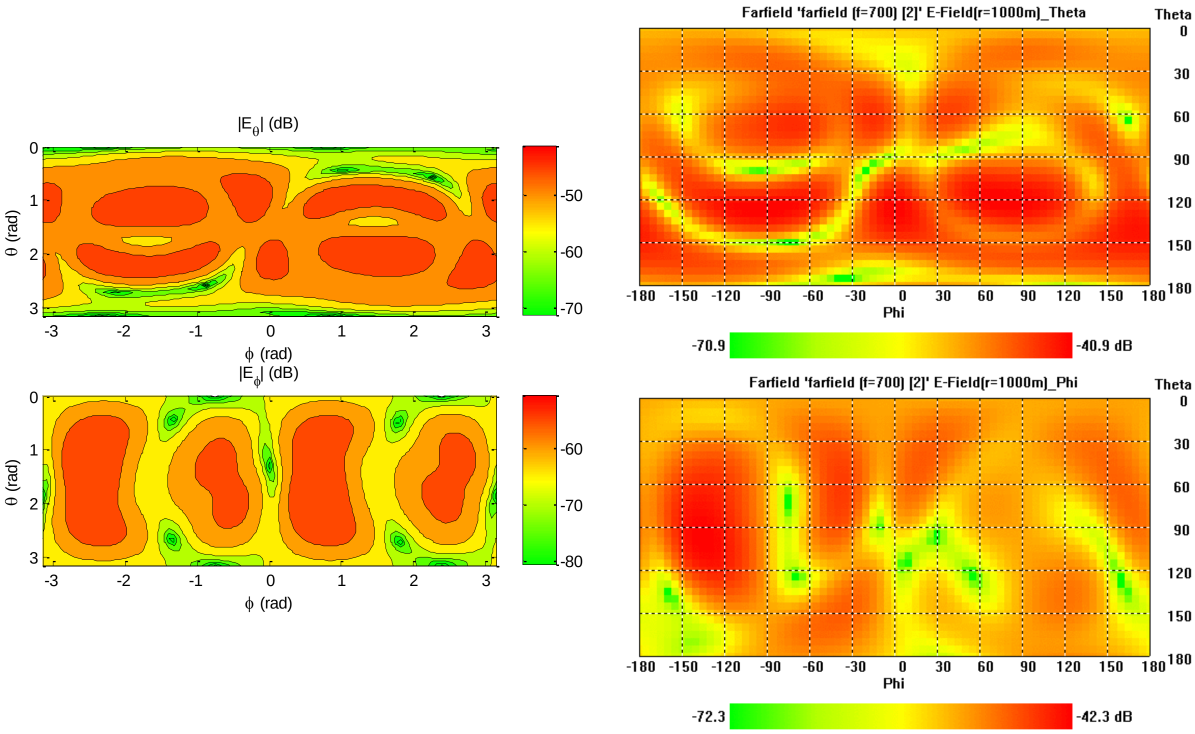


Fig. 9: Current distributions on the structure excited by coupling elements located where field maxima of particular characteristic modes occur. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz

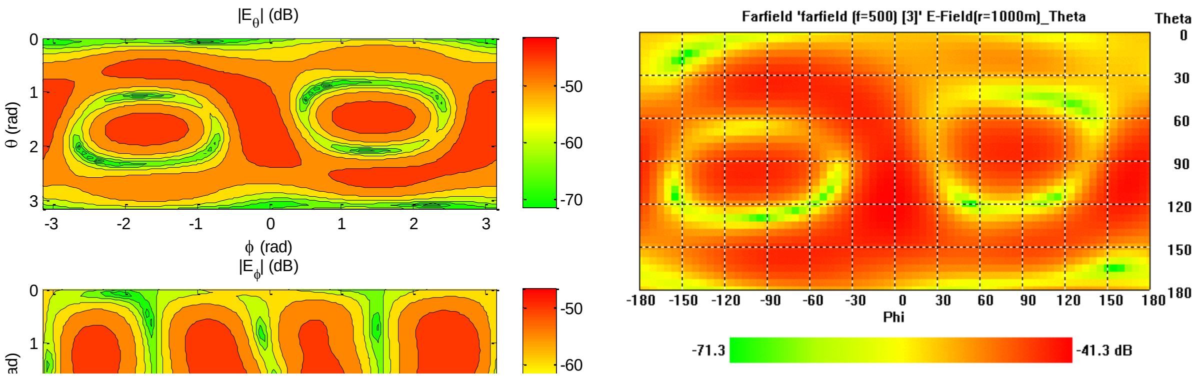


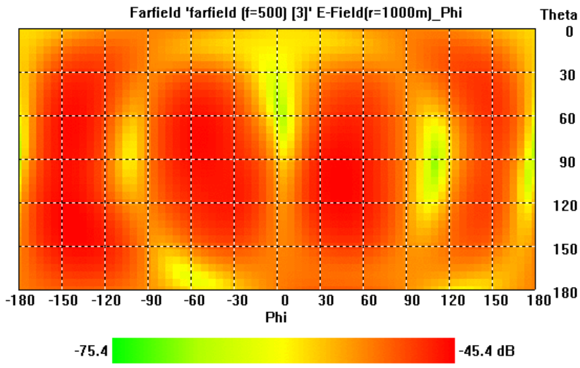

Farfield 'farfield (f=600) [1]' E-Field(r=1000m)_Phi
Theta
Phi
-76.7
-46.7 dB

a)

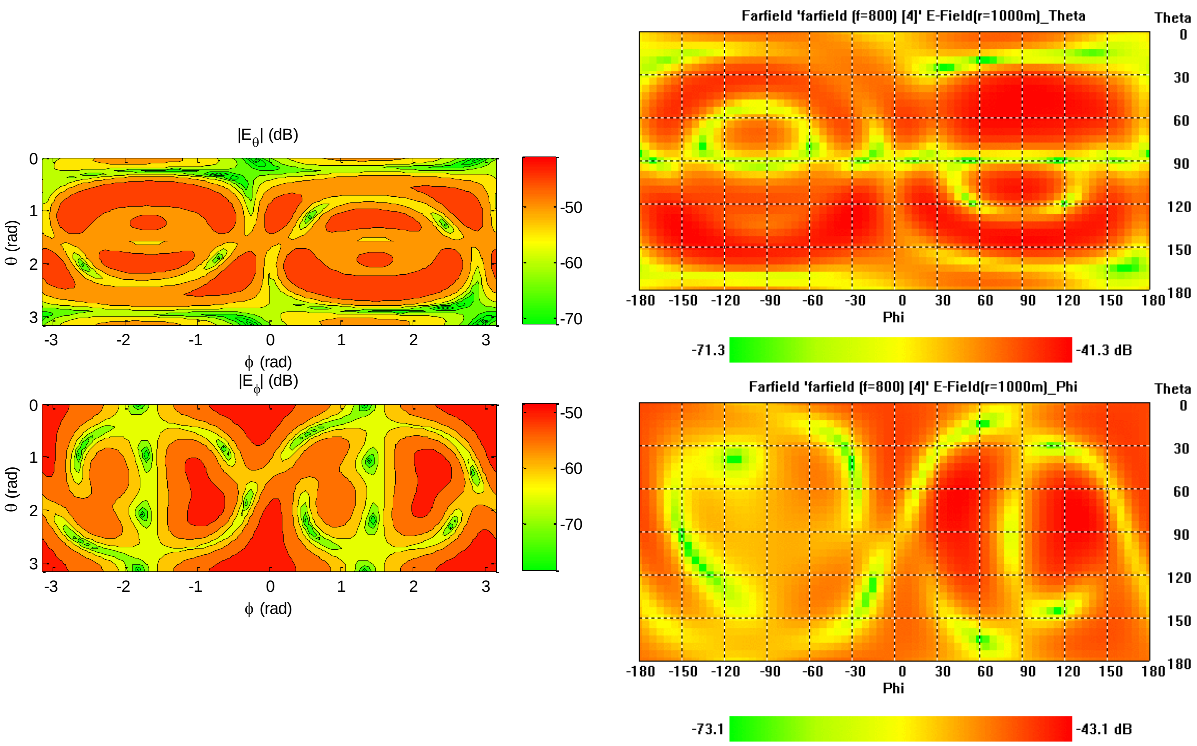

|E$_\theta$| (dB)
θ (rad)
ϕ (rad)
|E$_\phi$| (dB)
Farfield 'farfield (f=700) [2]' E-Field(r=1000m)_Theta
Theta
Phi
-70.9
-40.9 dB
Farfield 'farfield (f=700) [2]' E-Field(r=1000m)_Phi
-72.3
-42.3 dB

b)


|E$_\theta$| (dB)
θ (rad)
ϕ (rad)
|E$_\phi$| (dB)
Farfield 'farfield (f=500) [3]' E-Field(r=1000m)_Theta
Theta
Phi
-71.3
-41.3 dB

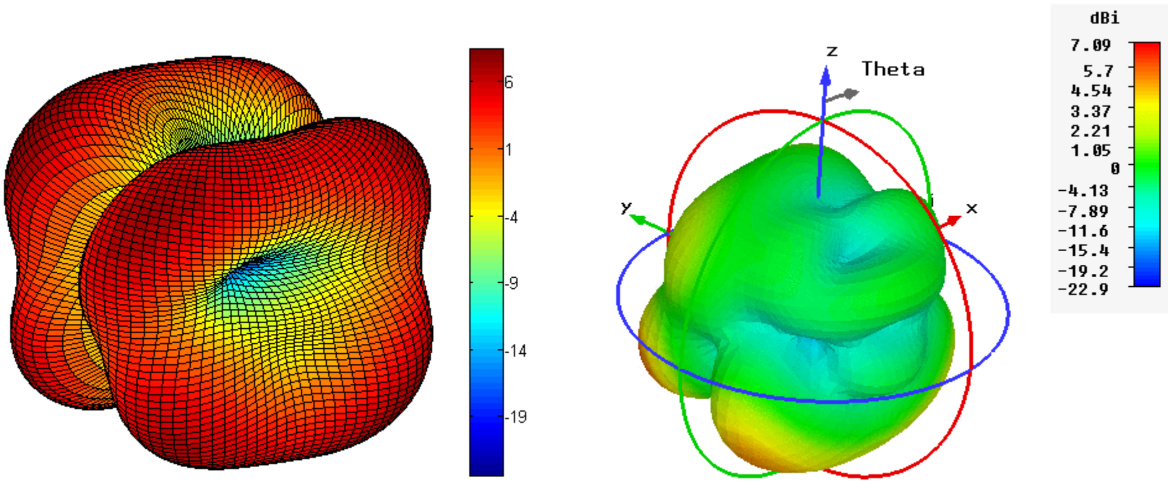


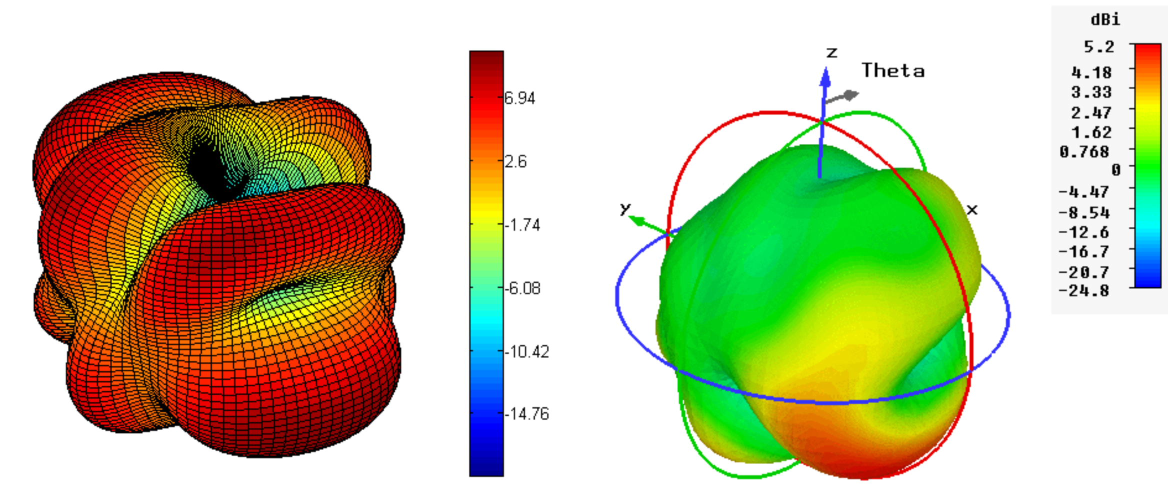
c)

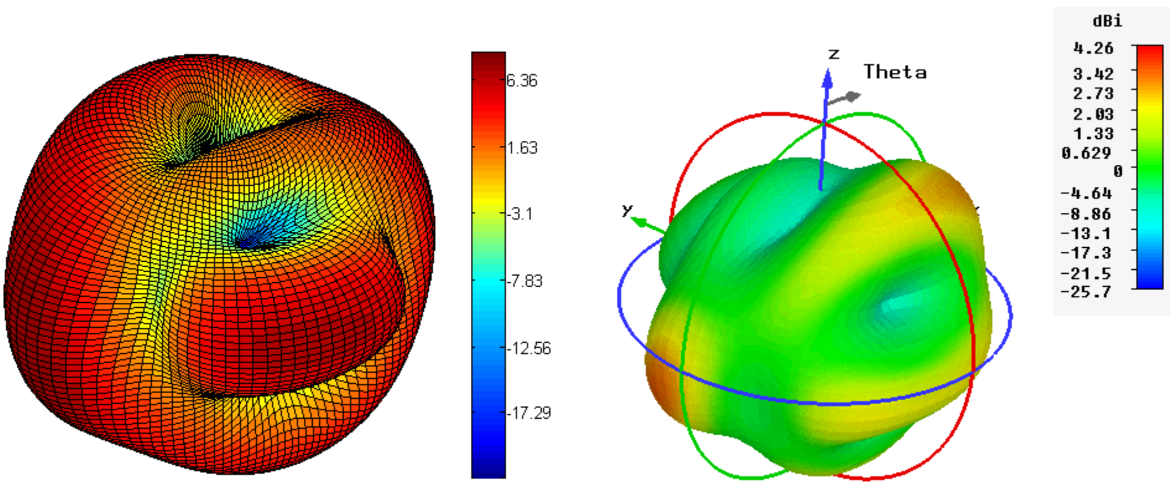


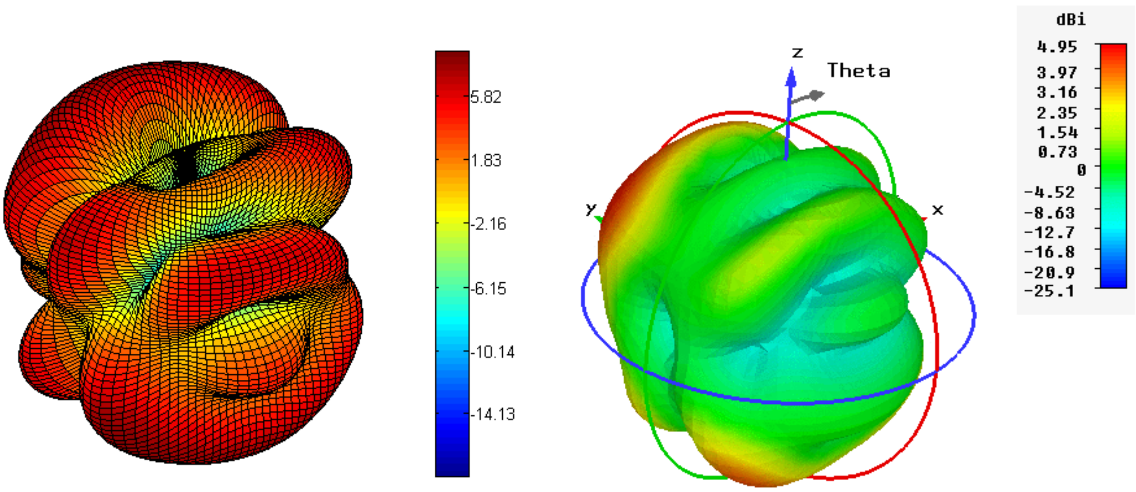
d)

Fig. 10: Comparison of particular field components in the far field depicted as two-dimensional diagrams. The far field of characteristic modes is in the left column, the actually radiated field in the right column. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz


6
1
-4
-9
-14
-19
z
Theta
y
x
dBi
7.09
5.7
4.54
3.37
2.21
1.05
0
-4.13
-7.89
-11.6
-15.4
-19.2
-22.9
a)


6.94
2.6
-1.74
-6.08
-10.42
-14.76
z
Theta
y
x
dBi
5.2
4.18
3.33
2.47
1.62
0.768
0
-4.47
-8.54
-12.6
-16.7
-20.7
-24.8
b)


6.36
1.63
-3.1
-7.83
-12.56
-17.29
z
Theta
y
dBi
4.26
3.42
2.73
2.03
1.33
0.629
0
-4.64
-8.86
-13.1
-17.3
-21.5
-25.7
c)



d)

Fig. 11: Three-dimensional polar radiation patterns for the particular characteristic modes. In the left column, ideal diagrams from the modal analysis are depicted [dBi], in the right column, real excited radiation patterns are shown. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz

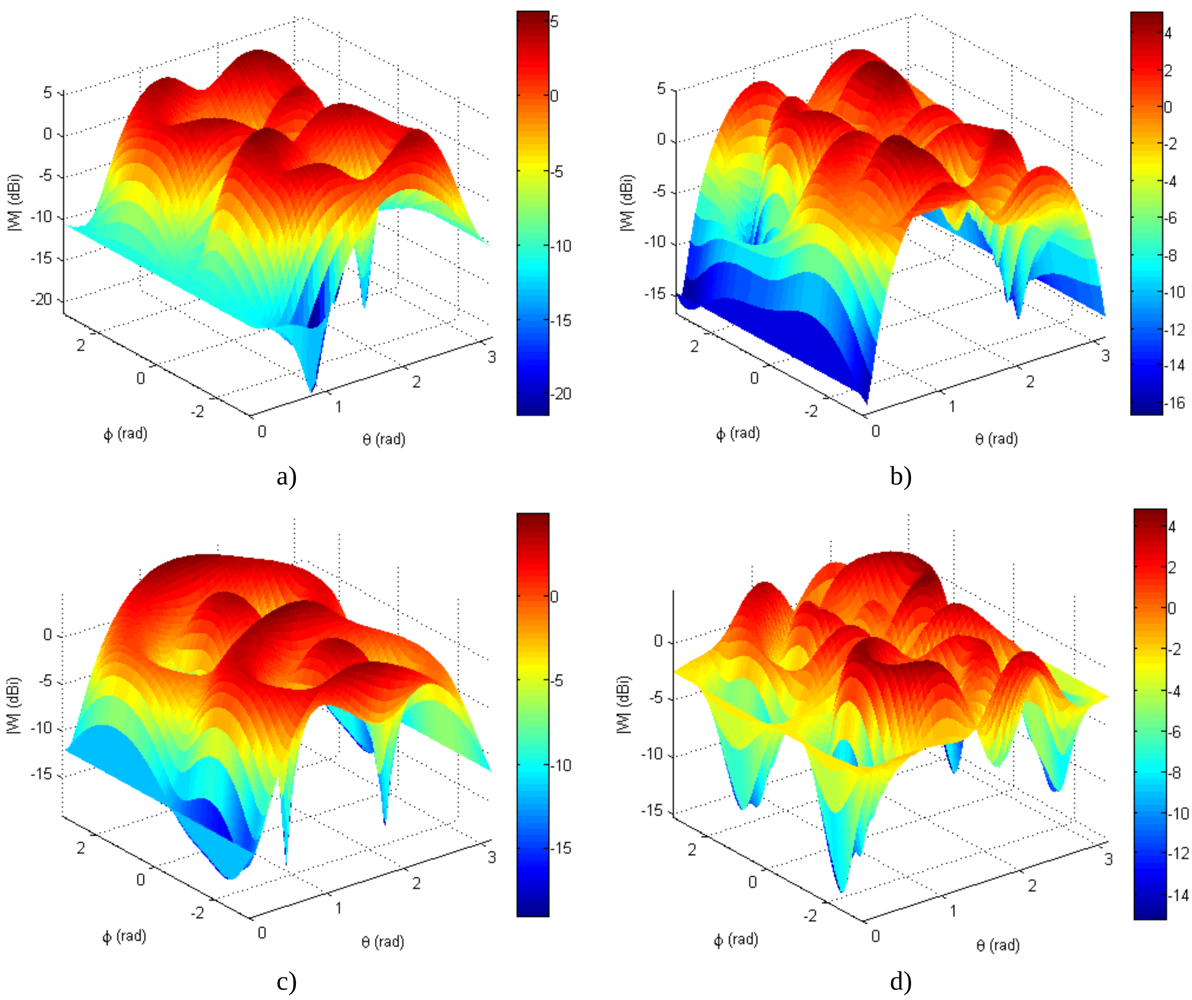
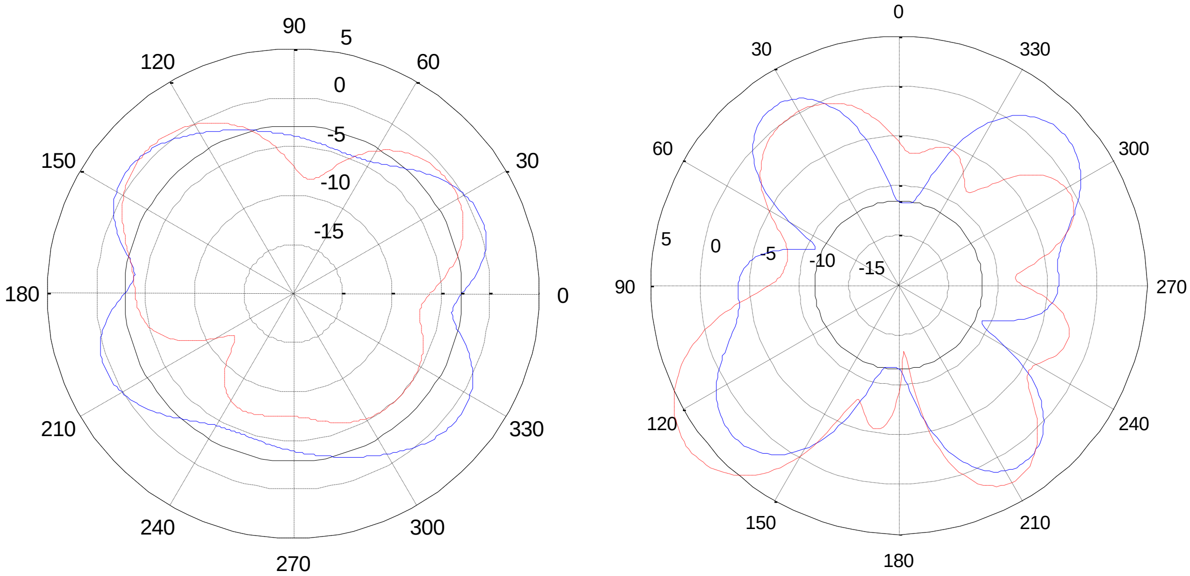
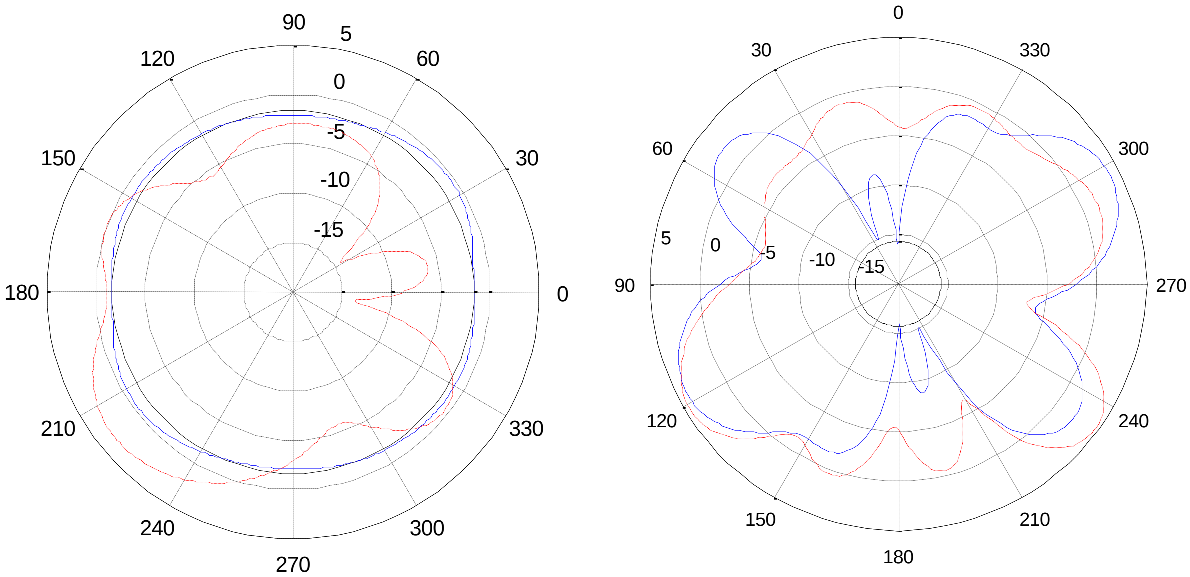
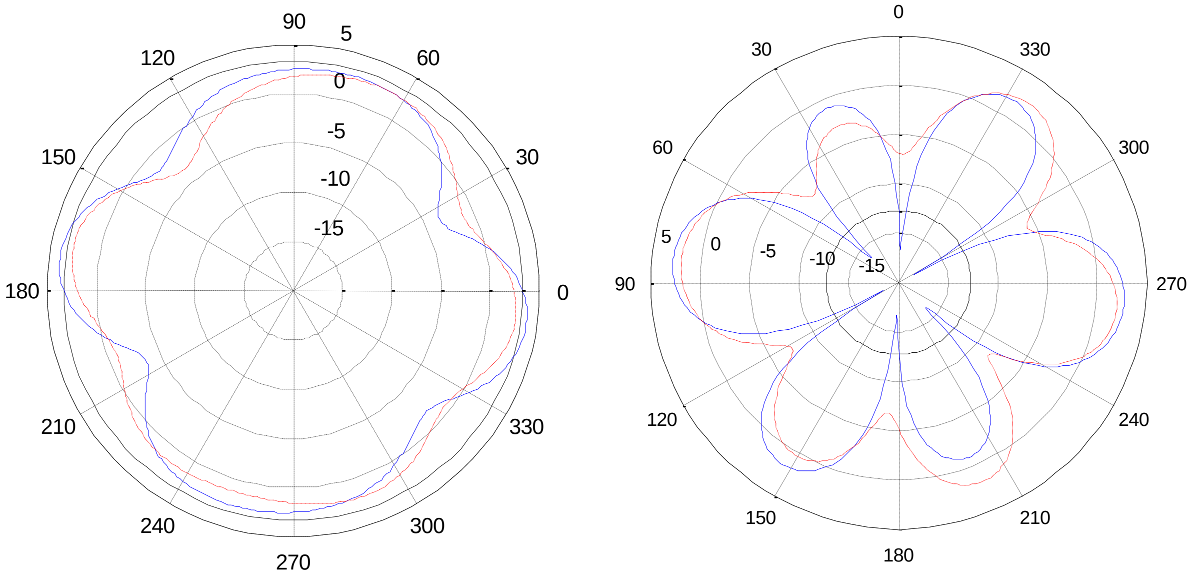


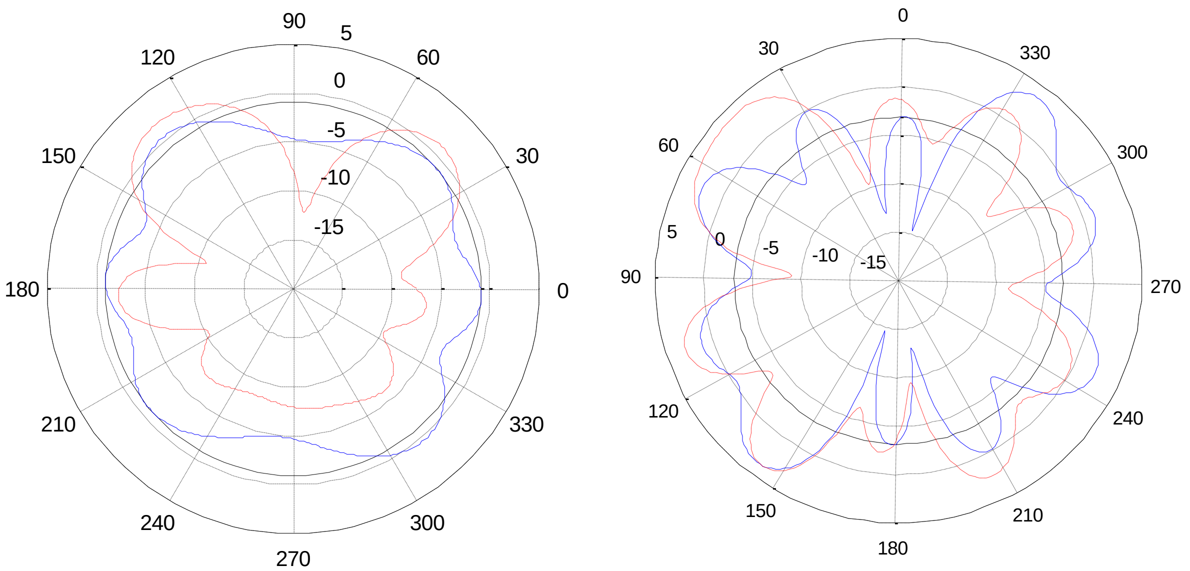
Fig. 12: Three-dimensional patterns of the far fields corresponding to isolated characteristic modes. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz


90
5
120
60
0
-5
150
30
-10
-15
180
0
210
330
240
300
270
0
30
330
60
300
5
0
-5
-10
-15
90
270
120
240
150
210
180
a)


90
5
120
60
0
-5
150
30
-10
-15
180
0
210
330
240
300
270
0
30
330
60
300
5
0
-5
-10
-15
90
270
120
240
150
210
180
b)



c)



d)

Fig. 13: Depiction of polar pattern cuts (in dBi) for ideal and excited (simulated) characteristic modes. The left column corresponds to the *xy*-plane cut, the right column to the *yz*-plane cut. The solid line comes from isolated (ideal) characteristic modes, the dashed line depicts the graphical representation of excited currents. a) f_{res} = 600 MHz, b) f_{res} = 700 MHz, c) f_{res} = 500 MHz, d) f_{res} = 800 MHz