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The Effect of Linear Conducting Scatterers in Mobile Environment

تأثير المبعثرات الموصلة الخطية في بيئة الاتصالات المتحركة

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ملخص

دراسة تأثير المشتتات (المبعثرات) الخطية الموصلة مثل الأسلاك محدودة الطول ومجموعة من الاسلاك المرتبة في منظومة خطية على شدة إشارة التليفون المحمول في بيئة ذات طابع مدني كشف ان هذه المبعثرات الخطية تعمل كمبعثرات مرآوية غير فعالة و يمكن استخدامها في بعض المناطق التي يكون فيها اشارة المحمول ضعيفة. هذه المناطق التي تتأثر بالحواجز الطبيعية والصناعية او التي تقع بالقرب من حدود خلية التليفون المحمول. عندما يكون المشتت (المبعثر) على نفس ارتفاع هوائي المحطة الرئيسية للارسال و يحقق شروط خط النظر بينهما وتكون المسافة بين المبعثر والمحمول صغيرة فان الاشارة المستقبلة من قبل المحمول عن طريق المبعثر سوف تكون أعلى في الشدة من الاشارة المرسلة من المحطة الرئيسيه وبذلك يكون قد تم عمل تحسين لإشارة التليفون المحمول في مناطق الظل بوسيلة سهلة ورخيصة .

Abstract: The effect of the linear conducting scatterers, such as finite-length thin wire scatterer, and linear array of such wires, on the mobile signal strength in the dense urban environment has been considered. The linear conducting elements, in some locations and orientations, act as passive specular scatterers. They can redirect the mobile signal in the regions, which suffer from mobile communication failure, like shadowing and areas near the cell boundaries. Results indicate enhancement in mobile signal for the cases of near and far distaoces, 5dB and 3dB for single wire, 17dB and 14dB for four-element linear array, respectively.

Key word-- Mobile signal propagation, mobile signal enhancement, linear scatterers, scattering from linear arrays.

1. INTRODUCTION

In a diffusion system for GSM mobile (cellular) communication, weakness of the electromagnetic signal communication problems exist due to propagation mechanisms, which are very complex and diverse. The main reason for this problem is the geography of the land to be covered. It is necessary to redirect the electromagnetic signal to shadow zones and cell's boundaries, where communication fails. This problem is even worse when the amplification of the signal is not possible as no source supply is available, or the operation cost is critical.

The suggested solutions can be summarized in the use of passive repeater or specular scatterers, which can forward the mobile signal to weak spots. The passive retransmitting repeater system consists of two back-to-back Yagi-Uda antennas with corner reflector supported by tower mast described in [1]. The individual urban features like lamppost, traffic lights, and metallic signs can be used as specular scatterers, which are located far below the base station. In the areas with low density of buildings, the effects of isolated scatterers will dominate the propagation [2].

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When the path between the base station and the scatterer is clear from buildings, where the line of sight condition is satisfied, and the distance between the scatterer and the mobile unit, is small. The received signal at the mobile unit, via the scatterer, becomes stronger than the direct signal from the base station. In this way, we can enhance the mobile signal in regions, which suffer from signal level deficiency using simple and cheap method.

There are two main factors affecting the path loss between the base station and the mobile unit via the scatterer. These factors are the location and the bistatic radar cross section (RCS) of the scatterer. The location of the scatterer must be far from the base station. The bistatic RCS of the scatterer is function of the polarization of the incident wave, the direction of incidence, the direction of observation, the geometry and the electrical properties of the scatterer, and the frequency of operation [3].

In the literature several different approaches have been used to obtain accurate and usually quite complicated expressions for deceptively simple problems of RCS of the thin finite-length wire scatterers. Those approaches are, 1) the integral equation method based on Hallen's linearized integral equation which is only used so far for calculating the back scattering cross section; 2) the variational method used for both backscattering, and bistatic scattering, 3) the direct method known as the Einarsson solution [4], 4) codes depend on integral equation Applet Java program [5], 5) unified method for thin material wire [6]. All the above approaches are presented for thin wire oriented in z-direction only, for any direction of the incident wave. It would not solve the scattering when the wire has arbitrary orientation in the space, where the wire orientation plays a basic role in its scattering patterns.

There are two methods to achieve RCS enhancement. First is the proper shaping of the target (scatterer) to present a large echo area over the ranges of parameter of interest. The second is the use of active diodes as load to the scatterer at selected points [7], [8]. The possibility of using loaded scatterer with active diodes in the operating mobile frequency range is low, because of high cost, and the diode-biasing problem.

In this paper, the problem of signal scattering from wire scatterers has been solved by using the Electric Field Integral Equation (EFIE) approach in conjunction with method of moments [9]. The induced surface current density on the wire with arbitrary orientation and arbitrary direction of incidence in free space is determined using modified Pocklington's integral equation. The scattered far field and bistatic RCS of the wire are calculated. For the linear array, the total scattered far field is determined by the vector addition of the scattered field by individual elements, and hence the bistatic RCS is calculated.

The numerical results for the bistatic RCS of the wire scatterer with different radii, different lengths, and different orientations are obtained. For the linear array, results show the effect of the three control factors, the number of elements, the direction of the array line, and the separation between the elements. Two examples for using the scatterers at different distances are given which show 5 dB, 3 dB and 17 dB, 14 dB enhancements at the cell's boundaries for wire and linear array, respectively.

2. PROBLEM FORMULATION

2.1 Straight Wire Scatterer Formulation

Consider a perfectly conducting circular cylinder of radius "a" and length "l" centered at the origin and aligned (oriented) along an arbitrary direction given by $\hat{l} = \hat{x}\cos\phi_l \sin\theta_l + \hat{y}\sin\varphi_l \sin\theta_l + \hat{z}\cos\theta_l$ as shown in Fig.1. A plane wave of amplitude $E_o = 1$ volt per wavelength and angular frequency ω is incident on the wire from the direction $\hat{i} = \hat{x}\cos\phi_i \sin\theta_i + \hat{y}\sin\phi_i \sin\theta_i + \hat{z}\cos\theta_i$. The outgoing direction $\hat{s}$ of the scattered wave is specified using the usual spherical angles θ_s, ϕ_s. The incoming wave polarization can be decomposed into two orthogonal components: E_{TE}^{inc} which is normal to the $\hat{i}$-$\hat{l}$ plane and is given by the unit vector $\hat{h} = \frac{\hat{i}x\hat{l}}{|\hat{i}x\hat{l}|}$ and E_{TM}^{inc} which is in that plane and is given by the unit vector $\hat{v} = \hat{h}x\hat{i}$. The current induced on the cylinder surface and the resulting scattered radiation patterns will be calculated. Only the incident field polarized parallel to the wire induces surface current.

Pocklington's integral equation for thin wire approximation can be used to determine the equivalent filamentary line-source current of the wire [3]. This equation was modified to be suitable for the arbitrary wire orientation. Thin wire approximation provides a surface current only in the axial direction and uniformly distributed around the wire. For wavelength independence, we can normalize the equation by λ, to be written as:

$$\int_{-L/2}^{L/2} I_l(\bar{l}')\frac{e^{-j2\pi\bar{R}}}{4\pi\bar{R}^5}\left[\left(1+j2\pi\bar{R}\right)\left(2\bar{R}^2-3\bar{a}^2\right)+\left(2\pi\bar{a}\bar{R}\right)^2\right]d\bar{l}' = -j\frac{1}{60}\lambda E_o e^{-2\pi\bar{i}\cdot\bar{r}}\hat{v}.\hat{l} \qquad (1)$$

where $\bar{R}$ is the distance between the field point and the source point, $\bar{a} = a/\lambda$,and $\bar{L} = L/\lambda$ are the normalized radius and length of the wire.

For observations along the axis of the wire, $\bar{R}$ is given by:

$$\bar{R} = \sqrt{\bar{a}^2 + (\bar{l} - \bar{l}')^2} \qquad (2)$$

The Method of Moments [9] with piecewise linear basis functions and point matching techniques is employed to determine the current distribution. By knowing the induced current, the far field component can be determined by [3]:

$$E_\theta^s = j\eta\frac{ke^{-jks}}{4\pi s}\sin\psi\left[\int_{-L/2}^{L/2} I(l')e^{jkl'\cos\psi}\,dl'\right] \qquad (3)$$

where: $\psi = \cos^{-1}(\hat{l}.\hat{s})$, and $\hat{s}$ is unit vector in the reradiating (scattering) direction. The bistatic RCS, σ_b is determined from the far scattered field according to [3]:

$$\sigma_b = \lim_{s\to\infty}\left[4\pi s^2 \frac{W_s}{W_i}\right] = \lim_{s\to\infty}\left[4\pi s^2 \frac{|E^s|^2}{|E^i|^2}\right] \quad (4)$$

where s is the observation distance from the scatterer (m), W_i is the incident power density (W/m^2), W_s is the scattered power density (W/m^2), and $E^i(E^s)$ is the incident (scattered) electric field (V/m).

$$\sigma_b(\hat{i},\hat{s})/\lambda^2 = 14400\,\pi^3\left|\sin\psi\left[\int_{-L/2}^{L/2} I(l')e^{-j2\pi l\cos\psi}\,d\bar{l}'\right]\right|^2 \quad (5)$$

2.2 Linear Array Formulation

Let us assume an array of N identical parallel conducting scatterers, which is positioned along a direction $\hat{u}$, where $\hat{u}$ leads the $\hat{x}$ axis with an angle ϕ_u as shown in Fig.2. The elements have arbitrary orientation, and the magnitude of the incident plane wave is the same for all elements (uniform magnitude). The total electric field scattered from the array is determined by vector addition of the fields scattered by the individual elements. The separation between elements, d_u, is assumed large enough to ignore the mutual coupling between the elements. Assuming a zero phase for the plane wave incident on the first element, which is situated at the origin, the total electric field is:

$$\bar{E}_T^s = \bar{E}_o^s + \bar{E}_1^s + \bar{E}_2^s + \ldots + \bar{E}_{N-1}^s \quad (6)$$

where $\bar{E}_o^s$ is the electric field of the reference element at origin and is given by (3).
In the far zone, the phase difference between the scattered field from the n[th] element and the reference one is $n\beta$ where $\beta = kd_u[\hat{u}\cdot\hat{s}]$ or $\beta = kd_u(\sin\theta_s \cdot \cos(\phi_u - \phi_s))$.

There is also a progressive phase lead $n\alpha$, where $\alpha = kd_u[\hat{u}\cdot\hat{i}]$, or $\alpha = kd_u(\sin\theta_i \cdot \cos(\phi_u - \phi_i))$ due to the delay effect of incoming plane wave. The electric field of the n[th] element can be written as:

$$E_n = j\eta k\,\frac{e^{-jks}e^{jn(\beta+\alpha)}}{4\pi s}\sin\psi\left[\int_{-L/2}^{L/2} I(l')e^{j2\pi l'\cos\psi}\,d\bar{l}'\right] \quad (7)$$

and the array factor can be written as:

$$AF = e^{j[(N-1)/2]\gamma}\left[\frac{\sin(N\gamma/2)}{\sin(\gamma/2)}\right] \quad (8)$$

where $\gamma = (\beta + \alpha)$

The bistatic RCS of the array, σ_{bT} is then determined from the total far scattered field according to (4).

$$\sigma_{b1}(\hat{i},\hat{s})/\lambda^2 = 14400\pi^3 \left| \sin\psi \left[\int_{-L/2}^{L/2} I(l') e^{-j2\pi l' \cos\psi} d\bar{l}' \right] \cdot AF \right|^2 \quad (9)$$

2.3 Path Loss in Mobile Environment

Propagation or path loss, PL, is the parameter commonly used to characterize the local average signal in mobile channels. It is defined as the relationship between the transmitted power P_t of the transmitter antenna and the received power P_r by the receiver antenna [10], and is given by:

$$PL = 10\log\frac{P_t}{P_r} = P_t(dBm) - P_r(dBm) \quad (10)$$

Various theoretical, empirical, and semi-empirical models have been developed to predict the path loss [11].

2.3.1 Path loss in the absence of the scatterer

The direct power P_d can be defined as the amount of power, which is received by the mobile unit from the base station in the absence of the scatterer using the general propagation model described in [11]. The path loss for direct path between the base station and the mobile unit is:

$$PL_d = P_t(dBm) - P_d(dBm) \quad (11)$$

$$PL_d = 35.72\log d - 20.9922\log h_b - 1.8142\log h_m + 26.16\log f + 81.4 + L_{DBI} \quad (12)$$

The diffraction loss $L_{DBI} = 10.5\log d + 12.4$ for dense urban areas, $L_{DBI} = 10.4\log d + 13.4$ for moderate urban areas, and $L_{DBI} = 9.6\log d + 10$ for geographically limited urban areas, where d is the distance between the base station and the mobile unit in km, f is the operating frequency in MHz, h_b and h_m are the base station and mobile antenna heights in meter, L_{DBI} is the diffraction loss.

2.3.2 Path loss in the presence of the scatterer

The path loss of the path via the scatterer is the summation of two path losses, PL_1, which is between the base station and the scatterer, and PL_2, which is between the scatterer and the mobile unit. The following assumptions have been made: 1) the scatterer is located at the same height as the base station and at a distance d_1 from it, 2) no multipath from the base station to the scatterer, and line of sight condition is satisfied, thus PL_1 is the free space propagation loss, 3) multiple scattering does not occur, 4) general propagation model is used to calculate the PL_2 due to distance d_2 between the scatterer and mobile unit. The transmitted power incident upon the scatterer is initially captured and then reradiated .The amount of captured power P_c is obtained by multiplying the incident power density by the bistatic RCS σ_b of the scatterer [3].

$$P_c = \sigma_b \frac{P_t}{4\pi d_1^2}$$

The path loss between the base station and the scatterer will be:

$$PL_1 = 20\log d_1 + 10\log(4\pi/\lambda^2) - 10\log\sigma_b \quad (13)$$

and, the path loss between the scatterer and the mobile unit is:

$$PL_2 = 35.72\log d_2 - 20.9922\log h_s - 1.8142\log h_m + 26.16\log f + 81.4 + L_{DB2} \quad (14)$$

The definition for L_{DB2} is the same as described above with d_2 replacing d_1. Then the overall indirect path loss is:

$$PL_{ind} = PL_1 + PL_2 \quad (15)$$

3. NUMERICAL RESULTS

This section presents numerical results, which illustrate the effect of the conducting elements, such as wire scatterer and linear array of identical elements on the mobile signal propagation. Firstly, we discuss some properties of the two types of the scatterers and then show their effect on the path loss. All data were generated with a Matlab codes for analyzing the scattering from thin conducting wire of arbitrary orientation, and from linear array of identical wire scatterers with uniform spacing.

Fig. 3 shows the normalized bistatic RCS σ_b/λ^2 versus θ_s of wire scatterer oriented to z-axis, which has length $L = 2\lambda$, for four different radii a (0.02λ, 0.015λ, 0.01λ, 0.005 λ), and for an angle of incidence $\theta_i = 45°$. It is clear that there is a large lobe at an angle of scattering equal to the incidence angle, but on the opposite side of the direction normal to the wire. This corresponds to specular reflection. This becomes more pronounced as the wire is made longer. The amplitude of the side lobes increases as the wire radius decreases, especially that one occurred at the incident angle .The maximum of the main lobe σ_b/λ^2 pattern is decreasing, as the wire is taken. The effect of the wire's length is shown in Fig.4. The maximum of the main lobe of σ_b/λ^2 pattern increases and becomes narrower as the wire is taken longer for the same radius.

For the array, to maximize the bistatic RSC, the array factor and the bistatic RCS of the single element should be maximized. The bistatic RCS of array can be written as:

$$\sigma_{bt} = \sigma_{single-element} \cdot (AF)^2 \quad (16)$$

The maximum value of the array factor occurs at:

$$\gamma/2 = (\beta + \alpha)/2 = n\pi \ , \quad n = 0,1,2,3,... \tag{17}$$

There is only one case in which the maximum of the array factor does not depend on the separation between elements. We shall refer to this case as broadside incidence broadside scattering. In this case $\phi_u - \phi_i = 90^\circ$ and $\phi_u - \phi_s = 90^\circ$ which results in $\alpha = 0$ and $\beta = 0$ for any separation. In all other cases, the maximum of the array factor depends on the separation between elements d_u and ϕ_u.

For specific incident, and scattering directions, ϕ_u, d_u are chosen to satisfy maximum condition (17).

To show how the passive scatterer may be used for enhancement of the mobile signal, two examples will be given.

Example 1: the base station is assumed to be transmitting isotropically and at 947 MHz continuous wave RF carriers. The heights $h_b = h_s = 40m$, and the height of the mobile unit is $1.7m$. The distance $d_2 = 38.7058m$. The projection on the ground of d_2 is $d_{p2} = 5.59m$. The distances d and d_1 are varied while d_2 is kept constant. The directions of the incident and the scattering waves are $\theta_i = 90^\circ, \theta_s = 171.69^\circ, \phi_i = \phi_s = 26.6^\circ$ as shown in Fig.5.

Fig.6 shows the path loss versus the direct distance d, for the single wire scatterer with radius $2a = L/74.2\lambda$, $L = 4\lambda$ and different orientation. As predicted, the suitable wire orientation is found to be at 45° with z-axis. It gives a main lobe of the bistatic RCS symmetric around the specular direction. Its path loss curve approaches to that obtained from the direct path at the boundaries of the cell. In Fig.7 the path loss of the single wire scatterer oriented at 45° angle with z-axis, $2\bar{a} = \bar{L}/74.2$, is plotted for different lengths of the wire. As expected, the bistatic RCS of the wire increases with its length, and when the scatterer is at long distance away from the base station, the free path loss between them became dominant. For these two reasons the path loss of the signal via the scatterer is less than the direct path loss by 3.1979 dB, and 5.0871 dB for $L = 10\lambda, L = 12\lambda$ respectively.

Next, we shall consider an array of four elements with $L = 8\lambda$. The elements are oriented at angle of 45° with the z-axis. Fig.8 shows the bistatic RCS versus ϕ_u, and the separation is assumed to be $d_u = 0.87382\lambda$. There is more than one value of ϕ that gives maximum $\sigma_{b,t}$. When ϕ_u is chosen equal to 116.6°, the array factor is maximum for any separation, which leads to broadside incidence and broadside scattered, case (1). When ϕ_u is chosen equal to 26.6°, the array factor is maximum at discrete values of the separation, which satisfies the maximum condition (17), case (2). Fig.9 shows the suitable normalized separation between the array elements, d_u/λ, for the two cases (1) and (2). It is clear that for case (1), any separation can achieve the maximum value, but for case (2) certain values only will give the maximum value of bistatic RCS.

Fig.10 illustrates the path loss of the system using linear array for different number of elements and different lengths of the individual wire with the direct distance. It is obvious that for large dimensions of the array (L, N), the scatterer becomes effective and sufficient to forward the signal to a certain mobile unit, which is located in shadow zones near to the base station.

Example 2: We take the distances $d_2 = 47.4146m$, $d_{p2} = 27.95m$. Because d_2 is different from the previous example, the scattering direction is consequently changed. θ_s decreases to 143.8785, then the orientation of the wire must be decreased from $45°$ to $30°$. The main lobe of the bistatic RCS of the wire is symmetric around the scattering angle $150°$. The other parameters have the same values as in example 1.

Fig.11 shows the path loss versus the direct distance for the two different types of the scatterers. Because the mobile unit is far from the scatterer, the single wire becomes useful only at the cell's boundaries. The arrays with different combination of (L, N) become more effective than the single wire by 12dB for $d = 365m$.

4. CONCULSIONS

The effect of linear conducting scatterers on the mobile environment is studied. The single wire scatterer as well as the linear array of wires is considered. For the linear array, there are many parameters affecting its bistatic RCS. The bistatic RCS is maximized by maximizing both of the bistatic RCS of the single wire and the array factor using its parameters ϕ_n, N, and d_a. Results show that the signal received via the scatterer, which is located far from the base station, is stronger than the direct one. Also many different wire and array parameters combinations may give nearly the same RCS.

This work shows the possibility of using passive scatterers to enhance the mobile signals especially in areas where the signal is weak or insufficient.

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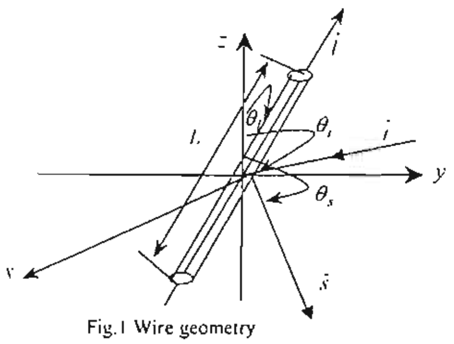

Fig.1 Wire geometry

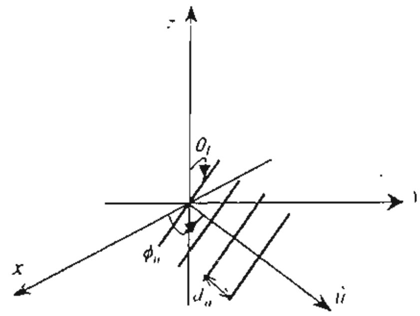

Fig.2 Array geometry

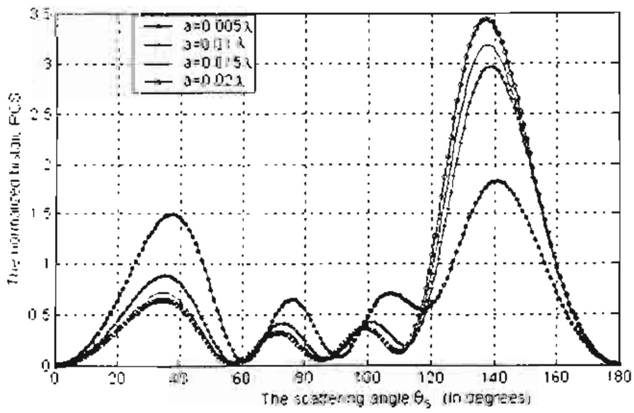

Fig.3 Normalized bistatic RCS of thin wire scatterer located at z-axis versus scattering angle $\theta_s, \phi_s = 0$, for $L = 2\lambda$, angle of incidence $\theta_i = 45°$.

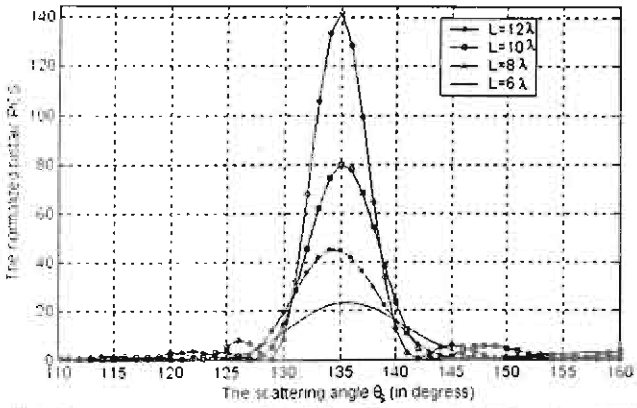

Fig.4 Normalized bistatic RCS of thin wire scatterer located at z-axis versus scattering angle $\theta_s, \phi_s = 0$, for $a = 0.5L/74.2$, angle of incidence $\theta_i = 45°$

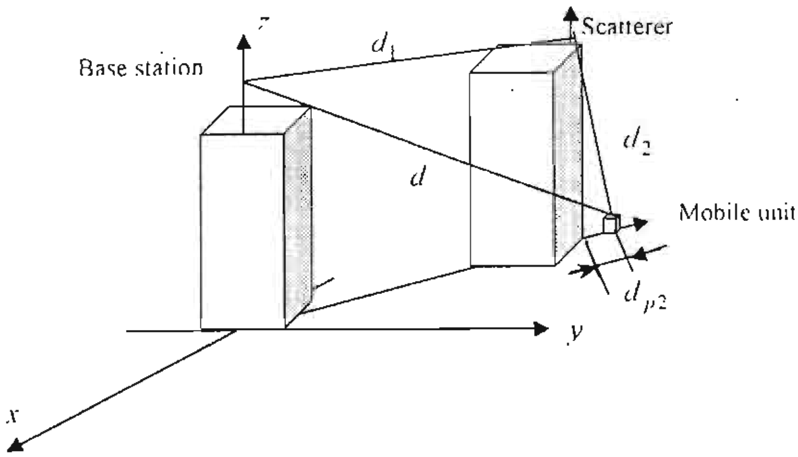

Fig 5 Configuration of the scatterer in the mobile environment

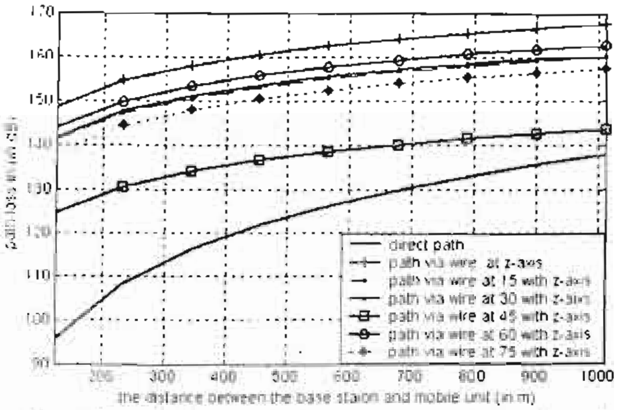

Fig.6 The path loss for single wire scatterer in the aligned system

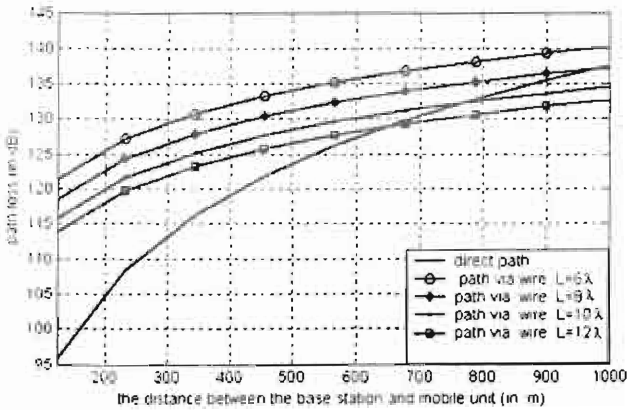

Fig.7 The path loss of single wire scatterer at 45° with z-axis for different lengths (Example 1)

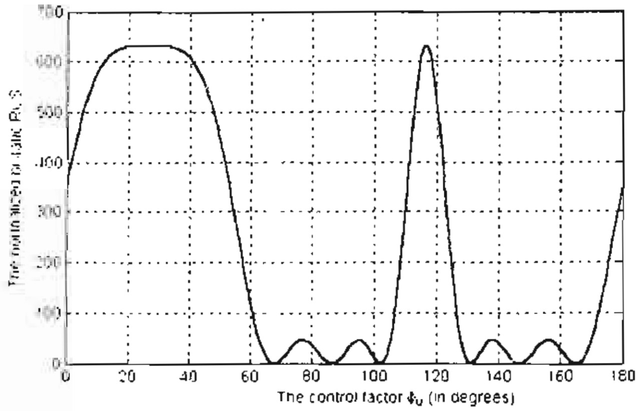

Fig 8 The bistatic RCS of linear array with $N = 4$ and $\bar{L} = 8$, for aligned system

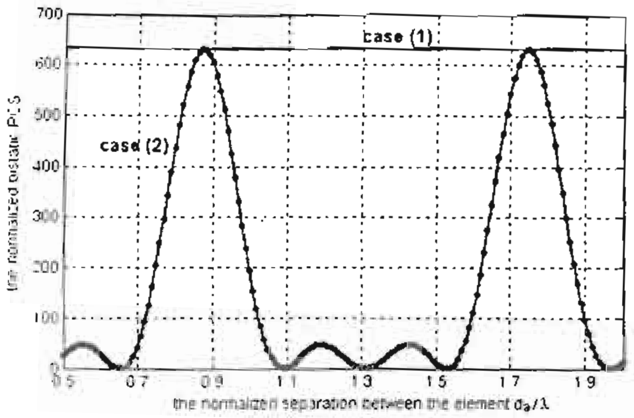

Fig 9 The bistatic RCS of the linear array, $N = 4$, $\overline{L} = 8$, and for the two cases.

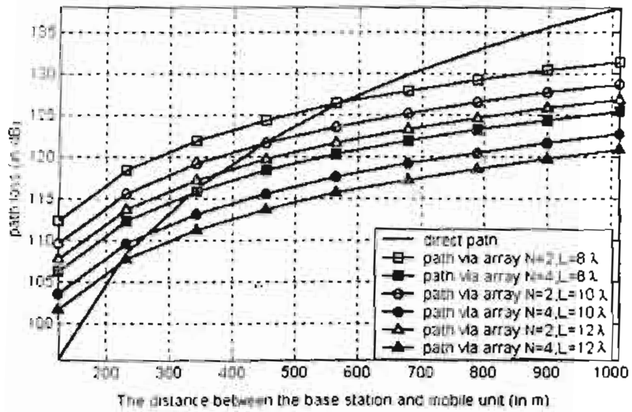

Fig 10 The path loss of linear arrays with the wires at 45° from z-axis (Example1)

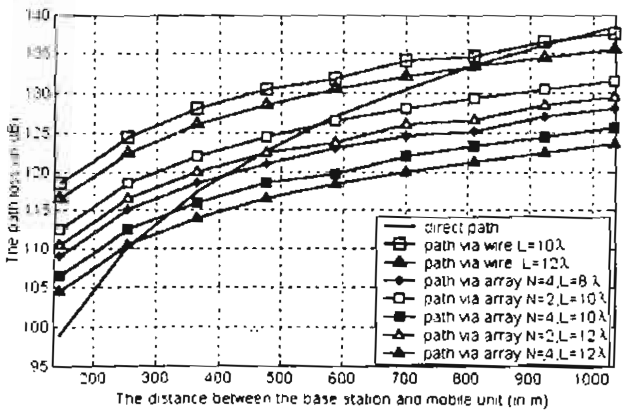

Fig. 11. The path loss of the linear array, with wires at 30° from z-axis. (Example 2)