On Effective Gain Variability with Antenna Orientation

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Abstract— Antenna pattern for both vertical and horizontal polarization varies with antenna's orientation angle. Varying antenna orientation is a common practice with advanced portable wireless devices such as smart phones. This orientation variability affects its effective gain, which has impact on performance of wireless communication system. In this work, we address effective gain variability with antenna orientation. We present the well-known mean effective gain (MEG), instantaneous effective gain (IEG) and stochastic effective gain (SEG). The data series of IEG and SEG is used to extract their statistics as function of the orientation angle.

1. INTRODUCTION

Antenna characteristics, in particular its gain,have major impact on link quality and performance of wireless communication system. Antenna gain is a crucial parameter in design of communication systems where direct line-of-sight (LOS) exists between transmitter and receiver such as in microwave links, where both transmitter and receiver are fixed. Such communication links require maximum gain of antenna in pointing direction to the other communications end. For such applications, the maximum antenna gain is a useful parameter to characterize and improve communications link quality. However, in other applications such as mobile communications, the mobile terminal could be in any direction relative to the main pointing direction of maximum gain of the fixed station (e.g., base station) antenna. The position of mobile terminal could be in LOS or non-line-of-sight (NLOS). In LOS, direct signal may arrive to a fixed antenna from directions other than that of maximum antenna gain and similarly with NLOS propagation conditions. It is well known that in multipath environment, the effective gain of antennas cannot be characterized by directive gain with sufficient accuracy. In multipath channel, the maximum directive gain can be used to increase coverage in particular geographical regions but it does not maximize the gain in a specific direction. Mean effective gain (MEG) has been introduced in literature [1–4] as a more descriptive parameter for multipath propagation environment that accounts for mutual relationship between antenna radiation pattern and strength of multipath components from different directions. MEG is a statistical average measure over a series of measurements along a "route" that is considered as environment measure. The MEG of antenna is usually given in a single number for fixed antenna orientation. This fixed number could be acceptable in in fixed antenna orientation but not for variable orientation. Communication systems based on reconfigurable antenna adopt switching between different antenna states in order to enhance its performance. Hence, neither directive gain nor MEG are anymore good metrics that are needed for switching decisions. Switching between antenna states has to be based on instantaneous information. This leads to the concept of instantaneous effective gain (IEG) [5], which is based on instantaneous signal power distribution. The IEG is more suitable than MEG to applications, where antenna pattern switching takes place.

In this work, we present variability of MEG with average cross polarization ratio (XPR) and antenna orientation in order to find the critical angle for half-wavelength dipole antenna, where the MEG is independent of XPR and find parameters that affect the critical angle. We also present variability of IEG with orientation angle for fixed and random parameters of vertical plane angle of arrivals in terms of cumulative distribution function (CDF). The statistics of IEG in terms of its mean are also presented as a function of inclination angle of dipole antenna. Then, we discuss our investigations on the statistics and variability of SEG in order to provide more insight in its variability with instantaneous XPRs and azimuthal and elevation angle of arrivals. We present how the CDF and statistics of the SEG vary with antenna orientation angles.

2. EFFECTIVE ANTENNA GAIN

The advance in handheld wireless terminals such as smart phones and portable devices require more care in antenna design due to dynamic variation of device's orientations. The match between directional radio channel response with polarization state and radiation pattern of antenna has significant role in performance of wireless devices. Handling of smart phones and portable wireless devices could have different orientation at dynamic convenience of a user. This makes it to have different angles relative to directional information of multipath components. This is reflected in the interplay between the antenna pattern and multipath components for different polarizations. This interplay can be characterized in the average sense by MEG of antenna, or in instantaneous sense by IEG. However, both parameters are obtained from stochastic nature of the interaction of antenna and arrived radio wave signals from different directions and polarizations. The MEG as a commonly used statistical measure can be written as [1]

$$MEG = \frac{P_{rec}}{P_\theta + P_\phi} \tag{1}$$

where P_{rec} is the average received power that is given as

$$P_{rec} = \oiint \left\{ P_\theta \Im_\theta \left(\Omega, \Psi\right) P_\theta \left(\theta, \phi\right) + P_\phi \Im_\phi \left(\Omega, \Psi\right) P_\phi \left(\theta, \phi\right) \right\} \sin\theta d\theta d\phi \tag{2}$$

and P_θ and P_ϕ are the average received power of electric field of θ- and ϕ-polarization states, since any incident wave can be decomposed into two polarized components, E_θ in vertical plane and E_ϕ in the horizontal plane, $\Im_\theta(\Omega, \Psi)$ and $\Im_\phi(\Omega, \Psi)$ are the θ- and ϕ-components of radiation gain pattern of antenna with orientation angle, $\Psi(\alpha, \beta)$, of inclination angle (α) and tilt angle (β), Ω is direction of arrivals of radio waves in elevation plane θ, relative to z-axis and ϕ in azimuthal plane, relative to x-axis. The average cross polarization ratio (XPR) is given as $XPR = P_\theta / P_\phi$, $P_\theta(\theta, \phi)$ and $P_\phi(\theta, \phi)$ are the weighted probability density function of angle of arrivals of the stochastic components angular power densities. The MEG as a function of XPR is commonly used as this ratio combines both P_θ and P_ϕ. It is given as [1]

$$MEG = \int_0^{2\pi} \int_0^{\pi} \left\{ \frac{XPR}{1+XPR} \Im_\theta \left(\Omega, \Psi\right) P_\theta \left(\theta, \phi\right) + \frac{1}{1+XPR} \Im_\phi \left(\Omega, \Psi\right) P_\phi \left(\theta, \phi\right) \right\} \sin\theta d\theta d\phi \tag{3}$$

It has been shown by many measurement campaigns [6] that XPR has a lognormal distribution for different indoor and outdoor environments. Hence, the MEG for fixed orientation angle, Ψ, can be written to include of being a function of χ as a random variable of XPR as follows

$$MEG = \int_0^{2\pi} \int_0^{\pi} \int_0^{\infty} \left\{ \frac{\chi}{1+\chi} \Im_\theta(\Omega, \Psi) P_\theta(\theta, \phi) + \frac{\chi}{1+\chi} \Im_\Phi(\Omega, \Psi) P_\Phi(\theta, \phi) \right\} \sin\theta d\chi d\theta d\phi \tag{4}$$

This formulation may be extended further assuming that Ψ has a random distribution, which makes it to have more integration levels, one is over random variable inclination angle (α) and other integration is over random variable tilt angle (β). The weighted probability density function of angle of arrivals has to satisfy

$$\int_0^{2\pi} \int_0^{\pi} P_\theta \left(\theta, \phi\right) \sin\theta d\theta d\phi = \int_0^{2\pi} \int_0^{\pi} P_\phi \left(\theta, \phi\right) \sin\theta d\theta d\phi = 1 \tag{5}$$

and can be given as [1]

$$\int_0^{2\pi} \int_0^{\pi} P_\theta \left(\theta, \phi\right) \sin\theta d\theta d\phi = \int_0^{2\pi} \int_0^{\pi} P_\phi \left(\theta, \phi\right) \sin\theta d\theta d\phi = 1 \tag{6}$$

$$P_\theta \left(\theta, \phi\right) = A_\theta \exp\left(-\frac{\left\{\theta - \left(\pi/2 - \mu_\theta\right)\right\}^2}{2\sigma_\theta^2} \right) \tag{7}$$

$$P_\phi \left(\theta, \phi\right) = A_\phi \exp\left(-\frac{\left\{\theta - \left(\pi/2 - \mu_\phi\right)\right\}^2}{2\sigma_\phi^2} \right) \tag{8}$$

where μ_θ and μ_ϕ, are the mean elevation angle of each θ- and ϕ-wave distribution, respectively, observed from horizontal direction and σ_θ and σ_ϕ are their corresponding standard deviation of wave distribution, A_θ and A_ϕ are selected to satisfy the above mentioned conditions in Eq. (5). For IEG, the following parameters has to be instantaneous values, $P_{rec}(t)$, $P\theta(t)$ and $P_\phi(t)$ {i.e., $XPR(t)$}. The formulation to compute ISG is same as MEG but the values are instantaneous values instead of average ones [5]. The IEG parameter combines the instantaneous interaction of radiation pattern of antenna under test with propagation characteristics of the environment relative to a reference antenna (e.g., isotropic) antenna. The impact of antenna on IEG depends on antenna characteristics such as antenna pattern, polarization, orientation, etc.. The IEG is a measure how a partial radiation gain interacts with a realization of a stochastic channel that varies with varying directional informations and matching angles. It is shown in [4] that IEG is maximized when antenna coefficients are equal to the complex conjugates of the expansion coefficients of the incoming field of the spherical vector waves.

The formulation in (3) shows that the MEG is a mathematical averaging of the random functions [6]:

$$G_{eff}^{\theta} \sim \frac{XPR}{1+XPR}\Im_\theta(\Omega,\Psi) \tag{9}$$

$$G_{eff}^{\phi} \sim \frac{1}{1+XPR}\Im_\phi(\Omega,\Psi) \tag{10}$$

This leads to definition of stochastic effective gain (SEG), which can be formulated as

$$SEG = G_{eff}^{\theta} + G_{eff}^{\phi} \tag{11}$$

The mean of SEG can be expressed as

$$MSEG = E\{SEG\} \tag{12}$$

where $E\{\cdot\}$ is the mean operator. The CDF of SEG as a function of antenna orientation angle Ψ can be obtained by Monte-Carlo method. The process is based on repeatedly generating large number of multipath components with arrival angles (θ_i, ϕ_i) and cross-polarization of each path is characterized by χ_i. Super-resolution analysis of multi-antenna measurement indicated that XPR multipath components can be modeled with lognormal distribution as shown [7] for different propagation environments. The SEG can also be characterized with second order statistics to a measure to fluctuation of antenna effective gain. This detailed knowledge of effect of antenna is also important for multiple antenna channels [8, 9].

3. NUMERICAL RESULTS

In this work, the antenna orientation is simulated with antenna orientation angle, Ψ, of antenna pattern of a half-wave dipole of a mobile device with varying inclination angle of the antenna (α) and assumed tilting angle (β) be zero, which makes $\Im_\theta(\Omega,\alpha) = \Im_\theta(\Omega,\Psi)$ and $\Im_\phi(\Omega,\alpha) = \Im_\phi(\Omega,\Psi)$. The θ-component of antenna pattern, $\Im_\theta(\Omega,\Psi)$ and ϕ-component of antenna pattern, $\Im_\phi(\Omega,\Psi)$, can be written as [1]:

$$\Im_\theta(\Omega,\alpha) = 1.64(\cos\theta\cos\phi\sin\alpha - \sin\theta\cos\alpha)^2 \frac{\cos^2(\pi\zeta/2)}{(1-\zeta^2)^2} \tag{13}$$

and

$$\Im_\phi(\Omega,\alpha) = 1.64\sin^2\phi\sin^2\alpha\frac{\cos(\pi\zeta/2)^2}{(1-\zeta^2)^2} \tag{14}$$

where $\zeta = \sin\theta\cos\phi\sin\alpha + \cos\phi\cos\alpha$ and the angle α is the inclination angle of the antenna element from z-axis in the vertical zx-plane, ϕ is the azimuth angle relative to x-axis, θ is the elevation angle relative to z-axis, the coefficient 1.64 corresponds to the directivity of the half-wavelength dipole antenna.

The presented simulation results are for indoor environment. It is assumed that the distribution of azimuth angle of arrival is uniform distribution within angular range of $(0, 2\pi)$ for both polarizations. The distribution of elevation angle of arrivals is assumed Gaussian with mean angle of arrival μ_θ and μ_ϕ for both θ- and ϕ-polarizations with standard deviation of σ_θ and σ_ϕ, respectively. We assume in the simulation that both polarization have same values of μ and σ (i.e., $\mu_\theta = \mu_\phi$ and

$\sigma_\theta = \sigma_\phi$), though they may not be same in reality. Figure 1 shows the commonly known behavior of MEG for different values of average XPR and antenna inclination angle, when $\mu_\theta = \mu_\phi = 30°$ and $\sigma_\theta = \sigma_\phi = 30°$. The 0° inclination angle has lowest MEG with lowest tested XPR value. At this angle, the MEG increases as XPR increases. The MEG in channels with negative average XPR values varies in a slower rate as inclination angle moves from 0°. The MEG varies slowly generally with inclination angle for positive average XPR values when compared to negative values of XPR. Measurement data for indoor propagation showed that XPR values are generally positive. Figure 1(b) shows a critical inclination angle that the MEG is independent of XPR, which is close to (±60°). Detailed investigation showed that the critical inclination angle is a function of both mean and standard deviation of angle of arrivals. Figure 2 shows the this critical inclination angles as a function of both μ and σ. We can see that space of critical angles is dominated by mainly two degree, i.e., 60° and 55° at which the antenna patterns for both polarization are quite similar. Figure 3 depicts behavior of IEG generated by large number of channel realizations where IEG is computed for every channel realization. Each channel realization is generated by large number of multipath components. Each signal is characterized by $(\theta_i, \phi_i, \chi_i)$, where θ_i, ϕ_i, χ_i are elevation angle of arrival, azimuth angle of arrival, and XPR value of radio wave signal i, respectively. The χ_i, instantaneous XPR, has lognormal distribution with mean of 8.7 dB and standard deviation

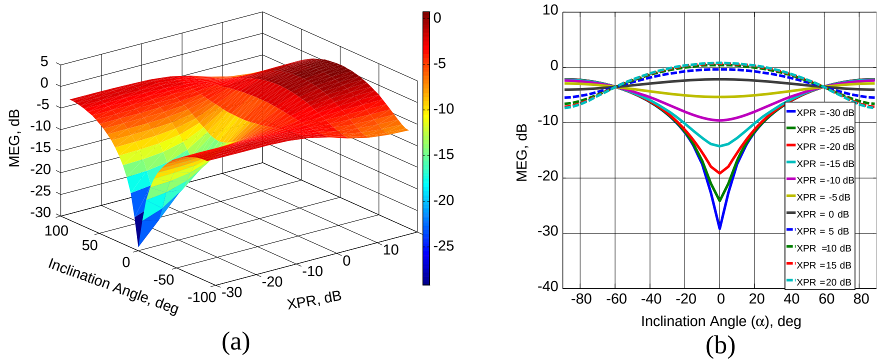


Figure 1: Behavior of MEG when $\mu_\theta = \mu_\phi = 30°$ and $\sigma_\theta = \sigma_\phi = 30°$.

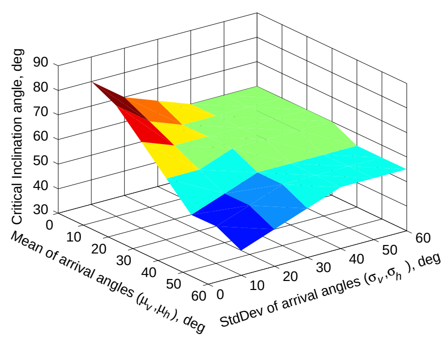


Figure 2: Critical inclination angles.

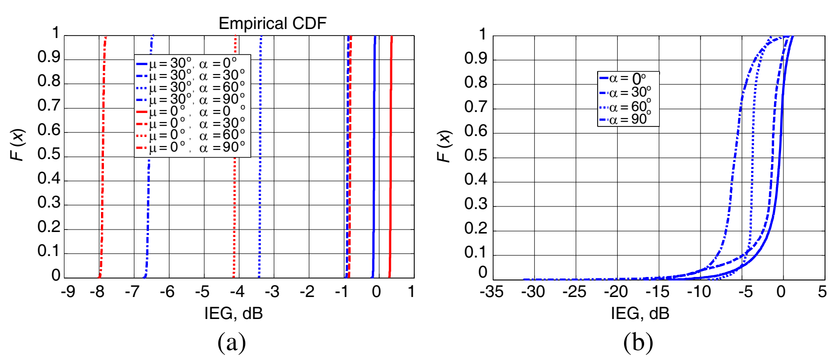


Figure 3: CDF of IEG. (a) Fixed $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$, (b) random $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$.

5.2 dB. In order to investigate IEG, two different Monte-Carlo experiments have conducted; 1) Fixed $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ for all realizations; and 2) Random $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ that differ from realization to other. Figure 3(a) depicts CDF of variability ofIEG with inclination angles for two fixed parameters $\mu_\theta = \mu_\phi = 0°$ for horizontal plane propagation and $\mu_\theta = \mu_\phi = 30°$ for oblique propagation. Both data sets are generated for $\sigma_\theta = \sigma_\phi = 30°$. We can see clearly that the mean offset increases with inclination angle of antenna but also depends on mean direction of elevation angle of arrival. The shape of CDF curves is still the same for different values of α but differ in offset values. Figure 3(b) shows the CDF of variability IEG as a function of α for random $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ where offset value and shape of CDF curves change. The estimated mean of IEG as a function of α for the three different sets of IEG realizations are depicted on Figure 4. The horizontal propagation makes higher mean IEG for low values of α and lower gain than that of oblique propagation at higher values of α. The mean of IEG for random $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ is lowest for small values α but is higher for large α. The SEG realizations are generated by assuming large number of arriving radio wave signals that follow particular statistical distributions in azimuth and elevation planes as described earlier. Figure 5 shows CDF of SEG for different values

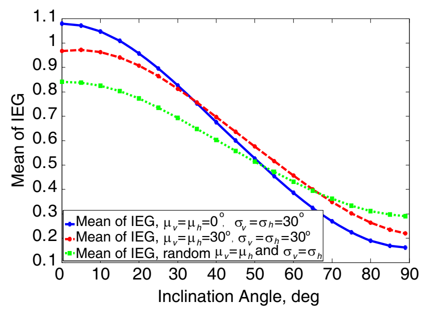
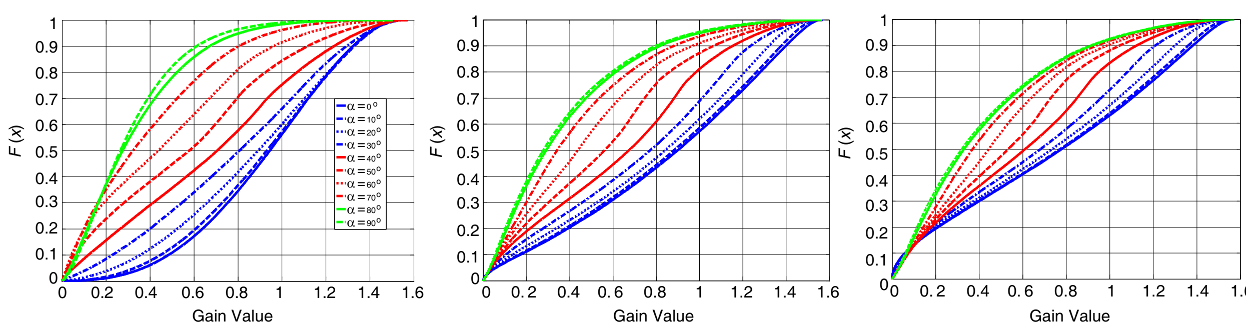
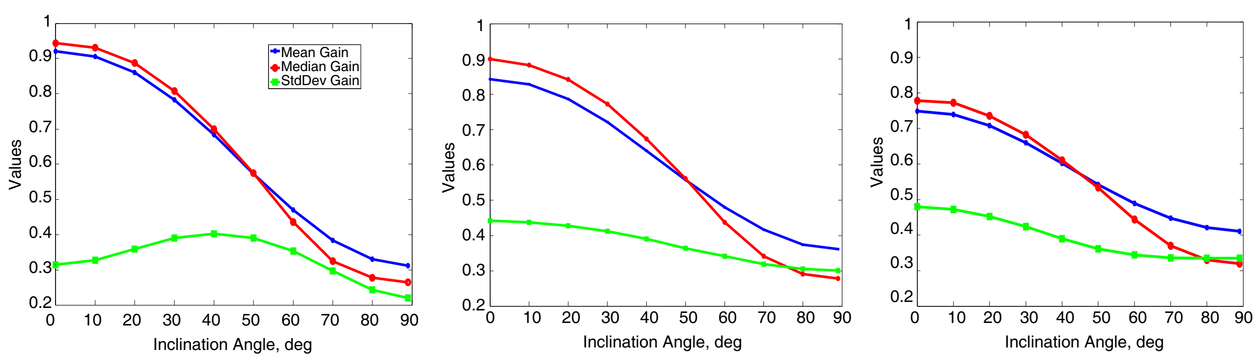


Figure 4: Mean of IEG.



(a) $\sigma_V = \sigma_H = 15^o$ (b) $\sigma_V = \sigma_H = 30^o$ (c) $\sigma_V = \sigma_H = 45^o$

Figure 5: CDF of SEG for different inclination angles and direction spread of elevation angle of arrival.



(a) $\sigma_V = \sigma_H = 15^o$ (b) $\sigma_V = \sigma_H = 30^o$ (c) $\sigma_V = \sigma_H = 45^o$

Figure 6: Mean, median and StdDev of SEG for different inclination angles and direction spread of elevation angle of arrival.

of inclination angles for different values of standard deviation of elevation angle of arrivals (i.e., $\sigma_V = \sigma_H = 15^\circ$, $\sigma_V = \sigma_H = 30^\circ$, $\sigma_V = \sigma_H = 45^\circ$) as indicated on the figure. The curves are obtained for $\mu_V = \mu_H = 30^\circ$ and instantaneous XPR has same parameters of lognormal distribution stated earlier. The range of inclination angles are shown in Figure 4(a) (i.e., 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°). This different inclination angles cause different antenna patterns for vertical and horizontal polarizations, which lead to different levels of interplay between multipath components of different values of $(\theta_i, \phi_i, \chi_i)$. The variability ranges of SEG with increasing inclination angles reduces with increasing σ for fixed μ. The $MSEG$ (given as mean gain on figure), median and standard deviations of SEG of the CDF curves as function of inclination angles are presented in Figure 5. The MSEG and median of SEG reduces with inclination angle for different values of $\sigma_V,\ \sigma_H$. The fluctuation of SEG around its MSEG increases with inclination angle with higher $\sigma_V,\ \sigma_H$.

4. CONCLUSION

This work has presented investigation resultson the critical inclination angle of half-wavelength dipole antenna and showed that, based on Monte-Carlo simulation, it is a function of mean and standard deviations of elevation direction of arrival. The common critical angle is close to 55° and 60°, where radiation pattern of both vertical and horizontal polarization are similar. Other critical inclination angles are also observed. Statistical analysis of Monte-Carlo simulation of both IEG and SEG have been presented. The mean of IEG reduces with increasing inclination angle of antenna for fixed $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ and keep same IEG distribution, however, though the mean reduces for random $\mu_\theta = \mu_\phi$ and $\sigma_\theta = \sigma_\phi$ but the shape of the IEG statistical distribution also changes. The mean, median of SEG reduces with inclination angle. The standard deviation of fluctuations of SEG increases with inclination angles. The statistical results are for different values of angular spread of elevation angle of arrival.

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