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INDUSTRIAL AND ENGINEERING PAPER

# Design of a coupled antenna array for mobile HyperLAN2 applications

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*This paper describes the design of a 12-monopole linear array to perform a radiation pattern in the array alignment plane. This antenna can be used for HyperLAN2 telecommunications in transit vehicles. The design is based on a rigorous method which synthesizes the feeds weights by considering the strong cumulative coupling between monopoles. The originality of this paper consists in considering the couplings to obtain the objective pattern. Without this approach, a significant performance alteration is observed. The array and the feed network have been designed and successfully measured.*

**Keywords:** Antenna array, Mutual couplings, Array synthesis, HyperLan applications

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## I. INTRODUCTION

Linear monopole arrays are extensively used in many antenna systems due to their simplicity, low cost, polarization purity, reasonable bandwidth, and power-handling capability [1]. However, the strong mutual coupling between neighbored antenna elements also results in radiation patterns and matching degradations. The feed network can also be directly affected. It has been theoretically demonstrated that mutual coupling effects on radiation patterns can be reduced with appropriate loads [2–5]. Recent studies [6] have shown that correlation and capacity of coupled antennas in multiple-input multiple-output (MIMO) systems can be greatly improved by introducing proper matching loads into the multiple-antenna system.

The aim of this paper is to design a linear array of 12 monopoles by considering the coupling. Moreover, the antenna design must be robust and easy to manufacture in order to be integrated on a vehicle roof, and thus, to undergo outdoor conditions such as rain and wind. A typical application of such an antenna might be a HyperLAN2 telecommunication scenario between transit vehicles and base stations to operate data transfer between 5.47 and 5.72 GHz. Besides these objectives, an evolution of this antenna to add beam scan functionalities might be investigated to increase its versatility for this kind of applications. That is why an antenna array has been preferred to other radiating devices such as Yagi-Uda or horn antennas. This work is an extension of a previous design presented in [7].

Section II describes how to simultaneously realize an objective radiation pattern and the best matching of the monopole array and its feed network by including the different couplings. A brief reminder of the global synthesis method from [8] is given. Section III deals with the design and performances of the monopole array and its feed network. A comparison to a design where the couplings are ignored is also investigated to emphasize the improvement. The manufactured prototype and its measurement results are then presented.

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## II. GLOBAL SYNTHESIS METHOD

The antenna array is composed of 12 monopoles with their feed network. The strong interactions between the monopoles involve an accurate feed network design to maximize the directivity.

The objective consists in the determination of the impedance matching and the incident power to reach both the objective radiation pattern and the best matching for the monopole array.

A theoretical method based on the synthesis of multi-feed electromagnetic band gap (EBG) antennas with strong couplings is applied for this monopole array design. It has been previously described in [8]. The different steps can be summarized as follows.

At first, the $S$ matrix and the radiation patterns of the 12 monopoles on a finite ground plane are computed by means of CST Microwave Studio. These different patterns, $\phi_i$ ($1 \leq i \leq 12$), are obtained by successively feeding each monopole to include the coupling effects when they are neighbored. Other monopoles are loaded on fixed impedances that are stored for the synthesis process. Then, the patterns are used to define the $\beta_i$ coefficients that correspond to the best linear combination to reach the objective radiation pattern $\phi_{obj}$, as expressed by equation (1). In other terms, they represent the weights that must be applied to the radiation pattern of each of the 12 monopoles. The objective radiation pattern is defined in equation (2) as the product of one-monopole radiation pattern $\phi_{monopole}$ by the array factor. In this relation, $d$ relates to the distance between each monopole and $\varphi_i$ denotes the phase shift at the $i$th monopole. It can be noted that this objective pattern can also be defined arbitrarily with specific constraints on the side-lobe level or the main-beam shaping. As a whole, $\phi_{monopole}$ can refer to a theoretical radiation pattern and is different from $\phi_i$. At last, equation (3) leads to the antenna impedances considered as a reference ($Z_{ref\_i}$) to reach the matching and equation (4) gives the input waves $a_i$ that the feed network must achieve. The reader can refer to [8] for more details on this synthesis method.

$$[\varphi_1 \varphi_2 \ldots \varphi_i] \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta i \end{pmatrix} \approx \varphi_{obj}, \quad \text{with} \quad 1 \leq i \leq 12, \tag{1}$$

$$\varphi_{obj} = \sum_{i=1}^{12} \exp\left[-(k_0 d \sin(\theta) + \phi_i) i\right] \varphi_{monopole}, \tag{2}$$

$$Z_{ref\_i} = \left( \frac{50[I+S](\beta)}{[I-S](\beta)} \right)^*, \tag{3}$$

$$a_i = \sqrt{50}[I+S](\beta) \frac{\sqrt{\Re(Z_{ref\_i})}}{Z*_{ref\_i}}. \tag{4}$$

## III. DESIGN OF THE ANTENNA ARRAY

This section describes the monopole array design for the HyperLAN2 bandwidth (5.47–5.72 GHz).

In order to avoid grating lobes and to obtain a radiation pattern in the array alignment, the space between two nearby monopoles must stay lower than $0.5\lambda_0$, which is why a $0.45\lambda_0$ (24.12 mm) has been chosen for our design. The 12 monopoles are fasten to a finite ground plane whose dimensions are $L_x = 100$ mm and $L_y = 330$ mm, as mentioned in Fig. 1. Each monopole is 2.53 mm in diameter. The connections between the monopoles and the feed network ports are made of 50 Ω coaxial transitions that are drilled through the ground plane as can be seen in Fig. 2. The feed network is printed at the rear of the antenna ground plane, onto a 0.508 mm thickness Duroid 6002 substrate ($\epsilon r = 2.94$, tg $\delta = 0.0012$).

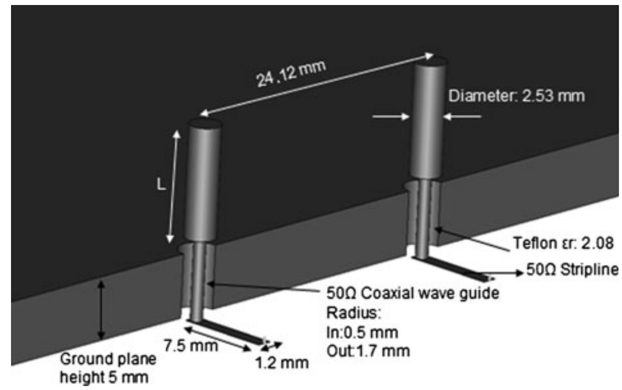


**Fig. 2.** Monopoles are fed by a coaxial guide drilled through the ground plane.

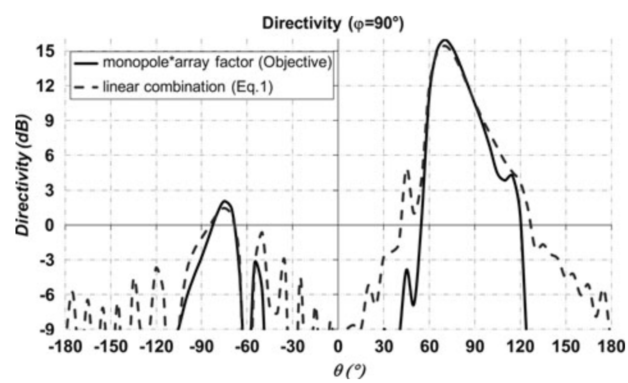


**Fig. 3.** Comparison of the objective radiation pattern (radiation pattern of monopole *array factor) with the linear combination of the radiation patterns of monopoles ($f = 5.6$ GHz).

The different steps of the design are now summarized:

1) First, the objective radiation pattern is set to obtain the main lobe in the direction $\theta = 75^\circ$. The array factor is deducted from equation (2) by applying equation (5). It allows setting the objective radiation pattern $\phi_{obj}$ of Fig. 3, which corresponds to the product of this array factor by the monopole radiation pattern. It should be noted that this result is approximated because the analysis considers that monopoles do not interfere with each other. However, it does not matter because the aim is only to define a goal function as in a classical synthesis procedure.

$$k_0 d \sin(\theta) + \phi_i = m 2\pi \Rightarrow \phi_i = 202^\circ. \tag{5}$$

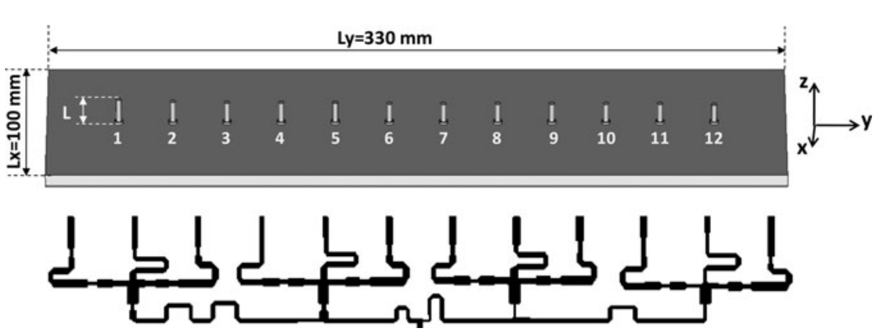


**Fig. 1.** Array of 12 monopoles designed with CST Mws separated by 0.45λ, and feed distribution network designed with Agilent ADS.

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**Table 1.** Normalized incident waves and reference impedances that optimize the antenna array performances for a specified radiation pattern (5.60 GHz). Values are given for two cases: couplings included or neglected.

| Monopoles $i$ | Length (mm) | $\beta_i$ (=weights for the coupled radiation patterns) | Normalized incident waves ($a_i$) and antenna impedances ($Z_{ref\_i}$) that optimize the efficiency (*couplings included*) | | Normalized incident waves ($a_i$) and antenna impedances ($Z_{ref\_i}$) that optimize the efficiency (*couplings neglected*) | | ($a_i$) realized by the new circuit considering ($Z_{ref\_i}$) of column 7 as reference impedances (*couplings neglected*) |
|---|---|---|---|---|---|---|---|
| | | | $a_i$ | $Z_{ref\_i}$ | $a_i$ | $Z_{ref\_i}$ | |
| 1 | 10.8 | $0.286e^{(-j^*48°)}$ | $0.288.e^{(-j^*49°)}$ | $29+j^*13$ | $0.307e^{(-j^*70°)}$ | $56-j^*8$ | $0.308e^{(-j^*69°)}$ |
| 2 | 9.8 | $0.293e^{(j^*155°)}$ | $0.30e^{(j^*152°)}$ | $32+j^*10$ | $0.306e^{(j^*139°)}$ | $69-j^*21$ | $0.309e^{(j^*139°)}$ |
| 3 | 9.3 | $0.279e^{(-j^*3°)}$ | $0.286e^{(-j^*6°)}$ | $31+j^*9$ | $0.285e^{(-j^*15°)}$ | $77-j^*32$ | $0.284e^{(-j^*15°)}$ |
| 4 | 9.3 | $0.284e^{(-j^*155°)}$ | $0.291e^{(-j^*164°)}$ | $30+j^*1$ | $0.291e^{(-j^*168°)}$ | $75-j^*31$ | $0.29e^{(-j^*168°)}$ |
| 5 | 9.3 | $0.284e^{(j^*47°)}$ | $0.287e^{(j^*35°)}$ | $27-j^*2$ | $0.291.exp^{(j^*34°)}$ | $73-j^*30$ | $0.28e^{(j^*34°)}$ |
| 6 | 8.8 | $0.280.exp^{(-j^*120°)}$ | $0.283e^{(-j^*124°)}$ | $29+j^*7.5$ | $0.277e^{(-j^*128°)}$ | $83-j^*43.5$ | $0.27e^{(-j^*128°)}$ |
| 7 | 8.8 | $0.266e^{(j^*82°)}$ | $0.262e^{(j^*79°)}$ | $24+j^*8.5$ | $0.264e^{(j^*75°)}$ | $82-j^*44$ | $0.253e^{(j^*74°)}$ |
| 8 | 8.8 | $0.264e^{(-j^*74°)}$ | $0.251e^{(-j^*77°)}$ | $20+j^*8.5$ | $0.262e^{(-j^*82°)}$ | $81-j^*44$ | $0.25.exp^{(-j^*82°)}$ |
| 9 | 8.8 | $0.254e^{(j^*131°)}$ | $0.227e^{(j^*124°)}$ | $15+j^*3$ | $0.251e^{(j^*123°)}$ | $82-j^*45$ | $0.247e^{(j^*123°)}$ |
| 10 | 8.8 | $0.275e^{(-j^*24°)}$ | $0.257e^{(-j^*35°)}$ | $18-j^*1.5$ | $0.271e^{(-j^*32°)}$ | $83-j^*46$ | $0.266.exp^{(-j^*32°)}$ |
| 11 | 8.8 | $0.319e^{(j^*180°)}$ | $0.323e^{(j^*165°)}$ | $28-j^*7$ | $0.313e^{(-j^*186°)}$ | $83-j^*48$ | $0.317e^{(-j^*186°)}$ |
| 12 | 8.3 | $0.361e^{(j^*0°)}$ | $0.377e^{(j^*0°)}$ | $48+j^*17$ | $0.33e^{(j^*0°)}$ | $98-j^*73$ | $0.334e^{(j^*0°)}$ |

2) Next, a full-wave simulation of the monopole array is performed to obtain the global scattering matrix [**S**] and the radiation patterns $\phi_i$. This study shows that the couplings between monopoles could reach −12 dB in the worst cases. The weights $\beta_i$ are then deducted according to equation (1) and reported in Table 1. Figure 3 points out the similarity between the objective radiation pattern and the linear combination of the neighbored monopole radiation patterns affected by the coefficients $\beta_i$.
3) Finally, the optimum weights $a_i$ and the input impedances $Z_{ref\_i}$, which simultaneously perform the objective radiation pattern and the matching of all the feeding ports, are calculated using equations (3) and (4), the [**S**] matrix, and the $\beta_i$ vector. These values are given in Table 1 (columns 4 and 5) with the optimized monopole lengths. These have been set to comply with the different impedance values resulting from the synthesis procedure and to minimize the feed distribution network complexity.
4) The feed network has been designed with the Agilent ADS software to perform the weights and the impedance matching specified in Table 1. The corresponding layout is shown in Fig. 2. The last step consists in the co-simulation of the whole antenna (monopoles and feed

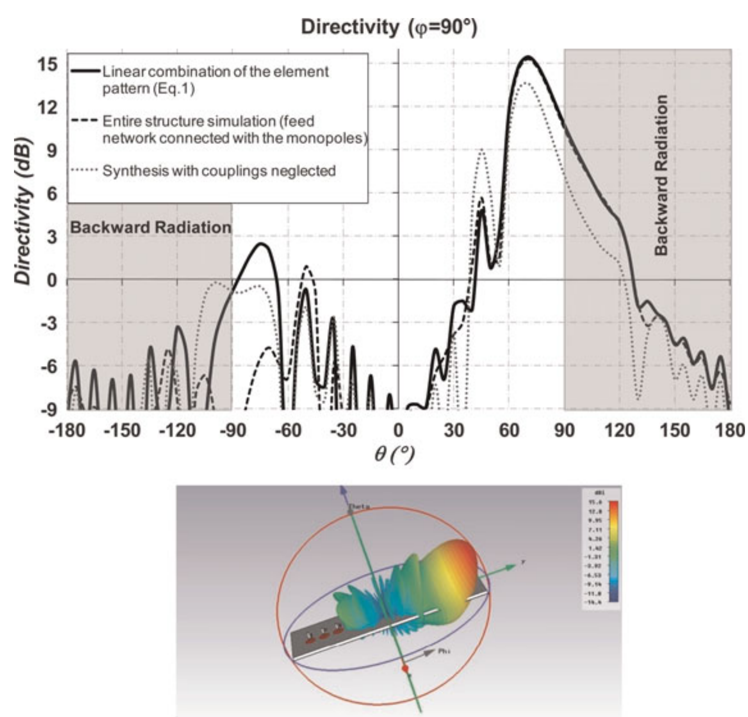


**Fig. 4.** Agreement of the synthesized radiation pattern with couplings and theoretical linear combination of the monopole patterns at 5.60 GHz. Resulting radiation pattern with couplings neglected is also presented to show the interest of including couplings in the design method.

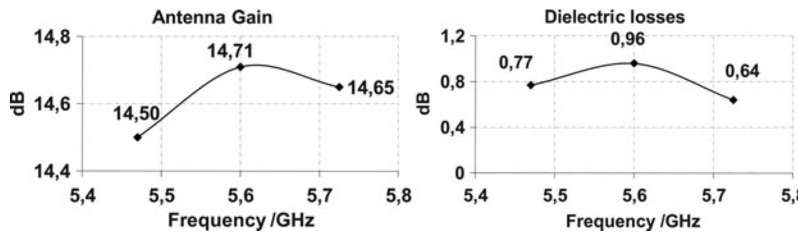


**Fig. 5.** Left: simulated gain in the direction $\theta = 75°$ (left plot) and dielectric losses for the entire structure simulation (right plot) over the frequency range.

network together) in CST Design Studio. The Agilent ADS layout is connected to the CST MWS simulation by Touchstone files including the $S$ parameters of the feed network. Thus, this full-structure simulation provides the performances of the whole antenna array with the synthesized feed network. The radiation patterns, gain, return loss, and dielectric losses are computed. The comparison of the synthesized radiation pattern obtained by this simulation is compared with the theoretical linear combination in Fig. 4. The gain and dielectric losses are evaluated in Fig. 5.

In order to prove the interest of the design method described in this paper, a classical design neglecting the couplings has been made for comparison. As a whole, the $S$ matrix in equation (3) has been simplified with the relations given in equation (6) to obtain the $S''$ matrix.

$$S''_{ij} = S_{ij}, \quad \text{for } i = j,$$
$$S''_{ij} = 0, \quad \text{for } i \neq j. \tag{6}$$

The new values for $Z_{ref\_i}$ and $a_i$ are determined using equations (3) and (4), whereas $\beta_i$ stays unchanged. The corresponding values are given in Table 1. Another feed network has been designed to find the incident waves (sixth column) that agree with the objectives $a_i$ (the last column).

Then, the effect of coupling has been evaluated in Fig. 4 presenting the antenna radiation pattern at 5.6 GHz. The results show that the directivity is 2 dB lower when the couplings are neglected.

By observing the coupling between monopoles in Fig. 6, the corresponding values can reach −12.5 dB in worst cases. It

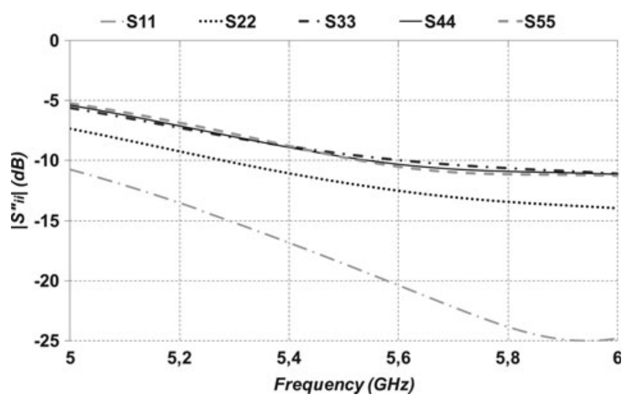


**Fig. 7.** Example of $S''_{ii}$ parameters of the monopole array showing a poor matching without the synthesis procedure.

leads directly to strong interactions between monopoles that dramatically affect the antenna array performances and the matching as can be seen in Fig. 7.

The interest to carefully design the feed network, as in Section III, is now clearly demonstrated.

Values are given for two cases: couplings included or neglected.

## IV. MEASURES

The monopole array and the feed distribution network were manufactured as can be seen in Fig. 8. The feed network is glued at the rear of the ground plane and screws were added to secure the radiofrequency (RF) contacts. Interactions

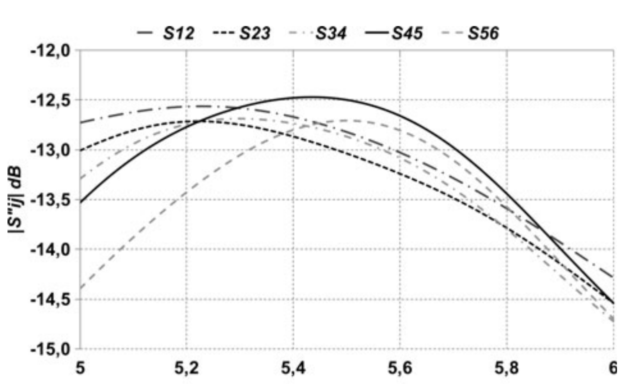


**Fig. 6.** Example of $S''_{ij}$ parameters of the monopole array showing the strong couplings.

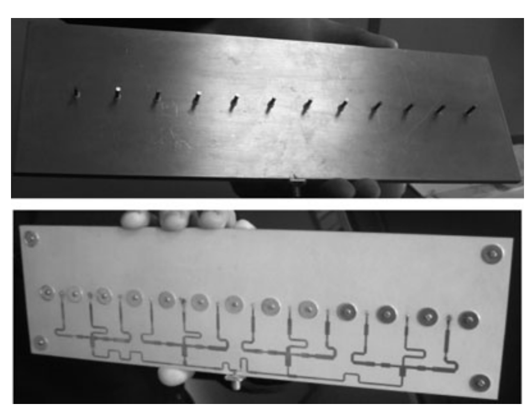

**Fig. 8.** Photograph of the monopole array and its feed network.

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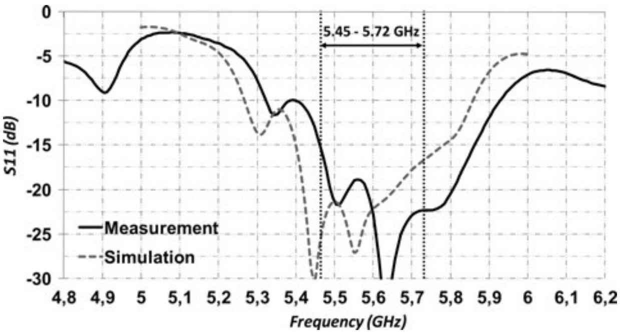


**Fig. 9.** *S*11 comparison between simulation and manufactured prototype.

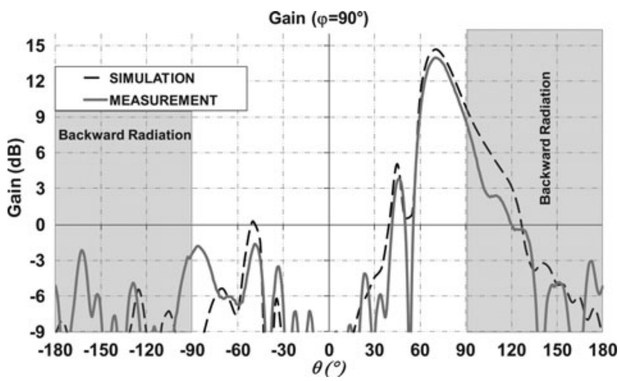


**Fig. 10.** Comparison of the simulated radiation pattern and measurement at $f = 5.6$ GHz.

between the screws and the circuit have been checked and considered as insignificant. An SubMiniature version A (SMA) connector is used to feed the array.

The measurements were achieved in the laboratory anechoic chamber between 5.47 and 5.72 GHz and have been compared with simulation. The antenna return loss depicted in Fig. 9 shows that values better than −15 dB are obtained on $|S_{11}|$. A slight discrepancy of 50 MHz can be observed compared to the simulation, but it represents only 0.9% of frequency shift that can be due to the mesh accuracy during simulation or manufacture tolerance. The radiation patterns are then compared at 5.6 GHz in the array *yz*-plane. The measured gain and pattern of Fig. 10 agree well with the prediction. The difference between the simulated and the measured gain over the frequency range is lower than 0.5 dB. Metallic losses in the feed network and the measurement accuracy of the anechoic chamber (±0.5 dB) can be responsible for this variation. This realization allows concluding that the synthesized design is reliable and that the global synthesis method detailed in [8] for EBG can be derived for classical antenna design with couplings. The impedance matching and the objective radiation pattern performances are correctly maximized through the synthesis design.

## V. CONCLUSION

In this paper, a monopole linear array has been designed and manufactured. In such a structure the monopoles strongly interact with each other. It is demonstrated that if no care is taken, the intensity of the coupled waves may damage the functioning of a feed network.

In our study, the feed network has been designed to deal with the couplings by considering the impedances and the input waves that optimize the antenna performances.

The feed network and the monopoles array were manufactured. The whole antenna was successfully tested. The experimental radiation pattern and return loss are very close to the simulation. Such an antenna is robust and can be optimized with the described method to satisfy specific applications that need an antenna on a vehicle roof for data transfer. As the method takes into account couplings, a particular beam pointing with reduced or controlled side lobes can be achieved easily. As further works, this method can be extended to an active monopole array to provide efficient beam scan capabilities.

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