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Reduction of squint in the slant polarised phased array antennas

Morteza Shahpari

In this letter, the nature of the squint problem in the electrically tilted phased arrays (e.g. BTS antennas) is explored based on the antenna theory and array theory. We consider the antenna elements in the horizontal, vertical, or slant polarisations. We show that the phased arrays with vertical and horizontal polarisations do not suffer from beam squint. However, it is illustrated that the issue of the squint becomes evident when one scans the beam along the vertical plane with slant antenna elements. A solution to reduce the squint problem is proposed which reduces the squint angle by a factor of two, and also improves the symmetry of the pattern.

Brief Introduction: Although squint phenomena have been known to antenna community at least since 1969 where squint angle was defined in [1]. However, as far as the authors are aware of, a deep theoretical analysis is not reported yet to shed light on why patterns are squinted while beams are tilted. The following definitions are proposed for squint in IEEE antenna definition [2].

Squint: A condition in which a specified axis of an antenna - such as the direction of maximum directivity or of a directional null departs slightly from a specified reference axis. Squint is often the undesired result of a defect in the antenna; however, in certain cases, squint is intentionally designed in order to satisfy an operational requirement. The reference axis is often taken to be the mechanically defined axis of the antenna: for example, the axis of a paraboloidal reflector.

Squint angle: The angle between a specified axis of an antenna, such as the direction of maximum directivity or a directional null, and the corresponding reference axis.

Base transceiver station (BTS) antennas can waste half of the electromagnetic power to altitudes higher than BTS tower. To prevent this issue, wireless mobile operators often tilt the beam down either mechanically or electrically. Electrical tilting is preferred over mechanical since it is performed faster and there is no need to make any structural change on the tower. For slant $\pm 45^\circ$ polarised antenna, the beam also shifts to the sides while the operator down-tilts the beam.

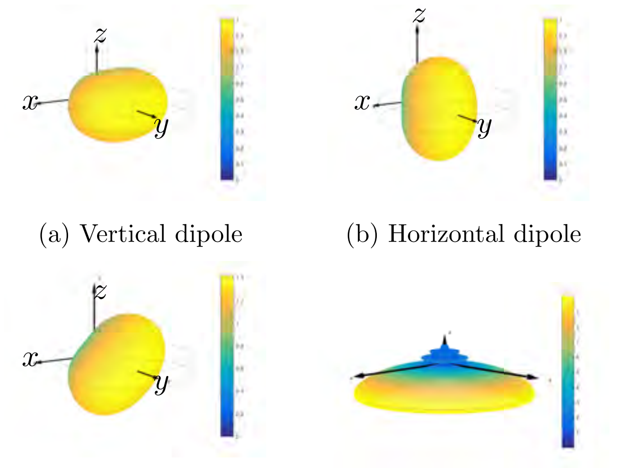
In this letter, we first consider the pattern of individual elements with different orientations. We elucidate on the physical origin and natures of the squint phenomenon by fundamental current elements. We illustrate that beam of slant polarised antennas have an asymmetric pattern which causes the squint when one tilts the beam of base transceiver station (BTS) antennas. Fig. 1 illustrates the 3D pattern of some elementary sources where dotted circles denote two different tilting cases. A down tilted array beam is also shown in Fig. 1(d). When we make a linear array with any antenna element, the total pattern is the product of the element pattern and array pattern (pattern multiplication rule). Since the pattern of a linear array is omnidirectional (whether tilted or not), the asymmetry in the element pattern is the main reason of the squint.

A rich history of the squint reduction techniques cannot be found in the literature. As far as the authors are concerned, most techniques are signal processing algorithms [3], not techniques based on the antenna array theory. We examine properties of linear and perturbed array configurations and propose a method to mitigate the impact of squint on the dual polarised antenna arrays.

Element Radiation Pattern: From the antenna textbooks [4], we know that the far field pattern of a linear antenna with current $\mathbf{J}$ is proportional to:

$$\mathbf{E} \propto \int_{V'} \mathbf{J} e^{-\jmath k \mathbf{r}' \cdot \hat{\mathbf{r}}} dV'. \qquad (1)$$

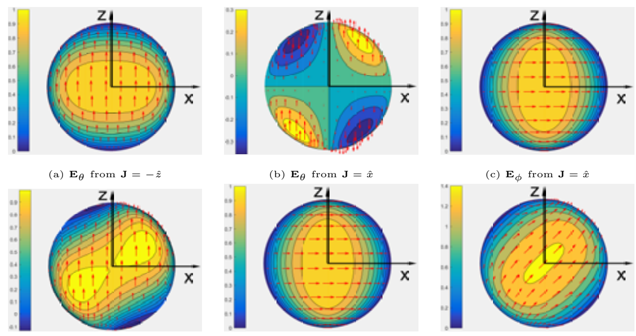
Hereafter, we omit time dependency by considering a time harmonic phasor of $e^{\jmath \omega t}$, and use bold font for vectors, and refer to the current of the Hertzian dipole with $\mathbf{\Pi}$. We also drop the spherical Hankel function and $\jmath \omega \mu_0$ coefficient since we are only interested in the radiation pattern in this letter.



(a) Vertical dipole (b) Horizontal dipole

(c) Slant dipole (d) Tilted array

Fig. 1 *(a)-(c) 3D radiation patterns of Hertzian dipoles in front of the ground plane (d) downtilted 3D pattern of array*



(a) $\mathbf{E}_\theta$ from $\mathbf{J} = -\hat{z}$ (b) $\mathbf{E}_\theta$ from $\mathbf{J} = \hat{x}$ (c) $\mathbf{E}_\phi$ from $\mathbf{J} = \hat{x}$

(d) $\mathbf{E}_\theta$ from $\mathbf{J} = \hat{x} - \hat{z}$ (e) $\mathbf{E}_\phi$ from $\mathbf{J} = \hat{x} - \hat{z}$ (f) $\mathbf{E}$ from $\mathbf{J} = \hat{x} - \hat{z}$

Fig. 2. Far field components $\mathbf{E}$ field from different current sources

Vertical polarization

We consider a z-directed current filament located at $(0, h, 0)$ above a PEC infinite ground at $x - z$ plane. Far field of such small dipole is found from (1) and image theory:

$$E \propto -\hat{\theta} \sin\theta \, \sin[kh \sin\theta \, \sin\phi] \qquad (2)$$

where the first sin function is due to the Hertzian dipole while the $\sin[kh \sin\theta \, \sin\phi]$ stands for the image contribution of the ground plane.

Horizontal polarization

By changing the $\hat{z} \rightarrow \hat{x}$, one finds the radiation pattern of a x-polarised small dipole above the ground plane

$$\mathbf{E} \propto (\hat{\theta} \cos\theta \cos\phi - \hat{\phi} \sin\phi) \, \sin[kh \sin\theta \, \sin\phi]. \qquad (3)$$

Slant polarizaion $\pm 45^\circ$

The current $\mathbf{J}$ on a slant polarised antenna can be considered as $\mathbf{J} = \hat{x} \pm \hat{z}$. Therefore, one readily finds the radiation pattern of a slant small dipole by superposition of (2) and (3).

$$\mathbf{E} \propto -\Big(\hat{\phi} \sin\phi + \hat{\theta}(\sin\theta \mp \cos\theta \, \cos\phi)\Big) \sin[kh \sin\theta \, \sin\phi]. \qquad (4)$$

Origins of squint: Examination of (2)-(4) reveals interesting properties of the radiation patterns. Starting by (2), we see a linear polarised $\mathbf{E}_\theta$ radiation from $\mathbf{\Pi}_z$ which is evenly symmetric around the boresight. As expected one does not find squint issues for vertical currents.

Radiation from $\mathbf{\Pi}_x$ is only purely ϕ polarised on the equator $\theta = \pi/2$ where the pattern is also symmetric relative to boresight (see Fig. 2). If we move away in any direction from the equator, then radiation from $\mathbf{\Pi}_x$

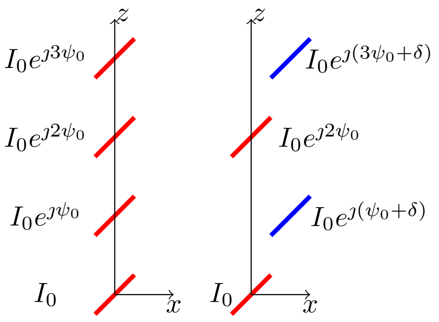


Fig. 3. (left) A linear uniformly spaced array; (right) A perturbed array

also contains $\mathbf{E}_\theta$ component. Another interesting fact is that sign of $\mathbf{E}_\theta$ changes at either of $\phi = \pi/2$ or $\theta = \pi/2$ lines due to $\cos\theta\,\cos\phi$ factor. Therefore, $\mathbf{E}_\phi$ and $\mathbf{E}_\theta$ have respectively even and odd symmetries around boresight. While tilting the beam, we do not observe squint issues in the arrays of horizontal dipoles since we consider the ϕ component as the co-polarised component [5, 6]. One often ignores $\mathbf{E}_\theta$ as the cross-polarised even with generalised or Ludwig 3 definitions.

Slant radiation pattern is a linear combination of vertical and horizontal dipoles. $\mathbf{E}_\phi$ is only impacted by $\mathbf{\Pi}_x$. Both $\mathbf{\Pi}_x$ and $\mathbf{\Pi}_z$ contribute to the $\mathbf{E}_\theta$. For a $+45°$, they cancel out in the first and third regions of the $x-z$ plane (where $\cos\theta\,\cos\phi > 0$), while add up in the second and fourth quarters of $x-z$ plane. Therefore, we see that pattern of slant $+45°$ is rotated by $-45°$.

Due to asymmetries imposed on the radiation of slant dipoles, we see that squint phenomenon is significant if one scans the beam away from the equator (planes of $\theta = \texttt{constant}$). Squint is also evident on the $\phi = \texttt{constant}$ planes which do not pass the boresight ($\phi \neq \pi/2$). Although this is not exactly observed in BTS antennas because one often does not need beam tilt in the horizontal direction.

For slant antennas with larger physical size, it is likely that the radiation patterns are more compact around $\theta = \pm\phi$ contours. Therefore, the slant pattern is more asymmetric and consequently, we often have larger squint values.

Solution to compensate the squint: BTS antennas are often constructed by a linear array of dual polarised antennas elements (Fig. 3 left). Array factor of a linear array with elements positioned on the z axis is the only function of elevation angle, regardless of the array excitation coefficients. Therefore, a linear array is not capable of the squint compensation.

In order to decrease squint, we consider perturbing a linear array by shifting half of the array slight in the x direction ($d_x < \lambda/10$). Therefore, the array is divided into two subarrays. By adding a phase gradient of between the left and right subarrays, the array factor is rotated in the azimuth direction (Fig. 3 right). As will be illustrated in the next sections, precise phase difference and positioning of the subarrays can effectively reduce the squint phenomenon.

The array factor for a linear array of uniformly spaced elements can be found in any antenna reference books [4, 7]. Assuming there are N elements in the whole array, k as the wavenumber, we can write pattern of each left/right subarray:

$$AF_1 = \frac{\sin\left[0.5Nkd_z(\cos\theta - \cos\theta_0)\right]}{0.5N\sin\left[kd_z(\cos\theta - \cos\theta_0)\right]}. \qquad (5)$$

where the $\theta_0 = \arccos[\frac{\psi_0}{kd}]$ is the tilt angle.

On the other hand, the two subarrays form a small two-element array that can be considered as one element on the origin, and the second element at $(d_x, \lambda/4, d_z)$. The second element also has a phase shift of $\psi_0 + \delta$. Therefore, we find the array factor for this small array in the following form:

$$AF_2 = \cos[0.5(kd_x\sin\theta\cos\phi + kd_z\cos\theta + \psi_0 + \delta)]. \qquad (6)$$

By pattern multiplication rule, we can find the final pattern from the product of AF_1, AF_2, and element pattern.

Results: We know that squint is more severely observed for typical antennas where the beamwidth is narrower and the antenna is more directive. Investigation of the problem for an antenna with $HPBW \approx$ 70° reveals that our proposed approach is more suitable for antenna elements with a larger squint (see Fig. 4). We summarised the performance of the arrays with traditional (linear) and compensated arrangements in Table 1. The locus of the squint angle changes for a typical $+45°$ slant from $90° - 83°$ with up to $10°$ tilting, which is squint of $\pm 7°$. In the compensated approach, maximum of the beam varies from $93° - 87°$ resulting in total squint of $\pm 3°$. That is a reduction in the squint of the array by more than a factor of two.

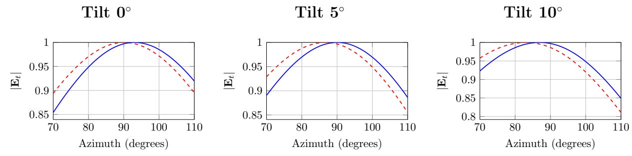


Fig. 4 *Typical BTS antenna ($HPBW = 70°$) in in traditiional (red dashes) and compensated (blue solid line) configurations.*

Table 1: Summary of the squint for a typical antenna with HPBW of 70°

	Squint Angle		**Symmetric FOM**	
Tilt	Traditional	Compensated	Traditional	Compensated
0°	0	3	1	1.0753
5°	3.6	0	0.9197	0.9941
10°	7	-3	0.8460	0.9190

We also defined a symmetric figure of merit in the following form:

$$FOM = \frac{|\mathbf{E}_{110°}|}{|\mathbf{E}_{70°}|}, \qquad (7)$$

to examine the asymmetries in the radiation patterns. Data in Table. 1 shows that with our approach patterns are also much more symmetric at different tilting angles.

Conclusion: In this letter, we illustrate deeper insights into the rise of squint in the phased array antennas while tilting the beam. Our analysis shows that squint is due to the asymmetries in the radiation pattern of $\pm 45°$ polarised arrays which is originated from odd symmetries of the $\mathbf{E}_\theta$ component. A method to compensate the undesired effect of squint is proposed which is based on perturbing the linear array and adding an extra phase shift to each subarray. The proposed solution can achieve a factor of two reductions in squint angle and improve the symmetry of the pattern.

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