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A Wideband Automotive 4x4-MIMO 5G Antenna System with Wide Double-Stage Decoupling Circuit for a Double Shark Fin Cover

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Abstract

In order to generate more data throughput in the 5th generation for mobile communications, more antennas per volume are generally required. This leads to smaller spacing of the antennas in MIMO systems and higher coupling values, especially in the automotive sector. In the following, a symmetrical 4x4 MIMO antenna system with a new decoupling network is presented, where each antenna performs in a low frequency band from 617 MHz to 960 MHz and the higher bands from 1.7 GHz to 5 GHz. The decoupling network is designed in two stages for an exceptionally high bandwidth. The network is exclusively realized by quasi-lossless devices such that the total efficiency of the pure antenna system is even increased by the network at the lowest frequency. This approach achieves decoupling values of better than -14 dB and matching values of better than -6 dB in the entire low band. In the high band, decoupling values of better than -17 dB and matching values better than -10 dB are achieved.

1. Introduction

The automotive sector is moving toward ever higher-numbered multi-antenna systems within low space. At the same time, the frequency range is also expanding, so that the low frequencies have now reached 617 MHz and the high frequencies 5 GHz. The low frequencies by nature have approximately omnidirectional directivity, but the problem of coupling due to their large wavelengths, because the car manufacturers keep the installation space small due to design rules. The decoupling network including an optional matching network should then decouple and match the antennas as broadband as possible in the low band and be almost invisible in the high frequency band. The more stages the decoupling network then has, the higher the broadband decoupling. Such decoupling networks including matching networks, developed empirically, have already been realized in [1] with the help of lossy elements as well as lossless elements. On the other hand, an appropriate theory with even and odd mode for symmetric systems resp. matrix calculation for asymmetric systems for decoupling and matching networks in single-stage form has been developed in [2] resp. [3]. Only nearly lossless elements have been used, such that the efficiency has been increased compared [1]. A single-stage network with parallel elements is used to equalize the imaginary parts of the antenna input admittances (even and odd) [4]. Other planar decoupling methods include the via fence structures [5], electro-magnetic band gap structures [6] and defected ground structures [7]. For the 5G low band an especially high bandwidth must be considered for the design of a decoupling circuit. Moreover, the coupling circuit has to be nearly invisible at the frequencies of the upper bands in order not to destroy the already good decoupling of the antennas there. These overall requirements are very challenging for the former approaches.

In this contribution a new two-stage decoupling circuit is presented for a 4x4-MIMO 5G antenna system using a strategy to make the two stages complement one another. The decoupling circuit will be constructed using only near-lossless devices. For this purpose, two perfect decoupling peaks at different frequencies ω_{k1} and ω_{k2} in the low band are widened to generate even more broadband. This generates an extremely broadband and high-level decoupling in the 5G low frequency band which allows to fulfill the requirements of 5G transceivers.

2. MIMO Antenna System Description

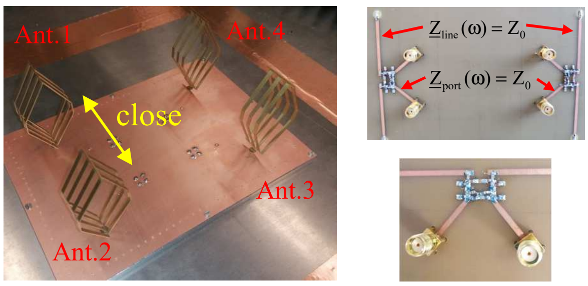

Figure 1. Hardware demonstrator: antennas with circuit

Figure 1 shows the hardware setup on a finite ground plane. The antenna shape can be fabricated by a milling process or by a stamping process from a single sheet of metal. This reduces the material consumption by half since the single antenna does not need to be folded.

Figure 2 shows the S-parameters of the input reflection of the 4x4 MIMO system without circuit. As can be seen, the antennas are still very poorly matched in the low band in the 617 MHz area and do not meet the requirement of - 6dB for the low band. In the high band from 1.7 GHz, however, the antennas meet the -10 dB requirement in the simulation and the measurement:

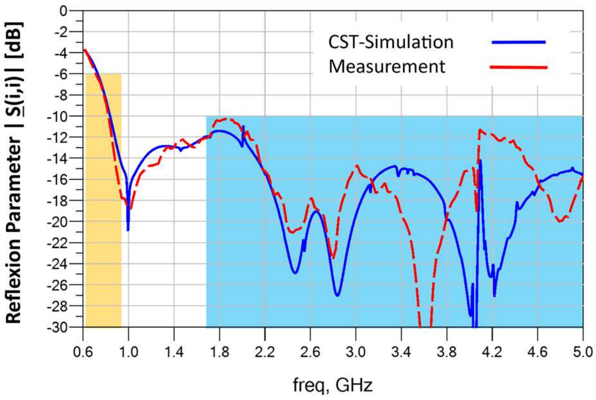

Figure 2. Reflection parameter S_{11} without any circuit

Figure 3 shows the coupling parameters of the antennas 1 and 2 that are close to each other (coupling of opposite antennas already lower than -15 dB for both bands):

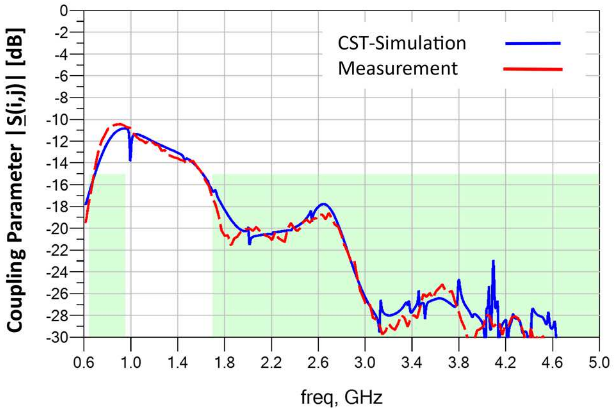

Figure 3. Coupling parameter S_{21} without any circuit

In Figure 3, the closely spaced antennas meet the -15 dB requirement in the high frequency band. In the low band, the decoupling values are still too high in the entire low band. These should be brought below the -15 dB requirement with the aid of the two-stage decoupling circuit. The efficiency of the pure antenna system without circuitry in Figure 4 shows, that the requirement of a radiation efficiency of -2dB is almost met in the low band and fully achieved in the high band. Since the two-stage circuit should be constructed only from almost lossless elements with high quality, it should be possible to keep the radiation efficiency approximate close to -2 dB in both bands:

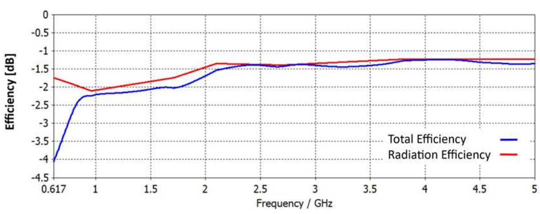

Figure 4. Efficiency without circuit and all losses

3. Description of the Decoupling Circuit

The circuit diagram shown in Figure 5 represents a general two-stage decoupling circuit in terms of structure, whereby the matching networks APN1 and APN2 are optional and are not initially required for perfect two-stage decoupling. The microstrip lines directly at the antennas have the impedance Z_0 and therefore do not change the magnitude of the S-parameters significantly. However, these Z_0 lines cause a significant phase rotation to be considered for the low frequency band. Unfortunately, this type of rotation cannot be set by a parallel SMD inductor or serial SMD capacitance. It has been shown that longer Z_0 lines and a subsequent SMD-only network, for the two-stage decoupling network, provide the best solution options between broadband decoupling and matching for the antennas presented here. Unfortunately, these lines lead to more losses for higher frequencies. If the antenna spacing is not almost exclusively bridged by these Z_0 lines, a network combined of SMD components and microstrip line must be formally used instead of the pure SMD network (i.e. for B_1 and B_2).

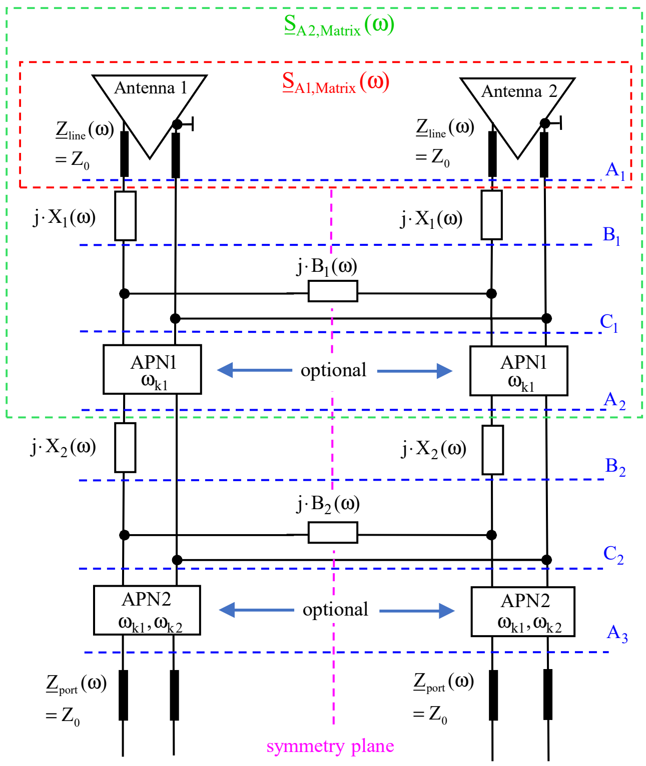

Figure 5. Matrix interconnection to achieve decoupling and matching

The input admittances for the even and odd cases at the plane A_i can be derived, using the even and odd excitation and the resulting magnetic and electric wall, respectively, in the plane of symmetry. After the first decoupling stage has been designed up to level A_2 for the first decoupling frequency ω_{k1}, the equations used can be analogously applied for level A_2 to calculate a second decoupling stage for a further second decoupling frequency ω_{k2}. In general, the first decoupling stage was designed for the first decoupling frequency ω_{k1}. Then the components calculated take on new values at the second decoupling frequency ω_{k2}, thereby generating new input impedances and thus new input admittances for the even and odd case at the next A_i level (A_2). Since only the closely spaced couple more strongly and in the low frequency band (Fig. 2), the antennas in the high frequency band are already sufficiently matched and decoupled, the two-stage decoupling network must have high-pass characteristics. Thus, it is possible for the two-stage network to decouple and match only in the low band and maintain the already suitable behavior in the high band. Therefore, all series elements must only be pure capacitors or e.g. parallel resonant circuits with high-pass characteristics. There is decoupling between the antennas at frequency ω_{k1} from level C_1, because the input admittances of even and odd case have made been equal at ω_{k1}. The matching network APN1 does not establish a new connection between the antennas (as the elements B_1 or B_2 do). Therefore, it does not change the set decoupling at level C_1 at ω_{k1}, such that at level A_2 the antennas are still decoupled for ω_{k1}. The same is true for element X_2 of the second stage. It has no effect on the decoupling at ω_{k1}, because this element X_2 is effective in both circuits (even and odd cases).

Matching and decoupling are always opponents, and the antennas are theoretically perfectly decoupled only at two frequencies (ω_{k1} and ω_{k2}) at level C_2 and are therefore independent only at ω_{k1} and ω_{k2} with respect to this fact. Hence, it is formally possible with the help of the optional matching networks to loosen the quality of the decoupling to increase the bandwith. This leads to the following circuit in Fig. 6:

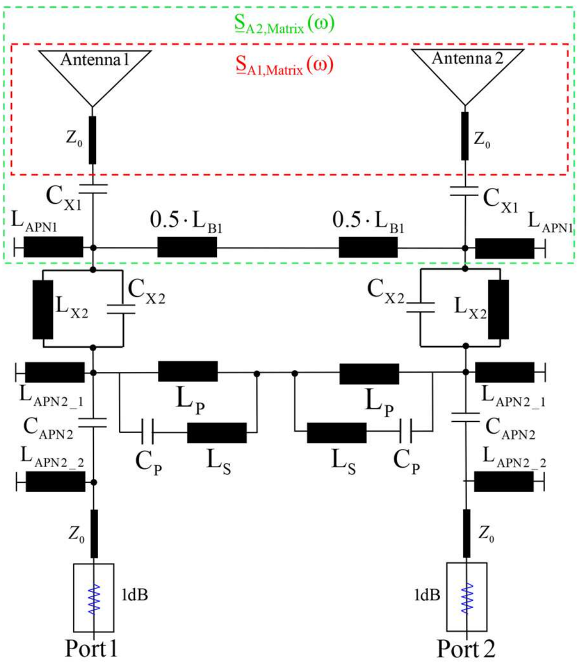

Figure 6. Circuit for ultra-wide bandwidth

4. Results Obtained by Decoupling Circuit

In Figure 7, all four antennas are matched with -6 dB or better in the low frequency band from 617 MHz to 960 MHz. The good matching of the pure antenna system in the high frequency band from 1.7 GHz to 5 GHz could be maintained by the high-pass characteristic of the two-stage decoupling circuit, such that the antennas satisfy the matching values required by the automobile manufacturers for both frequency bands (-6dB in the low band and -10dB in the high band):

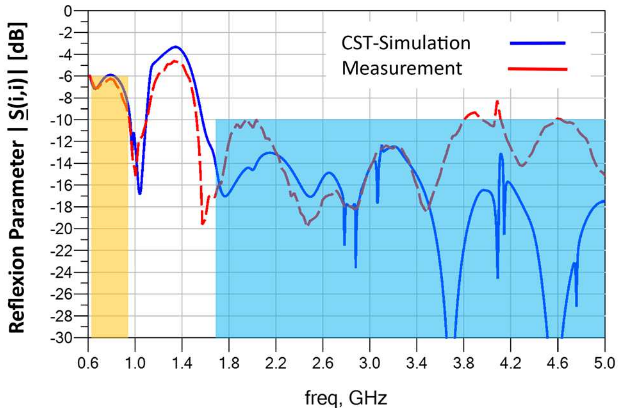

Figure 7. Reflection parameter S_{11} with a double decoupling circuit and all losses

The already good decoupling of the pure antenna system with respect to the closely spaced antennas (Figure 3) was maintained from 1.7 GHz and is still approx. -20 dB and thus has excellent values with decoupling circuit (see Figure 8). The poor decoupling values in the low frequency band from 617 MHz to 960 MHz for the pure antenna system (Figure 3) were greatly improved by the two-stage decoupling circuit and almost consistently meet the required -15 dB (Figure 8):

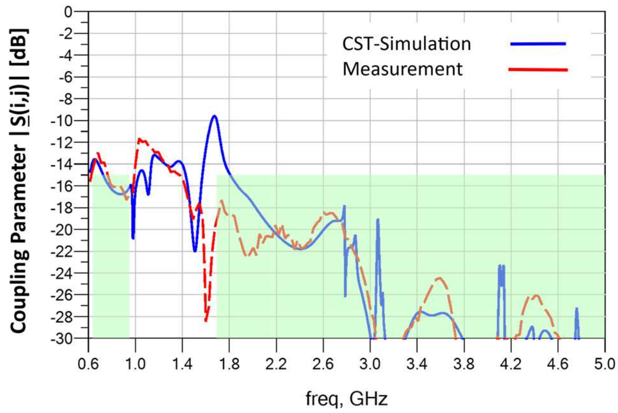

Figure 8. Coupling parameter S_{21} with a double decoupling circuit and all losses

Now the efficiency curves still must be considered. As already explained in the introduction, only capacitors and inductors with very high quality are used for the network, such that the components themselves are as lossless as possible. In the low frequency band, it can be seen (compare Figures 4 and 9) that the Radiation Efficiency, which is corresponding to the internal ohmic losses, is only reduced a little bit. In the pure antenna system (Figure 2) the antennas are very poorly matched around 617 MHz and are already very well matched in the 960 MHz range. The total efficiency in Figure 4, which is the product of the radiation efficiency and the port efficiency and thus includes the matching of the antennas, is therefore improved in the 617 MHz range in Figure 9 and is a little worse in the 960 MHz range. Due to the difficulty of realizing large bandwidth at lower frequencies, which the two-stage decoupling network is only capable to deliver, this is an excellent result for the total efficiency in the low frequency band:

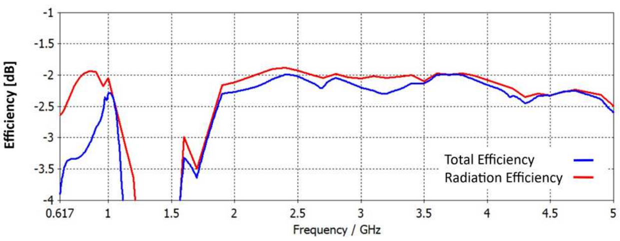

Figure 9. Efficiency with a double decoupling circuit and all losses

For the creation of a high-level two-stage decoupling circuit, it is necessary to first bridge the distance between the antenna ports and the circuit by use of transmission lines with a wave impedance of 50 Ω. By this way the impedance of the pure antennas is turned in the Smith chart and then it is supplemented by the SMD-Network X_2 which is designed as a parallel resonant circuit. The parallel resonant circuit for X_2, where we have to set its blocking frequency ω_{block} between 960 MHz and 1.7 GHz, naturally provides a blocking to the antennas in this range. This can also be clearly seen in the efficiency curves in Figure 9. In the high band above 1.7 GHz, the overall losses of transmission lines and SMD components lead to a slight decrease in efficiency, which still yields good results for all the 5G frequency bands up to the 5 GHz limit.

5. Conclusion

A 4x4 5G MIMO antenna system has been presented which can put into a double shark fin cover. All antennas are designed to fulfill matching requirements with reflection factors of less than -10 dB and decoupling with transmission factors of less than -15 dB in the whole frequency range from 1.7 GHz up to 5 GHz even without an additional network. For the lower frequency range from 617 MHz to 960 MHz a double stage decoupling and matching circuit is added to achieve matching of minimum -6 dB while keeping decoupling as low as possible. For the four antennas the input reflection factor is hence improved from -2dB to -6dB at the lowest frequency in the matching. Due to the double-stage decoupling circuit, decoupling in the low band could be improved with transmission factors between -14 dB and -17 dB. Radiation efficiency was largely kept in the range slightly below -2dB. Based on the two stages, which are supplementing each other in a broadband manner, a high-level decoupling is achieved for the complete 5G frequency bands with extremely wide bandwidth.

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