Design and Optimization of Antenna Arrays for 60 GHz Hybrid Smart Antenna Systems with Consideration of Inter-Element Electromagnetic Interactions

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Abstract

The use of directive elements, element tilting, and beamforming with a subarray are proposed by the authors in [1-2] in order to reduce computational complexity and cost of smart antenna array systems. This approach is termed as the Hybrid Smart Antenna System as it combines advantages from both the adaptive and switched beam approaches. A genetic algorithm based array geometry optimization procedure that determines the element tilt angles to uniformly cover a given angular range by adaptive beamsteering for 60 GHz wireless applications is described in [3,4]. In this paper, additional considerations, namely the electromagnetic interactions between the array elements are considered and a more realistic implementation and optimization of the hybrid smart antenna technique is discussed.

1. Introduction

The unlicensed frequency band in the 60 GHz range, offering a contiguous 7 GHz wide spectrum, presents a plausible opportunity for the implementation of high data rate indoor wireless communication applications. Since data rates in the range of gigabits per second are demanded by the emerging applications such as the wireless transmission of high definition television signals, the development of communication systems utilizing the 60 GHz band is highly desired. However, there are several factors hindering these development efforts such as the high propagation losses, due to the absorption of the signal by the oxygen in the air, and lack of signal transmission through obstacles.

Several methods to extend the communication range in the 60 GHz frequency range are proposed including the use of very high gain antennas, and the use of fully adaptive beamforming with omni-directional elements. The problem with the use of high gain antennas and switching between them according to the signal's angle of arrival (AOA) is the excessive scalloping effects, in other words, the fluctuation of the received signal power with the AOA. When the fully adaptive beamforming with isotropic elements is considered, two problems are observed. First, the number of array elements to achieve the required gains is too high, thus, requiring a smart antenna receiver with many independent channels. This increases the hardware cost significantly, and renders this approach infeasible for household communications applications. Second, the complexities of the adaptive beamforming algorithms scale with the second power of the number of array elements, therefore, array processors with high computational power are required, hence, further increasing the system costs. The number of array elements can be reduced by employing highly directive antennas in a linear array, however, the drawback in this is related to the limited beam-scanning range that is determined by the beamwidth of the array elements. This is the main reason why the majority of the smart antenna systems employ omnidirectional array elements. To avoid this problem, deploying directive array elements with different look directions (main beams pointed towards different directions) is briefly mentioned in earlier literature [5], but deemed infeasible since optimization procedures for determining the look directions were not then available.

To compensate for the high propagation losses in the 60 GHz band, and to provide good alignment with the transmitter and receiver with minimal scalloping effects, our group at the Hawaii Center for Advanced Communications (HCAC) proposed the Hybrid Smart Antenna System (HSAS). HSAS is a combination of the antenna switching and fully adaptive beamforming approaches existing in the literature and avoids the fallbacks of both methods while combining their advantages. This algorithm combines the use of directive array elements in the antenna array with adaptive beamforming using a subset of the array to provide perfect beam alignment with minimal scalloping effects. The major difference of the HSAS from an antenna switching system is the selection of multiple array elements in contrast to one in the antenna switching case, and the subsequent application of adaptive beamforming. In literature, it is shown that a similar performance to that of a fully adaptive beamforming system can be obtained by utilizing about one third of the elements in the array [1].

In order for the HSAA to provide uniform beam scanning coverage for an angular range, the array geometry

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needs to be optimized, in terms of the traditional geometrical parameters but also including tilt angles, so that when the outputs of multiple elements are combined, the output power should remain the same for all signal AOA. This optimization procedure is handled by a novel GA optimization formulation, and its performance is validated by array simulations in [3]. Although employing realistic array element patterns, however, this earlier study did not include any consideration of the interaction/mutual coupling between the array elements and the changes in elements characteristics in an array arrangement with the tilt angles.

In this paper, the considerations for a more realistic optimization procedure for the antenna array geometry including the inter-element electromagnetic interactions are discussed and the use of full wave electromagnetic simulation software packages such as HFSS in this procedure is described. The rest of the paper is organized as follows: In Section 2, the Hybrid Smart Antenna System is briefly described. Section 3 compares and contrasts the cases of using directive antennas in an array with and without tilting in the array geometry. In Section 4, the GA optimization procedure for a realistic array element is outlined and the results are described. Section 5 describes the limitations of the GA optimization approach because of the lack of taking the electromagnetic interactions between the array elements into account. In this section a two tiered approach combining electromagnetic and digital signal processing assets to realize a more realistic array optimization approach, is described. Section 6 concludes the paper.

2. Hybrid Smart Antenna System (HSAS)

The Hybrid Smart Antenna System (HSAS) proposed by HCAC for low-cost adaptive beamforming applications is shown in Fig. 1 [1]. By utilizing several directive array elements with their beams oriented towards different directions, this system simultaneously provides high antenna gains, and uniform coverage in the desired angular range. Significant cost savings are achieved by using a few neighboring elements in the adaptive beamforming process. The array elements to be used in the beamforming are selected to be the neighboring elements with the highest combined received signal power. By using only a subset of the available array elements, the number of receiver channels in the smart antenna system is significantly reduced as opposed to the traditional high-cost approach of utilizing all of the array elements in the beamforming operation.

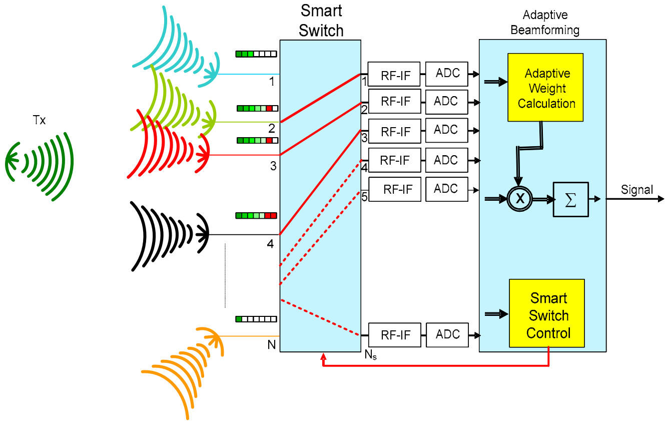


Fig. 1. The HSAS block diagram.

In a traditional smart antenna system, omnidirectional, low-gain array elements are used in a linear fashion, therefore, the received signal powers of all elements for all AOAs are identical, that is why all the elements have to be included in the beamforming. This condition is avoided in the HSAS, by utilizing highly directive elements, and individually tilting each of them so for a given AOA, only a few elements will receive significant signal power, hence, the need to select a subset. The loss in the array gain by utilizing only a subset of the array elements in beamforming is compensated by the individual element gains in the HSAS so similar performance to the fully adaptive systems are obtained at a fraction of the cost.

3. Arrays of Highly Directive Antennas and the Need for Tilting

In the previous section, it was described that the HSAS uses highly directive antennas and only selects a subset of the array for low-cost adaptive beamforming. The use of highly directive elements in the antenna arrays has been long avoided since it significantly limits the possible beam scanning range and leads to scalloping effects. The HSAA avoids this fallback of using highly directive antennas by including array element tilting as a new array design variable. In Fig. 2, a linear array of patches with no element tilting is illustrated. Fig. 3 illustrates the case of a linear array in which each element is tilted at an angle with respect to the array axis to obtain element beams oriented toward different directions, with this configuration, received powers at each array element will be different as opposed to the identical powers in the no-tilt case in Fig. 2, and selection of a sub-array becomes possible. In Fig. 4 and Fig. 5, some sample beam scanning

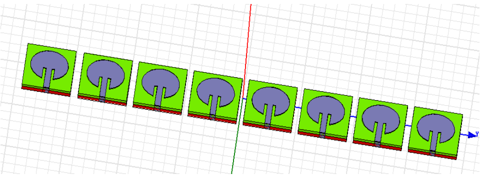


Fig. 2. A linear antenna array with directive elements (no tilting)

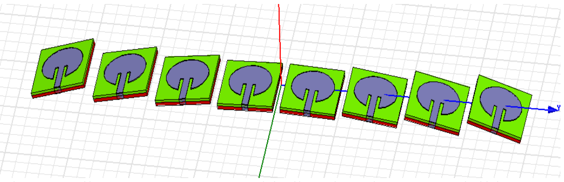


Fig. 3. A linear antenna array with directive elements and tilting.

patterns for no-tilting and tilting cases are illustrated respectively. In these figures, the bold dashed lines indicate the traces of beam peaks when the beam is scanned in the indicated angular range. For the no-tilting case in Fig.4, the peaks of the scanned beam patterns follow the shape of the element radiation patterns as dictated by the principle of pattern multiplication. Therefore, as the beam is scanned away from the broadside direction, the received power decreases significantly and limits the available beam scanning range. This is the main reason for avoiding the use of directive elements in antenna arrays. For an antenna array with tilting, additional degrees of freedom are made available by carefully adjusting the tilt angles of each array element such that when a subset of these elements are used in beamforming, the power of the beam peak becomes independent of the scan angle, therefore, beam scanning range is not limited as illustrated in Fig. 5.

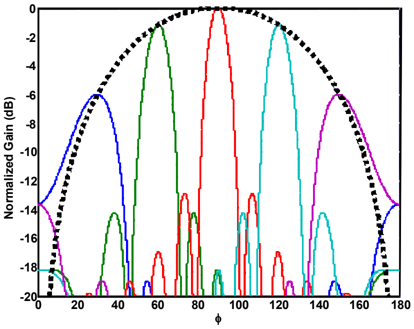


Fig. 4. Sample beam scanning patterns with no tilting

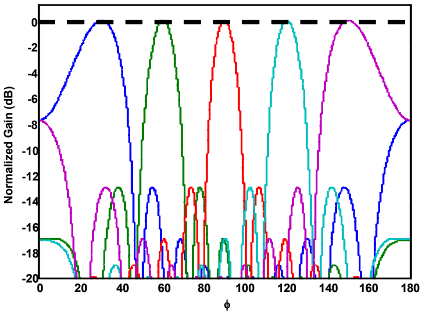
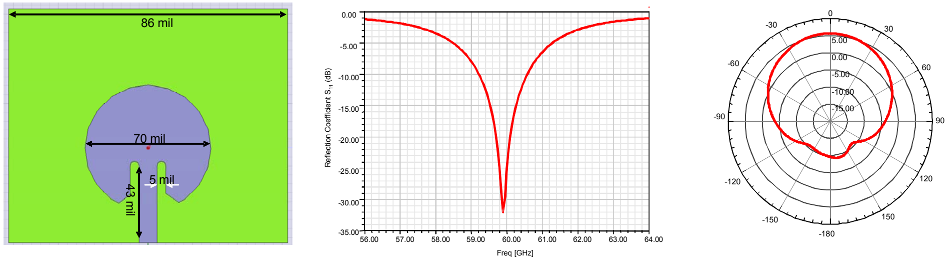


Fig. 5. Sample beam scanning patterns with element tilting

4. Optimization of the Tilt Angles by Genetic Algorithm

In [3,4], a genetic algorithm (GA) based array optimization procedure is proposed by the authors. In [3], this method is applied for the optimization of an antenna array consisting of 60 GHz patch antennas. The patch antenna geometry, simulated reflection coefficient, and the simulated H-plane radiation pattern of the designed patch antenna are illustrated in Fig. 6 [3]. Mainly, the simulated radiation pattern of the patch antenna is imported into the GA algorithm and the resulting tilt angles are calculated. Then this optimized array geometry is used in array simulations and a performance similar to Fig. 5 is obtained that shows beam scanning in the -90° to 90° angle range by selecting a 3 element subarray of the 8 element array for each AOA depending on the received signal strengths.



(a) (b) (c)

Fig. 6. (a) the geometry (1mil=0.001"), (b) the simulated return loss (S_{11}), (c) the simulated H-Plane radiation pattern of the patch [3].

The proposed GA optimization routine is run to achieve -90° to 90° uniform beam scanning for a hybrid smart antenna system with a 3 channel receiver, and an 8-element array. Therefore, a selection of a 3 element subarray out of the available 8 elements takes place. The individual element radiation patterns after being tilted by the optimized angles are shown in Fig. 7. Similar to Fig. 4 and Fig. 5, the solid line at the top in Fig. 7 indicates the trajectory of the beam peaks when the beam is scanned in the indicated angular range. As it is seen, the power levels of the beam peaks remain almost constant exhibiting minimal scalloping effects, in this case about 0.30 dB fluctuation is observed [3].

5. Consideration of the Electromagnetic Interactions Between the Array Elements

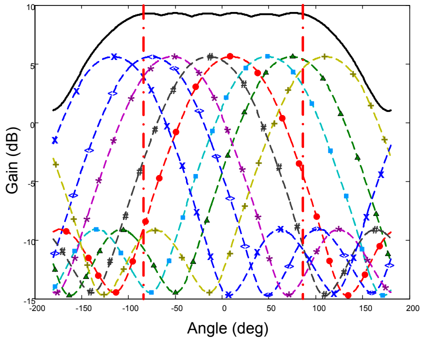


Fig.7. Array element patterns after being tilted by the GA optimized angles, solid line indicates the trajectory of the beam peaks as the beam is adaptively scanned in the indicated angular range.

In the GA based optimization procedure described in Section 4, the electromagnetic (EM) interactions between the array elements and their change with the tilt angle is not considered. Considering the tilt angles such as those used to illustrate the proposed procedure in Fig. 7 are expected to cause considerable changes in the characteristics of the radiation elements as well as impact their associated mutual coupling effects when physically realizing and practically implementing such an array. For example, an excessive tilt angle in Fig. 3 will cause some of the array elements radiate towards the ground planes of the neighboring elements. As a result of this, the radiation patterns of some array elements will be distorted, in other words will not be perfectly rotated as indicated in Fig. 7. Consequently, there will be significant discrepancies between the GA predicted array performance and the actual array performance.

To avoid these problems, a two tiered approach for the array optimization is proposed. First, full wave electromagnetic simulators such as HFSS are utilized to determine the maximal possible tilt angles without encountering significant EM interactions between the array elements. In the second step, these tilt angle limits are imported into the GA based optimization procedure as additional constraints to minimize the changes in the array element characteristics, therefore, minimize the discrepancies between the GA predicted and actual array performances. This approach, therefore, provides a step closer towards the physical realization of a low cost antenna array system with optimized beamforming and beamsteering capabilities using directive elements.

6. Conclusions

This paper summarized the ongoing efforts towards a practical and low cost realization of an optimized antenna array system. Besides traditional optimization of geometrical parameters of the array, we introduce the tilt angles as an additional optimization term so that a uniform beam scanning coverage be achievable over a given angular range. This is particularly important when highly directive array elements are used for low-cost high performance adaptive beamforming applications. Electromagnetic interactions and mutual coupling effects between the array elements, including when taking the tilt angle into account is also considered in this analysis It is shown that, a combination of electromagnetic and digital signal processing assets is required for a more accurate optimization and performance prediction of an array geometry. It is also shown that including the tilt angles, as an additional degree of freedom, resulted in a further overall optimization of the array performance.

7. References

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