2018 IEEE AP-S Symposium on Antennas and Propagation (APSURSI), Boston, Massachusetts, USA, July 8-13, 2018

Beamforming concept for multi-beam antennas based on characteristic modes

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Beamforming Concept for Multi-Beam Antennas based on Characteristic Modes

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***Abstract*—A novel beamforming concept for small cells in 5G cellular systems at millimeter wave frequencies is proposed. Base station antenna arrays may be mounted on street lights or similar elevated structures to form small, densely deployed cells. In such a scenario, the power received by a mobile user within a cell depends on the scan angle due to varying directivity and propagation losses which has considerable impact on the base station efficiency. In order to overcome these issues, multi-beam antennas are employed as array elements. Depending on the scan angle, a suitable beam is selected and then steered towards the user. The multi-beam antennas are designed by means of the theory of characteristic modes. The basic feasibility of the proposed concept is demonstrated.**

I. Introduction

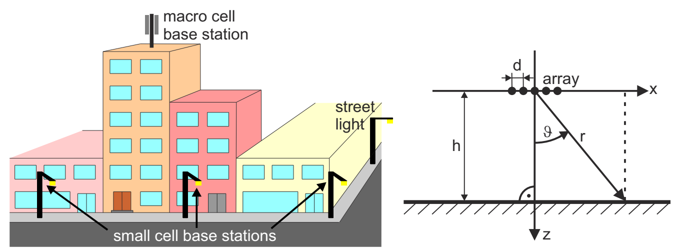
One of the key enabling technologies for 5G cellular systems is the use of millimeter wave frequency bands which offer broader bandwidths and thus higher data rates [1]. As an additional advantage, antenna arrays consisting of a large number of elements can be realized with a compact form factor due to the small wavelengths compared to sub-millimeter wave frequencies. Such electrically large antenna arrays inherently offer highly directive beams, enabling the use of beamforming schemes in the base stations [2].

Due to the increased path loss and atmospheric absorption at millimeter wave frequencies, cell sizes will be smaller than in current cellular networks. Cell radii of up to 200 m have been reported in [1] for different propagation environments. This is, however, not a drawback since densely deployed cells increase the spatial reuse of the wireless resources [3]. Furthermore, beamforming with highly directional beams can be used to overcome the propagation losses.

A conceivable scenario in order to create such small cells is to mount base station antenna arrays on available elevated structures like street lights or traffic lights, which is possible due to the small array size at millimeter wave frequencies (see e.g. [2]). This way, a dense cellular network consisting of small cells can be created without installing additional base station towers.

II. Small Cell Beamforming

An example scenario is shown in Fig. 1(a) where antenna arrays are mounted on street lights which serve as base stations for small cells. The two-dimensional structure of such a cell and its corresponding coordinate system are depicted in Fig. 1(b). The base station antenna array is mounted at a height h above ground. The user's position with regard to the antenna array is defined by the angle ϑ (scan angle) and the distance r.



(a) Example: Street lights as base stations. (b) Coordinate system.

Fig. 1. Small cell scenario.

The array elements are aligned along the x-axis with uniform spacing d and uniform excitation amplitude. For the sake of simplicity, only two-dimensional radiation in the xz-plane will be considered troughout the rest of the paper.

Fig. 2 shows the normalized directivity of an array consisting of five isotropic radiators with half-wavelength spacing for different excitation phases β. Due to the scan loss [4], the directivity decreases if the main beam is steered out of broadside. In order to ensure that the user receives the same amount of power at every scan angle, the radiated power has to be increased to compensate for the decrease in directivity. This has a negative impact on the efficiency of the base station's power amplifier as it has to cope with a high dynamic range of output power [5]. In Fig. 2, the directivity has a range of more than 10 dB. The region where it decreases by 3 dB with respect to broadside is marked by the black lines (approximately from −22.5 ° to 22.5 °).

III. Multi-Beam Antenna

In order to mitigate these issues, multi-beam antenna elements are proposed whose beams are selected depending on the scan angle. The theory of characteristic modes [6], [7] is applied to design such multi-beam antennas. In Fig. 3, the directivities of two characteristic modes of a rectangular patch antenna are shown. Obviously, mode 1 is well suited for

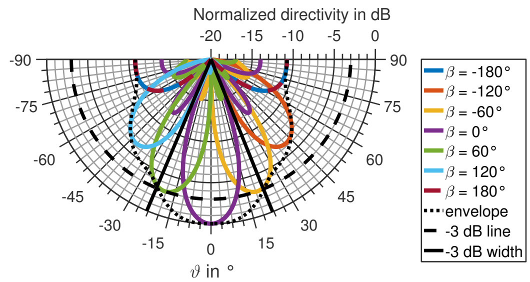
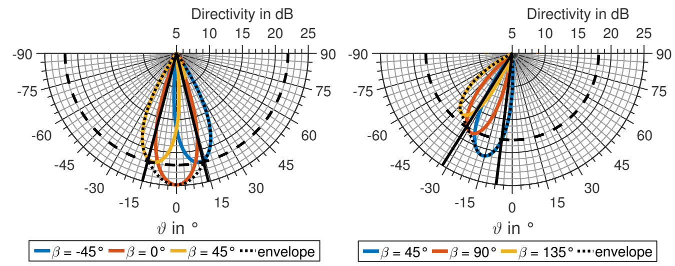


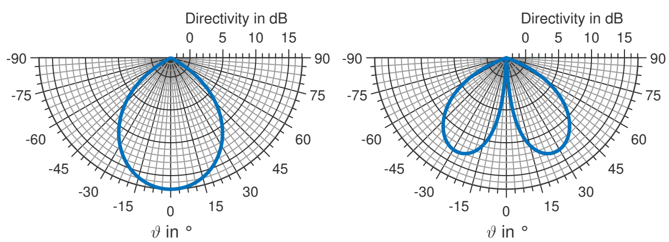
Fig. 2. Directivity of five-element array of isotropic radiators with half-wavelength spacing for different excitation phases β.



(a) Beam 1. (b) Beam 2.

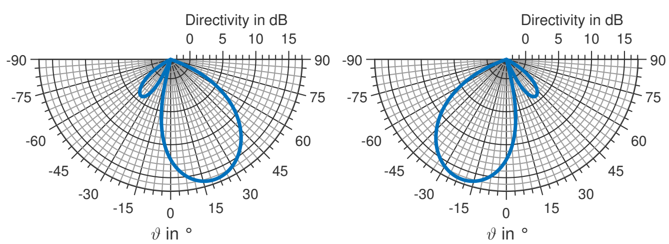
Fig. 5. Beamforming with five-element array of multi-beam antennas with half-wavelength spacing.

broadside radiation whereas mode 2 has two main lobes and is thus not optimal for beamforming. However, by skillfully superimposing both modes, a radiation pattern with one off-broadside main beam can be achieved as shown in Fig. 4.



(a) Mode 1 (beam 1). (b) Mode 2.

Fig. 3. Modal directivity of rectangular patch antenna.



(a) Mode 1 + Mode 2 with 90° phase shift. (b) Mode 1 + Mode 2 with −90° phase shift (beam 2).

Fig. 4. Directivity of superimposed characteristic modes of rectangular patch antenna.

IV. Beamforming Concept

Beamforming with an array consisting of five multi-beam antennas with the modal beams of Fig. 3(a) (beam 1) and Fig. 4(b) (beam 2), respectively, and half-wavelength spacing is shown in Fig. 5. Beam 1 is steered by excitation phases from $-45°$ to $45°$, beam 2 is steered by phases from $45°$ to $135°$. This way, high side lobe levels are avoided. The scan angles which do not decrease the directivity of beam 1 by more than 3 dB with respect to the maximum directivity range from approximately $-15°$ to $15°$ (black lines), those of beam 2 range from approximately $-30°$ to $-7.5°$.

Although beam 2 has a lower maximum directivity than beam 1, the regions where the respective scan losses do not exceed a maximum of 3 dB do not fully overlap, so that beam 1 is used for broadside beamforming and beam 2 for off-broadside beamforming. The two beams are fed by different power amplifiers whose maximum output powers are adjusted to the respective maximum directivity such that the EIRP (equivalent isotropic radiated power) is the same for both beams. With this concept, each amplifier has to cope with a maximum scan loss of only 3 dB and thus a strictly limited output dynamic range, drastically reducing efficiency issues as explained in section II.

V. Conclusion

A beamforming concept for small cells in 5G cellular systems is presented. It aims at reducing the effects of scan loss on base station power amplifier efficiency. To this end, multi-beam antenna elements are used in the base station antenna array. The multi-beam antennas are designed intuitively by means of characteristic mode theory. It is shown that, by using suitable beams for different scan angles, the scan loss can be limited. Based on these promising results, further research will be conducted towards a complete system analysis and design.

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