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MULTIPATH FADING IN CELLULAR COMMUNICATIONS DURING INTER-CITY TRANSPORTATION

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Abstract: *An analysis is presented of the multipath fading rate variability at the base station of a cellular communication system when receiving a signal from a mobile unit traveling within the cell during inter-city transportation. The fading behavior and its variability are studied as determined by the distance between the base station and the road or the railway on which the mobile unit travels. It is shown that the variability of the fading rate is larger when the road passes nearby the base station. When the road passes further away from the base station the average fading rate becomes larger with less variability.*

Key words**:** *Fading, mobile communications, multipath channels, propagation, scattering*

INTRODUCTION

The cellular communication networks are created to serve mobile users that can be either pedestrians or traveling by some kind of a vehicle. The mobile radio channel is an object to multipath fading caused by multiple reflected and scattered signal replicas incoming with the main signal at the receiver. The numerous radio waves add in a constructive and destructive interference causing a fluctuation of the received signal. This phenomenon has been extensively studied [1, 2] for a mobile unit in a multipath environment. The multipath fading at the base station (BS) has been traditionally modeled using the reciprocity of the channel [3, 4]. Certain issues of signal fading at the BS arise and need to be addressed, especially during inter-city automobile or railway transportation when the mobile user is fixed inside a vehicle traveling in the coverage area (cell) of a given BS.

Usually the fading is modeled assuming a static multipath channel determining a constant signal fading rate when the mobile unit travels at a constant speed in a given direction [1, 2]. Such an assumption is reasonable in characterizing a local area or volume around the mobile unit. However, when the mobile unit is traveling at a given speed and direction within a large cell, which is the case during inter-city transportation, the vehicle's position relative to the BS changes during the communication process and the static channel assumption no longer holds. Instead, the scattering and reflecting objects around the mobile unit cause variability in the fading behavior at the BS receiver as the vehicle changes its position. This implies that the channel is affected differently at different time instants meaning that at one and the same communication rate the performance of the wireless link is space-time-dependent. Therefore, the variability of the fading behavior needs to be analyzed in order to adequately determine the performance of the cellular communication channel. Such an analysis would help in developing sophisticated methods for modulation, coding and diversity that increase the performance. Examples for inter-city transportation vehicles include cars, buses and trains. In all of them the user is in a fixed position inside a certain space surrounded by reflecting walls and windows determining the multipath fading.

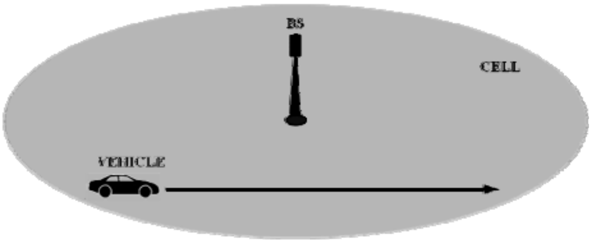
This paper addresses the variability of the multipath fading behavior determined by the geometric parameters of the placement and motion of the vehicle within the cell covered and served by a given BS. First, the physical model features are outlined. Next, based on the physical model properties, the fading behavior is explained. Finally, the geometrical parameters corresponding to the physical model are studied with their influence on the fading behavior expressed as a multipath signal fluctuation at the BS.

PHYSICAL MODEL

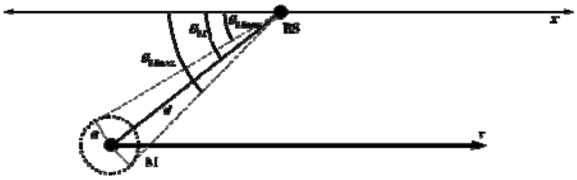
In an inter-city transportation model the mobile unit is surrounded by numerous fixed scattering and reflecting objects inside the vehicle. Those objects may be assumed to be generally non-uniformly distributed on a scattering sphere around the mobile unit inside the vehicle. For a given almost constant speed in inter-city transportation, that spatial distribution determines a Doppler spectrum with almost fixed shape between the minimum and the maximum Doppler offset at the mobile receiver [3, 4]. The spread of the Doppler spectrum is directly proportional to the rate of fluctuation of the signal, or the *fading rate* [1]. Assuming a reciprocal channel, the spatial distribution of the objects on the scattering sphere inside the vehicle also determines the Doppler spectrum and hence the fading rate at the BS [3, 4]. However, due to the motion of the mobile unit relative to the BS, the Doppler spectrum at the BS changes, thus determining a change in the fading rate of the signal at the BS receiver.

For obtaining a maximum coverage, the BS is usually mounted far away from scattering objects in its cell. This is particularly true in less populated areas where the user density is much lower compared to that in an urban area. Then, in order to cover larger areas with a smaller number of BSs to serve effectively the lower density of mobile users, each BS radiates at a higher power, thus covering a bigger area [5]. As a result, during inter-city transportation the vehicle spends a considerable amount of time in a given cell served by a particular BS. During that time a variation in the fading rate of the signal received at the BS should be expected due to the changing geometrical configuration of the mobile channel as the vehicle moves.

The Doppler spread at the BS is usually much less than the corresponding Doppler spread at the mobile unit due to the fact that the BS is far away from the scattering sphere around the mobile unit in the vehicle. On the other hand, during inter-city transportation the vehicle usually travels at much higher speeds compared to city transportation, thus determining larger positive and negative Doppler offsets. The so increased Doppler spread determines a significant fading rate. In addition, depending on the distance and the travel direction of the mobile unit relative to the BS the fading rate exhibits certain variability in its value, as shown in the next section.



(a) Placement within the cell



(b) Geometrical configuration

Fig. 1. A typical scenario description.

A typical scenario of a mobile unit served by a BS is depicted in Fig. 1 with Fig. 1(a) showing the placement within the cell of the BS. It's important to note that in inter-city transportation conditions the mobile unit travels with almost constant speed in an almost straight line that passes at some distance from the BS. This means that the speed direction and magnitude may be considered fixed parameters for determining the fading rate at the BS. Fig. 1(b) shows the geometrical configuration of the channel determined by the placement shown in Fig. 1(a). The mobile unit is denoted as M and the scattering sphere with radius a around it is illustrated with a dotted line. The azimuthal angle θ_M of the mobile unit relative to the BS and the corresponding distance d are changing as the mobile unit travels with speed v parallel to the x axis at the BS, and hence the multipath fading rate changes as described in the next section.

FADING BEHAVIOR

As seen in Fig. 1(b), the distance d and the radius a determine the maximum and the minimum azimuthal angles, θ_{Mmax} and θ_{Mmin}, of the direction of arrival of the signal replicas from the mobile unit to the BS according to the relations

$$(1)\qquad \begin{array}{l} \theta_{\mathrm{M\,min}} = \theta_{\mathrm{M}} - \arcsin\left(\dfrac{a}{d}\right) \\ \theta_{\mathrm{M\,max}} = \theta_{\mathrm{M}} + \arcsin\left(\dfrac{a}{d}\right) \end{array}.$$

The relations in (1) determine the maximum and the minimum Doppler offsets, f_{max} and f_{min}, at the BS caused by the scattering sphere around the mobile unit in the vehicle at azimuth θ_{M}:

$$(2)\qquad \begin{array}{l} f_{\mathrm{min}} = \dfrac{v}{\lambda}\cos\left(\theta_{\mathrm{M}} - \arcsin\left(\dfrac{a}{d}\right)\right) \\ f_{\mathrm{max}} = \dfrac{v}{\lambda}\cos\left(\theta_{\mathrm{M}} + \arcsin\left(\dfrac{a}{d}\right)\right) \end{array}$$

with λ being the signal carrier wavelength.

The minimum and the maximum Doppler offsets put the frequency limits of the Doppler spectrum $S_{\mathrm{BS}}(f)$ at the BS determined by the configuration of the reflecting objects on the scattering sphere around the mobile unit inside the vehicle. The scattering sphere also determines the Doppler spectrum $S_{\mathrm{M}}(f)$ at the mobile unit [6]. In [3] it is shown that under the general assumptions of a reciprocal channel and a ratio $d/a >> 1$, $S_{\mathrm{BS}}(f)$ is a scaled version of $S_{\mathrm{M}}(f)$, shifted to the Doppler offset f_{M}, determined by θ_{M} through the relation

$$(3)\qquad f_{\mathrm{M}} = \frac{v}{\lambda}\cos\theta_{\mathrm{M}}\,.$$

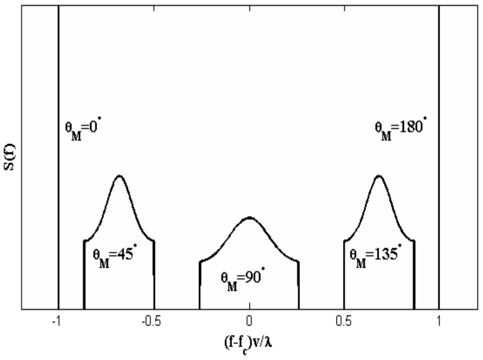


Fig. 2. Doppler spectra at the base station for five azimuths θ_{M} of the mobile unit relative to the *x*-axis: 0°, 45°, 90°, 135° and 180°.

In Fig. 2 are shown examples of normalized Doppler spectra $S_{\mathrm{BS}}(f)$ for some arbitrary spectrum $S_{\mathrm{M}}(f)$ and several azimuthal positions θ_{M} of the mobile unit relative to the BS according to the assumption that $d/a >> 1$. In the figure f_c is the signal carrier frequency. It is seen that the Doppler spread and hence the fading rate have maximum values when the vehicle's direction is perpendicular to the line connecting the mobile unit with the BS. As the azimuthal angle θ_{M} departs from 90°, the Doppler spread and the fading rate decrease. At $\theta_{\mathrm{M}} = 0°$ and $\theta_{\mathrm{M}} = 180°$ the Doppler spectra become Dirac delta functions at $\pm f_{\mathrm{M}}$ if the higher-order dependence of $S_{\mathrm{BS}}(f)$ on $a/d << 1$ is neglected [3]. The Doppler spread then becomes zero, implying a zero fading rate when the vehicle's motion is purely radial relative to the BS, without an angular component. However the mobile unit cannot pass through the cell's center.

GEOMETRICAL PARAMETERS OF THE CELL DETERMINING THE FADING RATE

Depending on the road configuration, the traveling vehicle can enter different cells in the coverage area at different angles as shown in Fig. 3. This difference results in different geometrical parameters determining the fading behavior in each separate cell.

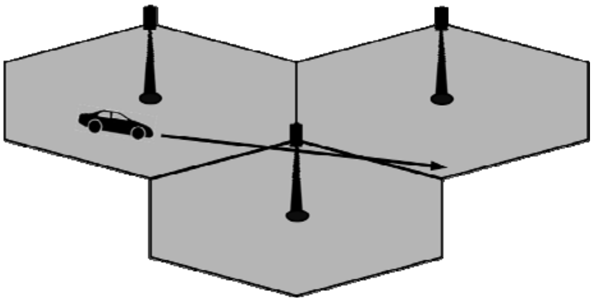


Fig. 3. A vehicle traveling through the cell coverage with different d_{min} for the different cells.

As mentioned earlier, the vehicle is assumed to travel in a straight line during inter-city transportation. Therefore, in each cell the traveling line of the mobile unit is placed at a specific distance from the corresponding BS and that is the shortest possible distance d_{min} between the mobile unit and the BS within that cell.

Fig. 4 shows the geometrical parameters determining the fading rate. The mobile unit travels at a constant speed v along a line at distance d_{min} from the BS. The maximum distance between the mobile unit and the BS is equal to the cell radius R_C, determined by the radiating power of the BS. It is seen from the figure that the azimuthal angle θ_{M} is determined by

$$(4)\qquad \theta_{\mathrm{M}} = \arcsin\left(\frac{d_{\mathrm{min}}}{d}\right)$$

with range of values given by

(5) $$\arcsin\left(\frac{d_{\min}}{R_C}\right) \le \theta_{\mathrm{M}} \le 180^{\circ} - \arcsin\left(\frac{d_{\min}}{R_C}\right).$$

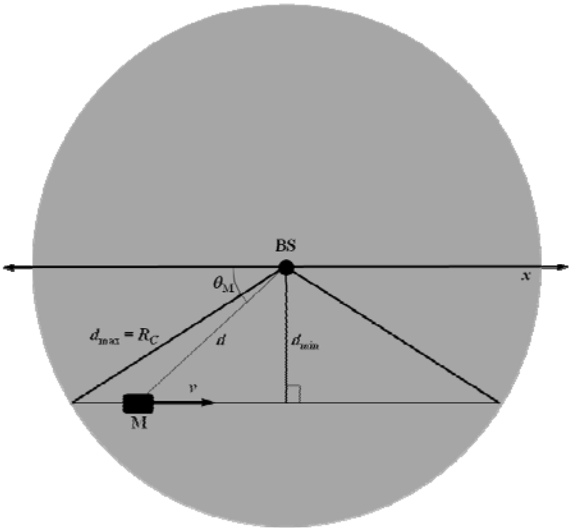


Fig. 4. Geometrical parameters determining the fading rate within a cell.

The mobile position with respect to the x axis at the BS in Fig. 4 is determined by

(6) $$x = \pm\sqrt{d^2 - d_{\min}^2}$$

with the sign in (6) depending on which side of the vertical line through the BS is the mobile unit in Fig. 4.

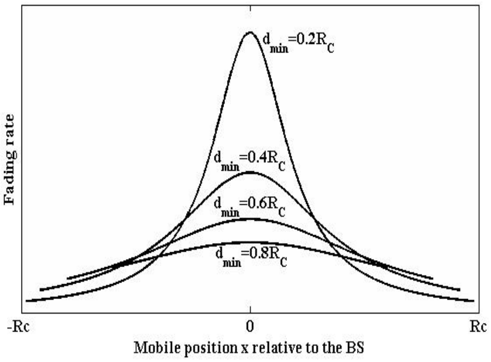


Fig. 5. Fading rate variability vs. $d_{\min}$ for R_C/a=10.

Based on the geometry in Fig. 4, the fading rate versus the mobile position x is shown in Fig. 5 for four different values of $d_{\min}$ and a ratio $R_C/a = 10$. It is seen that upon entering and exiting the cell by the mobile unit, the fading rate has its minimum value throughout the time of stay within the cell. The maximum fading rate occurs when passing through the point of minimum distance between the mobile unit and the BS ($\theta_{\mathrm{M}} = 90^{\circ}$) where the motion of the mobile unit is purely angular relative to the BS, without a radial component. As seen in the figure, a smaller value for $d_{\min}$ determines a larger variability of the fading rate compared to the smaller variability for larger values for $d_{\min}$. This is explained by the fact that as $d_{\min}$ decreases, the motion of the mobile unit upon entering and exiting the cell becomes almost radial without an angular component relative to the BS. At $\theta_{\mathrm{M}} = 90^{\circ}$ it can be readily seen from the expressions in (2) that the difference between $f_{\min}$ and $f_{\max}$ becomes

(7) $$\left|f_{\max} - f_{\min}\right| = 2\frac{va}{\lambda d_{\min}}.$$

The expression in (7) determines the large Doppler spread and hence the large fading rate for small values of $d_{\min}$. Note that $d_{\min}$ is always greater than the radius a of the scattering sphere around the mobile unit because the BS physically has to be outside the vehicle. Also, for values of $d_{\min}$ closer to a, the assumption that $d/a >> 1$ [3] no longer holds, the higher-order dependence of $S_{\mathrm{BS}}(f)$ on a/d comes into effect and hence the fading rate plot around the midpoint in Fig. 5 is a rough approximation to its true value. However, that approximation is enough to show the dependence of the fading rate variability on $d_{\min}$.

Further, as $d_{\min}$ increases approaching R_C, the time spent by the mobile unit within the cell decreases and the fading rate variability during that time also decreases. On the one hand, the larger the value of $d_{\min}$, the larger the fading rate upon entering and exiting the cell because at those points the mobile unit travels almost angularly without a significant radial motion relative to the BS. On the other hand, the larger the value of $d_{\min}$, the smaller the fading rate at the midpoint in Fig. 5 because at $\theta_{\mathrm{M}} = 90^{\circ}$ the expression in (7) has its minimum value with respect to $d_{\min}$, with the corresponding minimum fading rate.

CONCLUSION

This paper addresses the fading behavior in a cellular communication channel during inter-city transportation. The mobile channel is assumed static at the mobile receiver that is surrounded by scattering and reflecting fixed objects inside the vehicle. However, at the BS receiver the mobile channel appears dynamic due to the motion of the vehicle inside the cell. It is shown that when the vehicle crosses the cell, passing near its center, large fading rate variability is observed at the BS, caused by the change from a purely radial to a purely angular motion and then back to a radial motion relative to the BS. When the vehicle crosses the cell, passing near its edge, a large average fading rate with a small variability is observed at the BS, caused by the almost purely angular motion relative to the BS. The differences in the fading rate at different time instants require more careful modeling of the wireless channel performance. The variability in the fading rate implies that sophisticated adaptive algorithms for coding, modulation and diversity methods may be developed to mitigate the effects of the variable multipath fading behavior.

The analysis in this paper can also serve as a basis for creating new algorithms for localization of mobile units during inter-city transportation on roads or railways within the coverage of a given cellular network. In addition, based on this study, new cell planning and design methodologies can be developed when a particular fading behavior is preferred. Certain placement of the BSs nearer or further away from the road or the railway may lead to an optimized recourse management in the cellular network depending on the performance measures characterizing the cellular network.

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МНОГОПЪТНО ЗАТИХВАНЕ НА КЛЕТЪЧНИТЕ КОМУНИКАЦИИ ПРИ МЕЖДУГРАДСКИ ПРЕВОЗИ

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***Ключови думи**: затихване, мобилни комуникации, многопътни канали, разпространение, разсейване*

***Анотация**: Представен е анализ на променливата скорост на намногопътно затихване на базовата станция на клетъчна комуникационна система при получаването на сигнал от мобилно устройство при междуградски превози. Затихването и неговата променливост се разглеждат като функция на разстоянието между базовата станция и пътя или ж.п. линията, по която се движи мобилното устройство. Позазано е, че променливостта на скоростта на затихване е по-голяма, когато пътят преминава вблизост до базовата станция.*