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Connected Dipole Antenna Cluster of Enhanced Spherical Coverage CDF for mm-Wave Applications

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Abstract—In this paper, we present an antenna cluster concept operating in millimeter-wave (mm-Wave) frequency bands for 5G applications. Unlike conventional arrays made up of identical elements, a cluster array is constructed using non-identical dipoles with high coupling that are placed in a 2-mm wide slot. The cumulative distribution function (CDF) of the spherical coverage gain is used to evaluate the beam-forming capability. High coverage gain over a wide band can be achieved by adjusting the amplitudes and phases of excitation vector. To further enhance the spherical coverage, reactive elements are loaded into the gaps between adjacent dipoles. These reactive elements are selected from a pre-defined database using genetic algorithm-based optimization. The proposed connected dipole cluster demonstrates hemispherical coverage gains greater than 4 dB in the low band (24 to 29.5 GHz) and greater than 6 dB in the high band (37.5 to 43.5 GHz) at the 50% -tile CDF.

Index Terms—5G, mm-Wave, beam-forming, genetic algorithm, spherical coverage.

I. INTRODUCTION

In the past decades, mobile communication has experienced rapid growth, and 5G (5th generation) technology is now being adopted globally. Because of the limited frequency spectrum in Sub-6 GHz, millimeter-wave (mm-Wave) frequency band is to be used. Third-Generation Partnership Project (3GPP) has assigned five frequency bands n257, n258, n259, n260, and n261 (from 24.5 to 43.5 GHz) for the mobile communication. A new standard has also been defined to characterize the beam forming capability with the cumulative distribution function (CDF) of equivalent isotropic radiated power for mm-Wave applications [1], [2].

Some published works aimed at covering the low frequency band from 24 to 29.5 GHz [3], [4]. In [5], a low profile magneto-electric (ME) monopole antenna array of vertical polarization was proposed which can cover the mm-Wave frequency band from 23.5 to 44 GHz. A dual-band dual-polarized antenna array could realize the frequency bands 25.4–30.8 GHz and 38–40 GHz [6]. It is challenging to cover all five mm-Wave frequency bands, particularly in mobile devices because of the limited space available for antenna module.

Unlike the conventional method of avoiding mutual coupling, the tightly coupled array intentionally introduces mutual coupling to achieve a wideband antenna array. [7].

Recently, a new frequency reconfigurable cluster concept was proposed in [8]. In addition to lumped components, amplitudes and phases of feeding vector are adjusted to achieve frequency tunability. However, this work was conducted at sub–6 GHz and did not have the capability for beam-forming.

In this paper, we explore the antenna cluster concept characterized by spherical coverage gain in mm-Wave frequency band. An antenna cluster is placed in a 2-mm wide slot which acts as a metallic housing for antenna module in mobile devices. Dipoles with different lengths are employed to achieve high spherical coverage gain across a wide frequency band through adjusting amplitudes and phases of excitation. In addition, reactive elements between the adjacent dipoles are added to define their mutual coupling. Antenna structures are simulated in CST, and then optimized in MATLAB.

II. THEORY

Related equations are first introduced to maximize the array gain using amplitude and phase of the excitation. Then, the selection of the optimal reactive elements based on genetic algorithm (GA) is described.

A. Maximizing the Array Gain

According to the definition, the antenna gain is presented as

$$G(\theta, \phi) = \frac{4\pi U(\theta, \phi)}{P_{in}}$$

(1)
Fig. 2. Flow chart of the optimization with GA.

where $G(\theta,\phi)$ and $U(\theta,\phi)$ are the gain and radiation intensity in a given direction, respectively; $P_{in}$ is the incident power [9]. $U(\theta,\phi)$ is defined as

$$U(\theta,\phi) = \frac{1}{2\eta}(|E_\theta(\theta,\phi)|^2 + |E_\phi(\theta,\phi)|^2)$$

where $E_\theta$ and $E_\phi$ are two orthogonally polarized components of the electric field in the far field, and $\eta$ is the intrinsic impedance of free space. As shown in Fig. 1, the total electric field of the desired beam is a superposition from all radiators:

$$E_{\text{total}} = E_1 + E_2 + \cdots + E_N$$

where $E_i$ ($i = 1, 2, 3, \cdots$) is the embedded pattern with 50 ohm termination. In a similar manner as scattering parameter in the antenna port interface, we use a transmission coefficient $\Gamma$ to express the ratio of the electric field over the air to the excitation vector $a$

$$\Gamma = \frac{E}{a}.$$ (4)

From the above equations, the array gain can be rewritten as

$$G = \frac{4\pi}{\eta} \frac{a^H \Gamma \Gamma^H \Gamma a}{a^H a}.$$ (5)

Here, $H$ means the conjugate transpose. It can be seen that Eq. (5) is a Rayleigh quotient and the maximum array gain is the largest eigenvalue of $\Gamma^H \Gamma$ when $a$ is the eigenvector corresponding to this largest eigenvalue.

B. Selecting the Optimal Reactive Elements

In order to further improve the array gain, reactive elements are loaded between adjacent dipole elements (c.f. in Fig. 1). Corresponding reactive values are chosen through GA. The iterative optimization process is shown in Fig. 2. An antenna cluster is first simulated in CST, and then the resulting far-field and scatting matrices data is exported to MATLAB for post-processing. A pre-constructed database containing various reactances is utilized. The optimal reactance is selected through GA and loaded into the corresponding ports. Next, the spherical coverage gain of the loaded cluster is calculated according to the equations in the previous subsection, and presented with CDF curves. The spherical coverage gain at the 50%-tile CDF is set as the fitness of GA. After reaching the stop criterion, optimal reactive values and excitation vectors are the outputs.

III. ANTENNA SIMULATIONS

A. Antenna Design

To accommodate the growing number of functions in mobile devices, more and more antenna elements are being placed in a small volume. In this paper, a 2-mm wide slot is used as housing of an antenna array as shown in Fig. 3(a). It is easy to achieve the linear polarization along y-axis or perpendicular to the slot. However, achieving another linear polarization is very difficult in this narrow slot due to the limited efficiency and gain bandwidth for radiation of the EM wave with E-field polarized along x-axis. A four-element dipole array is first designed as a reference. Dipole elements are printed on a substrate with $\epsilon_r = 5$ and $\tan\delta = 0.004$. A superstrate of the same material represents display for mobile devices. Four 50-Ω discrete ports are used to feed the array elements in CST.

A tightly coupled dipole cluster (Cluster–I) of different lengths is built in the same environment as shown in
Fig. 3(b). The cluster array of different resonances can achieve better performance across a wide frequency band based on previous study [10]. For a initial design, the resonances can be evenly distributed across the desired frequency band. Afterward, the lengths can be tuned to increase the distribution of resonances on the frequencies of weaker performance. In addition, reactive elements are used to adjust the mutual couplings among antenna elements. Next, optimal reactive elements are selected based GA by cascading the corresponding scattering parameters in MATLAB. All the dipole elements are connected together through reactive ports in a linear configuration, as shown in Fig. 3(c) (Cluster-II).

B. Spherical Coverage Gain

The employed dipole elements in the reference array can cover a frequency band from 24.5 GHz to 29 GHz with $-10$ dB reflection coefficient if the metal frames are removed. However, it is hard to realize a good impedance matching within the limited space even with dimensional optimization.

In this paper, the upper hemisphere is considered when calculating CDF curves of spherical coverage gain. Besides, the amplitude values are normalized so that the total feeding power is 0 dB. The calculated CDF curves at selected frequencies are given in Fig. 4. We can see that the spherical coverage gains (with dashed lines) at the 50$^{th}$-tile CDF are from 2 dB to 3 dB across the desired frequency band. In comparison, the Cluster–I has better spherical coverage at high band.

The spherical coverage of the Cluster–I and Cluster–II are compared as shown in Fig. 5. It can be seen that the spherical coverage gain at low frequencies are improved by 1.5 dB while the performance at high frequencies are almost the same. Since the spherical coverage is worst at low frequencies, reactive components are chosen to improve it regardless of performance degradation at other frequencies unless the spherical coverage at other frequency becomes the worst one.

C. Tilted Beams

Figure 6 shows the 3D simulated radiation patterns of the Cluster–II in different directions at 27 GHz and 40 GHz. The steered beams realize the largest array gain in the directions $	heta = -60^\circ$, $20^\circ$, $60^\circ$ when $\varphi = 0^\circ$ with corresponding optimal feeding vectors. The steered beams are not symmetric because of the placement of dipoles, and the peak gains...
of steered beams at high frequencies are larger than those at low frequencies. In addition, there is no grating lobe of the antenna cluster when steered to a large angle. The non-uniform element spacing makes it possible to achieve a good trade-off between different beam scanning directions over the large frequency band.

IV. CONCLUSION

In this paper, a cluster concept that employs mutually coupled non-uniform radiators is proposed for mm-Wave frequency band with beam-forming capability. Mutual couplings among antenna elements are used and optimized according to the presented equations and algorithm to improve the spherical coverage across a wide frequency band. A cluster array, consisting of dipoles of varying lengths and non-uniform element spacing, is implemented in a 2-mm wide slot to validate the approach. Compared with the reference array, the spherical coverage gain at the 50%-tile CDF of the proposed cluster is increased by 1.5 dB and 4 dB at low band and high band, respectively. The proposed technique is a promising candidate for the mobile devices with limited volume available for antenna design.

REFERENCES