Antenna beam tilting effects in fixed and mobile communication links

M. V. S. N. Prasad*, M. M. Gupta, S. K. Sarkar and Iqbal Ahmad
Radio and Atmospheric Sciences Division, National Physical Laboratory, Dr K. S. Krishnan Road, New Delhi 110 012, India

Several remedial measures like space diversity, frequency diversity, route diversity, increase in antenna height, antenna tilting, etc. have been tried by many workers to overcome the debilitating effect of multipath fading in fixed line-of-sight microwave and mobile communication links. Among these remedial measures, diversity techniques have been extensively studied in terms of improvement factors, whereas the concept of antenna tilting is relatively less explored compared with other remedial measures. In the present study, the effect of antenna tilting on fixed and mobile communication links is investigated to find out the optimum tilting angles in terms of design parameters.

ANTENNA beam tilting effects have been effectively employed in the past to overcome multipath fading induced by superrefractive/ducting layers in microwave fixed line-of-sight (LOS) links. These approaches and experiments helped to design angle diversity schemes in LOS links. In these cases, upward tilting of the antenna cuts-off or reduces the radio frequency energy refracted by the ground-based layers and reduces the multipath fading. Taking the clue from these experiments, some workers have tried to employ the concept of tilting on mobile communications in cellular networks. It has been observed that downward tilting of antenna beam can reduce the interference effects in other macro cells. Since super-refractive and ducting layers would not affect the performance of cellular networks, upward tilting of antenna beam cannot yield appreciable improvements, except in special situations. Downward tilting decreases the probability of occurrence of unacceptable inter symbol interference (ISI) due to multipath propagation by diminishing the power level of echoes with long delay times. Delay time determines the rms delay spread, which in turn determines the transmissible bit rate. In analogue systems, fade depth can be decreased. In mobile communications, when the cell site uses a high gain antenna, downward tilting can direct the nulls in the antenna pattern towards the horizon to prevent the energy from propagating into other cells. In the case of a low-gain antenna, discrimination between horizon and edge of a cell is less. This can be improved with increase in height. Using a high gain, high antenna elevation and downward tilting, the base-station can reduce its power relative to what would be required from a low-elevation site. When the antenna height is close to that of buildings, any height increase would degrade the delay spread due to long-distance reflectors. It seems that high sites and downward tilting cannot be effectively used without each other. Improvement in raising base-station antenna is offset by long-distance reflectors, if downward tilting is not used. Also, in the case of a low-site, downward tilting is ineffective because the edge of a cell cannot be discriminated from the horizon. High antenna with downward tilting will be able to discriminate the edge of the intended coverage area and significantly reduce system interference. Upward tilting is useful if radio energy has to be reached in the upper floors of high-rising towers. Figure 1 illustrates the basic concept of antenna tilting. Chang and Kim have shown that a tilting angle of $10^\circ$ is necessary to obtain the effectiveness of down-tilt. Blackard et al. observed decrease in path loss and increase in delay spread with antenna height. Effect of low antennas with tall buildings on either side was reported. DeWeck et al. studied delay spread in mountainous terrain using various antenna patterns and heights. To avoid potential reflectors, they recommended high-gain antennas with appropriate down-tilting. Low antenna heights (13, 3 m) were studied by Feurestein et al. without tilting.

Results

In the present study an attempt has been made to find out the effects of tilting by evaluating system performance under multipath distortion. In the fixed category, effects of upward

Advantages of downward tilting

When the cell site uses a high-gain antenna, downward tilting can direct the nulls in the antenna pattern towards the horizon

*For correspondence. (e-mail: mvpasad@mail.nplindia.ernet.in)
tilting have been investigated in terms of experiments carried out on microwave LOS link at 2 GHz. The improvements obtained have been presented in terms of fade depths for different percentages of time for a given tilting angle. Here the angle of tilting was less than one degree. In the case of mobile communications, such type of experiments could not be conducted due to lack of experimental facilities. Hence we have evaluated theoretically the system performance using the approach of Tong and Akaiwa. The ratio of the energy of reflected wave to that of direct wave for untitled and tilted positions for various path loss exponents has been deduced. The most critical parameter characterizing a specific region is the path loss exponent. This has been deduced by us from our mobile communication experiments conducted in the northern region of India. This parameter reflects the rate of decrease of signal level in a given region and is an important design parameter. According to this, the signal power at the mobile is given by

$$P_m = AG_i[\tan^{-1}(h_b/r) - \theta_0]G_ar^{-n},$$  \hspace{1cm} (1)

where $h_b$ is the base-station antenna height, $G_i$ is gain of transmitting/base-station antenna, $G_m$ is gain of mobile antenna, $r$ is the path length or communication distance, $n$ is path loss exponent, $\theta_0$ is tilting angle, and $A$ is a constant related with transmitted power, frequency, antenna height, etc. In mobile communication, height of the receiving antenna is that of the body height of the vehicle while travelling. Hence, there would not be much variation in mobile antenna height. The power of the reflected wave is given by

$$P_r = A(r + x)^{-n}G_i[\tan^{-1}(h_b/r + x) - \theta_0]G_ar,$$  \hspace{1cm} (2)

Here $x$ is the excess path difference and reflection coefficient is taken as 1.

Excess path difference is the path difference between the direct ray and the ground-reflected ray. The ground-reflected ray travels a longer path length. Hence, the term popularly used in this field is 'excess path difference'. The energy of the reflected wave decreases with respect to the direct wave by a loss factor $\gamma$.

$$\gamma = \frac{P_m}{P_r} = \frac{G_i[\tan^{-1}(h_b/r) - \theta_0]}{G_i[\tan^{-1}(h_b/(r+x)) - \theta_0]}(r + x/r)^{-n}. \hspace{1cm} (3)$$

Using these inputs, the power ratio of untilting to tilting situations as a function of communication distance has been calculated for different path loss exponents deduced from our experiments. Figure 2 depicts the variation of maximum excess path difference calculated from the above equations as a function of $n$ for $h_b = 30$ m for both tilted and untitled positions for mobile communication system. A height of 30 m corresponds to the mobile communication system and 100 m corresponds to that of the fixed communication system such as LOS microwave communication links. The difference between the two appears in the height of the transmitting antenna as far as the eqs (1) to (3) are concerned. In the case of the mobile system with 3° tilted position, the excess path difference decreases with increase in $n$. From $n = 2.5$, the path difference decreases slowly, whereas in the case of the untitled position, the corresponding decrease appears at $n = 3.2$. Figure 3a and b depicts the variation of loss factor as a function of excess path difference deduced from eq. (3) for mobile communication system for tilting angles of 3° and 0° and for $n$ values ranging from 1.6 to 4.5. In the case of large path loss exponents in Figure 3a, a loss factor of 10 is seen at excess distances of less than 2000 m, whereas for $n = 3$ excess distances of 4000 m are seen for the same loss factor. The rise in loss factor is steep for large $n$ values, whereas in the case of small $n$ values, the rise is gradual. At loss factor values of 10, echoes would become weak and they can be neglected. These figures give an idea of excess path lengths, where echoes become weak for various path loss exponents at a tilting angle of 3°. In the case of Figure 3b corresponding to an untitled position, the corresponding excess path lengths are higher compared to 3° for the same path loss exponents. This indicates that when the antenna is tilted, delays would come down, which in turn decreases the inter-symbol interference and quality of the system goes up. Figure 4a shows the ratio of power received at the untitled position to power at 3° as a function of communication distance for a mobile system for tilting angles ranging from 3° to 10°. These help deduce the cell sizes for various tilting angles and can be of great importance to a design engineer. For a tilting angle of 3°, a cell radius of 3 km is seen at a power ratio of −6 dB. For a 10° angle, the corresponding cell radius comes down to 1 km. In the case of Figure 4b corresponding to fixed communication system,
a power ratio of $-6$ dB is not approached even at 10 km distances. At $7^\circ$ elevation angle, a power ratio of $-6$ dB is seen at 4.5 km distance. These figures give a fairly good idea of how much the power decreases for various tilting angles. From these graphs one can deduce cell sizes for different tilting angles and find out the optimum tilting angle where interference effects can be reduced to minimum. In Figure 4a and b, the ratio of power received at the untitled position to power at $3^\circ$ as a function of distance has been plotted. The power ratio has been deduced with reference to the untitled position, which is taken as standard. This has been carried out for LOS conditions only. It is not the absolute value of power that has been plotted, but the ratio of powers. Different curves are plotted for various tilting angles, all with respect to the untitled position only. Comparison with free space power arises when one is calculating only the magnitude of the received power under free space and LOS conditions.

In the present study, antenna tilting has been discussed for a fixed elevation beamwidth. The other important parameters are impact of site separation, network load and tilting scheme$^{15}$. When the antenna element is mechanically down-tilted, only the main lobe is down-tilted and the back lobe is up-tilted. Coverage is attained in the direction of side lobes, which are partially tilted. In the radiation pattern, a notch is seen when the mechanical down-tilting angle becomes large. Signal strength in the direction of the back and side lobes remains approximately the same when the antenna is down-tilted. Hence coverage in the main beam direction starts to shrink, decreasing interference leakage.

In the electrical down-tilt, side and back lobes are also tilted. Hence coverage and interference conditions are totally different in this case than in mechanical down-tilting.

In electrical down-tilt, interference radiation is smaller than in the mechanical case.
In rural areas where cell range is large, smaller tilt should be utilized in order to maintain coverage. In urban environments, down-tilt angle for interference reduction can be bigger because of good coverage. The tilt angle also depends on the load of the network. In a highly loaded cell, the range is effectively smaller than a low loaded cell and the required tilt angle would be smaller.

**Performance assessment**

Here also, following the approach of Tong and Akaiwa\(^\text{10}\), probabilities of different events are calculated for different bit rates. The events are divided by the range of excess delay time within which echoes appear. If the excess delay \( T < vT \), the corresponding probability is denoted by \( P_R \).

If \( vT < T < x_e/c \), the probability is \( P_S \). \( c \) is the velocity of the radio wave, \( T \) is the symbol duration, \( v \) is a parameter determined by the performance of receivers and \( x_e \) is the maximum echo distance at which echo power becomes very weak due to higher path loss.

The probability of excess path length \( x \) is given by\(^8\),

\[
P(X > x) = \exp[-\lambda/4((x/r + 1)(x/r)^2 + 2x/r^{1/2}),
\]

where \( \lambda = \rho \pi r^2 \) and \( \rho \) is the echo density; \( \lambda = 10 \) for urban and smaller for less irregular terrain.

Using these inputs, the probabilities of different events are calculated for different transmissible bit rates (normalized bit rate \( r/T_c \)) for path exponent of 3.5 corresponding to dense urban area and \( v \) value of 3.3 for both untilted and 3° tilted conditions. \( P_R \) indicates that echoes can be handled by the receiver, whereas \( P_S \) indicates the range where serious inter-symbol interference occurs. These probabilities decide the use of equalizers. If an equalizer is not used, then \( P_S \) is very high and the mobile communication system would be operating over a small range. If the equalizer is incorporated, the range of operation becomes larger, since the equalizer reduces inter-symbol interference. These are shown in Figure 5, where probability is plotted as a function of normalized bit rate. From the variation of \( P_R \), one can see the data rates where no interference occurs. The transmissible data rates are higher for the tilted position than for the untilted position. These can be repeated for different system performance parameters and these studies are imperative for optimizing system design under given conditions.

**Discussion**

In this section we critically examine how the optimum tilting angle has been achieved by various workers in their experiments. Their investigations have revealed that tilting angle and height of antenna affect the path loss at different distances. It is also seen that various angles of tilting decreased excess path difference, which in turn decreased the delay spread. This helps optimize the data transmission rates.

Details of these investigations are described below along with our theoretical investigations using COST 231 Hata and COST 231 Walfisch & Ikegami methods\(^\text{13}\).

Chang and Kim\(^7\) observed that when the tilting angles are 3 and 7°, suppression of power level received by the mobile cannot be obtained because half power beam widths of antennas are 3, 7, 10.9 and 12.5°. Therefore, even if the mobile is far away from the base-station, by more than 1 km, the position of the mobile antenna falls within the main lobe of the fixed antenna. As a result, it is necessary to utilize a down-tilting angle larger than 10° together with a reduced half-power beam width in order to obtain the effectiveness of the down-tilt.

The level of the side lobes remarkably increases when the down-tilting angle is larger than 10°. It has also been observed\(^4\) that a 10° down-tilted fixed antenna with a height of 3 m presents a 20 dB more path loss at 900 m from base-station compared with untilted fixed antenna with a height of 6 m.

Benner and Sesay\(^9\) conducted extensive investigations of combined effects of antenna height, high-gain antennas and antenna down-tilting for micro cellular applications. In relation to path loss data, they noticed that the signal will experience a harsher environment when a high antenna is used. Increase in antenna height reduced the diffraction effect of buildings in the proximity of the mobile. This improvement was substantial when the mobile was closer to the base-station and the improvement decreased as the distance between base-station and mobile increased. Their experimental results suggested that a high antenna site
strengthens the direct path relative to the reflected paths. Due to this, large amount of energy would be concentrated in the earlier arrivals resulting in a reduced delay spread. These results strengthen our calculations that various angles of tilting showed decreased excess path difference, which in turn can decrease the delay spread.

Forkel et al.\textsuperscript{14} extended the down-tilting concept to UMTS (universal mobile telecommunication systems) to minimize sectoral interference. In GSM, adjacent sector interference is not a serious concern since base-stations are equipped with sectored antennas. In UMTS, where the sectoral antenna concept is not employed, antenna down-tilting is utilized to reduce sectoral interference, i.e., either mechanical or electrical. When the antenna is tilted as a whole, it amounts to mechanical and when single segments of the antenna surface are shifted against each other, it is called electrical down-tilting.

Depending on the chosen down-tilt, a geometric cell radius \( R = \Delta h / \tan \theta \) can be estimated, where the main beam hits the ground. \( \Delta h = h_b - h_m \). Here \( h_m \) is taken as 1.5 m and the base-station antenna height is varied from 10 to 30 m. The cell radius is estimated for tilting angles ranging from 3 to 10°. Using this cell radius, a plot of path loss as a function of tilting angle has been deduced using the COST 231 Walfisch & Ikegami and COST 231 Hata models for PCS frequency of 1800 MHz for various base-station antenna heights. The cell radius becomes the range. Figure 6a depicts the variation of path loss at cell boundary as a function of base-station antenna height for various tilting angles ranging from 3 to 10°. Here the path loss at a particular cell boundary has been deduced using COST 231 Hata method. Figure 6b shows the same variation of path loss deduced from the Walfisch & Ikegami method. The cell boundary is easily deduced from simple geometry. In Figure 6a, it is seen that at the base-station height of 20 m with a 3° tilting angle, the path loss is 165 dB and it decreases to 148 dB for 10° tilting angle. When the antenna height is 30 m, the corresponding values are 161 and 144 dB respectively. For an increase in base-station antenna height from 20 to 30 m, the path loss at cell boundary decreased by 4 dB for 3° and at 10° tilting angle also, the corresponding change is 4 dB. In Figure 6b, where Walfisch & Ikegami method is used for computing the path loss, the values are 166 and 158 dB respectively, at 3° for antenna heights of 20 and 30 m. At 10° angle, the corresponding values are 147 and 138 dB respectively. Here changing the antenna height from 20 to 30 m produced a change of 8 to 9 dB. Also in Figure 6a, the separation between the curves for different antenna heights is large compared with Figure 6a. This shows that in the case of the Walfisch & Ikegami method, reduction in path loss is high compared with COST 231 Hata method.

Figures 7a and b denotes path loss at the cell boundary for COST 231 Hata and Walfisch & Ikegami methods respectively, as a function of base-station antenna height for various tilting angles, i.e. 3 to 10°. As discussed earlier, the transition from 20 to 30 m in antenna height is pronounced in the case of the Walfisch & Ikegami method. These figures can serve as preliminary design considerations for deciding the degree of tilting in cellular networks.

**Conclusion**

In the present study the effect of antenna tilting, especially the transmitting one, on the performance of fixed and mobile
communication systems has been investigated. Here, fixed communication systems correspond to a transmitting antenna height of 100 m, and in the case of mobile link, the transmitting antenna height is taken as 30 m, which is the typical base-station antenna height. The path loss exponents deduced over this region from our UHF experiments have been utilized to deduce the path length differences for untitled and tilted positions of 3°. Here the excess path difference decreases with increase in path loss exponent. The loss factor for higher path loss exponents representing dense urban environments is very steep, whereas the curve for $n = 1.6$ increases slowly in the case of mobile links. In the case of 3° tilted position at $n = 2.16$, the excess path difference comes to 600 m and in the case of an untitled position for the same $n$, the path difference comes to 11,000 m. In the case of the mobile system as the tilting angle increases, the cell radius decreases. A cell radius of 1 km is seen for a tilting angle of 10°. In the case of fixed links, this comes to 10 km. These figures can be of great help for optimizing tilting angles and cell radius. Apart from this, COST 231 Walfisch & Ikegami and COST 231 Hata methods have been utilized to deduce path loss at the cell boundary as a function of base-station antenna height for tilting angles ranging from 3 to 10° at a PCS frequency of 1800 MHz. Reduction in path loss with increase in antenna height is steep in the case of Walfisch & Ikegami method, whereas the variation is less for COST 231 Hata method. These studies would be useful for optimally utilizing the concept of antenna tilting in mobile and fixed systems.


Received 7 January 2004; revised accepted 2 December 2004