論 文

도시내 이동무선에서의 다중파전파전파의 특성 및 모델에 관한 연구

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Models and Characteristics of Multipath Propagation on Mobile Radio in an Urban Area

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要 約 도시내 이동통신에 있어서는 주위의 건물에 의한 다중파간섭 페이딩으로 통신품질이 현저하게 열화되어, 신호 전송에 대한 큰 장애가 된다. 시가지에서의 다중파전파전파모델은, 수신점에 같은 정도의 크기의 평면파가 무수히 도래하며 그 도래방향과 위상이 Random하다는 Random Model이 일반화 되어 있다. 본 논문에서는 전파도래방향과 거의 직각 또는 평행으로 구성되는 시가지 도로상에서의 전파전파모델은 2파모델로 근사화할 수 있음을 보였다. 특히 주파수상관법에 의한 지연다중파의 지연시간 추정방법을 제안하여, 이 방법에 의한 지연시간 측정에 있어서 다중파전파의 전파모델을 2파모델로 가정한 경우와 랜덤모델로 가정한 경우와를 비교 검토하였다. 그 결과 주파수상관법에 의한 지연다중파의 지연시간 측정법에 있어서도 전파모델을 2파모델로 근사화 시킬 수 있음을 알 수 있었다.

ABSTRACT In this paper, the models and characteristics of multipath propagation in an urban environment are described. Three propagation models (a random model, a ray model and a simplified two-ray model) are explained, and a method of estimating time delay is proposed based on the envelope correlation between two radio frequencies. It is shown on the basis of laboratory simulation and field tests that the simple two-ray model is an adequate model for the fundamental study of the multipath propagation characteristic of the mobile radiowave and the estimating time delays of multipath-propagated waves in an urban area.

1. INTRODUCTION

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Land mobile communication suffers from signal strength attenuation due to buildings and multipath fading caused by reflection from surrounding objects. This is essentially severe in dense urban areas. As is well-known, delays of multipath-propagated waves cause frequency-selective fading, resulting in signal waveform distortion, and hence degraded transmission quality. Because of the broad bandwidth of TV transmission compared to the narrow bandwidth of voice signal transmission, TV signals are more easily affected by frequency-selective multipath fading. In order to understand the impairment of picture quality for mobile TV reception in urban areas, first of all, it is necessary to examine the characteristics of multipath propagtion.

Time delays in multipath propagation result from signals diffracted or reflected by buildings or other prominent urban structures. Because the reflected transmission paths are longer than the direct transmission path from the base station, the signals are delayed.

Time delay may constitute a serious limitation for the performance of transmission systems employing a wide modulation band, such as a high speed digital signal transmission system. In case of TV signal transmission, a large time delay causes frequency-selective fading, which in turn causes severe waveform distortion of composite video signals, which in turn causes picture impairment. Specially, delays of 1 microsecond or more are common in an urban area, these excess time delays lead to ghost images which flutter(i.e., fluttering ghost)[1]

In the following sections three models are described which are relevant to the analysis of multipath propagation in urban areas, and field tests of time delay are conducted in an urban area based on the envelope correlation between two radio frequencies.

2. TYPICAL PROPAGATION MODELS

2.1 Random Model

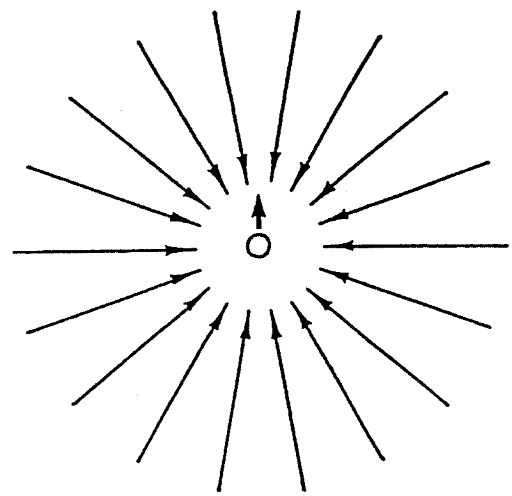


Fig.1 Random Model.

Assume that signals received by a vehicle in motion on a street consist of a large number of primarily horizontally travelling uniform plane waves whose amplitudes, phases, and angles of arrival relative to the direction of vehicle motion are random (see Figure 1). This is hereafter referred to as the random model of multipath propagation[2,3]. It is well known that the probability distribution of received signal strength in this model is given by the Rayleigh distribution[4,5]. In general, the Rayleigh distribution takes place when the signals are infinitely large in number, of equal amplitude and frequency, but random in phase. The phases are uniformly distributed from 0 to 2π. Also, the amplitudes and phases of multiple waves are assumed to be statistically independent.

This model can be a good approximation in some special propagation situations, e.g., the over-the-horizon scatter propagation in the troposphere. However, in the case of line-of-sight microwave propagation, this is not always a good approximation. In urban mobile radio communication, on the other hand, the randon model is a good approximation when a broad receiving area is considered, or when no stationary rays are received.

Because of a convenience in analytic calculation, the random model is widely used in analysis of fading phenomena in propagation in urban areas.

2.2 Ray Model

This model assumes that signals are received by a vehicle via ray-theoretical propagation paths, they are, diffraction over buildings and reflection at building walls[6]. This model is illustrated in Figure 2. As multiple diffraction and reflection cause large signal strength attenuation, the number of principal waves are limited in ordinary cases.

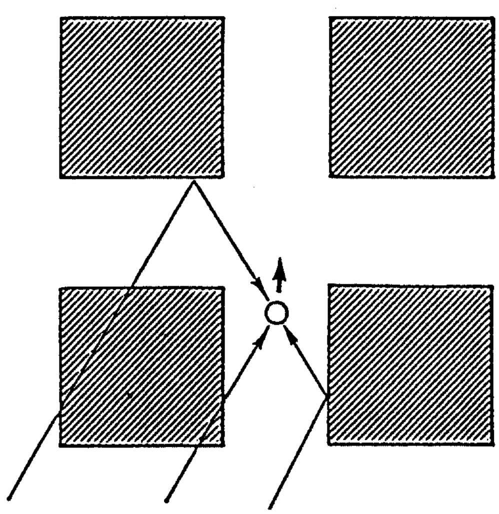


Fig.2 Ray Model.

In the actual urban propagation, there are other modes of propagation, such as scattered wave by building surfaces and guided mode wave along a street[7]. In moderate city, it is observed that the wave components other than the principal ray-theoretical waves are generally weak in signal strength[8]. In addition, ray-theoretical waves are observed to exist stationarily along a street. On the contrary, the waves of other modes appear at random when a vehicle moves along a street. For these reasons, most of the major propagation characteristics in urban areas can be understood by the ray model.

The ray model may be very useful to analyse the propagation phenomena as far as ray-theoretical modes are predominant.

2.3 Two-ray Model

A simplified ray model, called the two-ray model, is a fundamental model of multipath propagation in urban areas. The fundamental effects of multipath propagation on signal transmission can be analysed by the simple two-ray model in principle. Therefore, this model is widely used for the basic analysis of communication performance in multipath environments[9,10].

However, the two-ray model is not only an idealizd model, but also is observed in the actual urban radio environments. When the street angle (defined to be an angle between the orientation of a street and the direction of an incident wave)is small, that means when the incident wave is nearly parallel to a street, the propagation structure is well approximated by the two-ray model. In this case, the two-ray model is used for the analysis of propagation and the performance evaluation of a practical system as well.

If ray-theoretical waves are dominant, the two-ray model is important to describe the mean field strength on urban streets. As shown in Figure 3, two principal rays are dominant on most parts of urban streets, for an ideal city structure of regularly laid out buildings of same height. In each case, the mean field strength is given from the square root of power sum of the two rays, and major characteristics of mean field strength on urban streets are expressed by the use of this model [8].

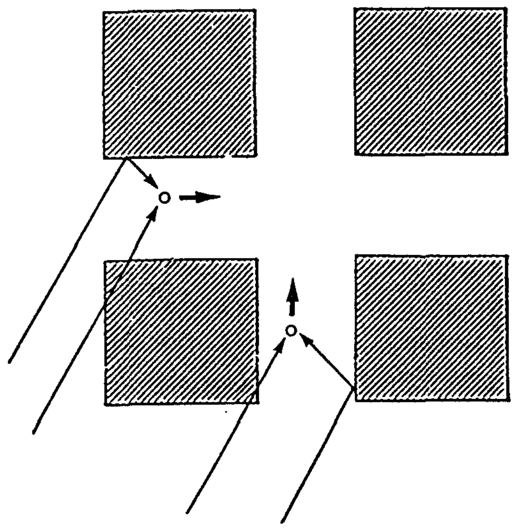


Fig.3 Two-ray Model.

For these reasons, the two-ray model is frequently used to simulate the multipath radio environments, especially for the fundamental analysis of transmission performance.

Two types of two-ray models are frequently used, the stationary two-ray model and the Rayleigh-distributed two-ray model. The stationary two-ray model corresponds to a fixed reception, and manual change of the multipath parameters is made in laboratory experiments to observe the basic effects of the variations in multipath parameters on system performance.

The Rayleigh-distributed two-ray model represents a dynamic multipath fading. The amplitudes of two rays fluctuate subject to the Rayleigh fading. Often, a model is assumed in which the two rays fluctuate without correlation. This model is called the independent (or uncorrelated) Rayleigh-distributed two-ray model, or the Rayleigh-distributed two-ray model with no correlation. The multipath propagation in urban areas can be well approximated by this model when two waves are predominant.

3. BASIC PROPERTIES OF MULTIPATH PROPAGATION

3.1 Spatial Period of Fading

First, consider a ray received directly from a transmitting station. Assume that a mobile unit is travelling in the direction of the positive X-axis at a constant velocity V, and receiving a signal at an arrival angle θ, with respect to the X-axis, as illustrated in Figure 4(a).

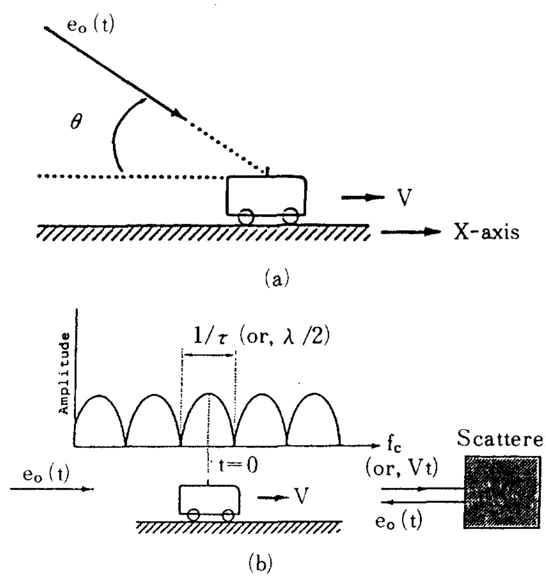


Fig.4 Received-signal envelope for a vehicle in motion:
(a) direct signal received from transmitting source (Doppler shifted);
(b) Doppler shifted direct signal plus scattered signal from perfect reflector.

The signal transmitted from the station is expressed as:

$$e_o(t)=E_o \cdot \exp[j(\omega_c t+\phi_o)],$$

and the received signal e(t) is expressed as:

$$e(t)=E_o \cdot \exp[j(\omega_c t+\phi_o-\beta Vt \cdot \cos\theta)], \quad (1)$$

where E_o is the initial amplitude of the transmitted carrier signal, ϕ_o is the phase of transmitted carrier signal, w_c is angular frequency of the transmitted carrier singnal and is equal to $2\pi f_c$, where f_c is the carrier frequency, and $\beta=2\pi/\lambda$ where λ is the wavelength of the the transmitted carrier signal. In addition, there is a Doppler shift due to the motion of the mobile unit. This can be expressed as follows:

$$f_d=f_m \cdot \cos\theta, \quad (2)$$

where $f_m=V/\lambda$ is the maximum Doppler frequency.

To introduce the effects of multipath propagation, first consider the simple and idealized case of a horizontally travelling transmitted signal reflected 180 degrees from a perfect reflector. This is illustrated in Figure 4(b). The resultant signal received by the mobile unit moving at a velocity V assuming an arrival angle of $\theta=0$, can be expressed as follows[11]:

$$\begin{aligned} e(t) &= E_o \cdot \exp[j(\omega_c t+\phi_o-\beta Vt)] \\ &\quad - E_o \cdot \exp[j(\omega_c t+\phi_o+\beta Vt-\omega_c\tau)] \\ &= -j2E_o \cdot \sin(\beta Vt-\omega_c\tau/2) \\ &\quad \cdot \exp[j(\omega_c t+\phi_o-\omega_c\tau/2)], \end{aligned} \quad (3)$$

where τ is the time that it takes for the wave to travel to the reflector and return to the t=0 line. The standing wave envelope of received waves can be interpreted as a fading phenomenon. In the case where linear detection is applied, then the envelope of Eq.(3) can be expressed as follows:

$$A(t)=2E_o \cdot |\sin(\beta Vt-\omega_c\tau/2)|, \quad (4)$$

where A(t) is the amplitude output of the linear detector. When $\beta vt=n\pi+w_c\tau/2$, then a fade of zero amplitude will be observed.

In order to examine the spatial period of the fade, first consider the case where the mobile unit is stationary (i.e., V=0). Then Eq.(4) becomes:

$$A(t)=2E_o \cdot |\sin(\omega_c\tau/2)|. \quad (5)$$

Thus, a fade period between successive zeroes interval of zero amplitude in the frequency domain can be derived from Eq.(5) as follows:

$$\Gamma\tau=1, \quad (6)$$

where Γ is the frequency separation between two consecutive notch frequencies of the regular signal strength pattern vs. frequency.

When the mobile unit is in motion with a constant velocity V, a fade interval T of zero amplitude in the time domain can be drived from Eq.(4) as follows:

$$T=\lambda/2V. \quad (7)$$

Similarly, a fade interval of zero amplitude in the space domain can be drived from Eq.(4) as follows:

$$\Lambda=VT, \quad (8)$$

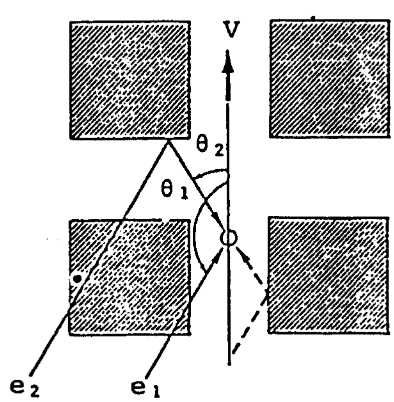
where Λ is the sapatial fade period of the received signal. Thus, the spatial fade period of the received signal for the two-ray model can be derived from Eq.(7) and Eq.(8). The spatial period of fade is $\Lambda=\lambda/2$.

A more general form of the spatial period of fade can also be derived for the two-ray model from geometrical optics. Consider the more general case of two rays, e_1, e_2, received at arbitary angles θ_1, θ_2. This is illustrated in Figure 5(a). In this case the spatial period of fade can be expressd as follows.

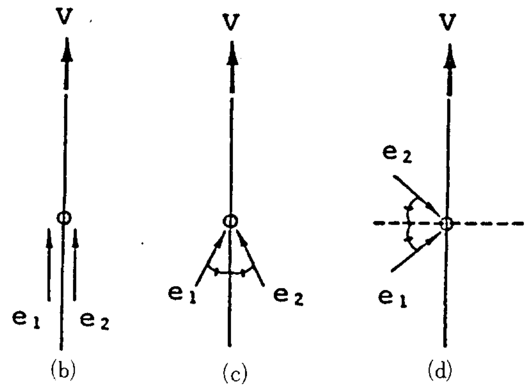
$$\Lambda=\lambda/|\cos\theta_1-\cos\theta_2| = \lambda/|2\cdot\sin[(\theta_1+\theta_2)/2]\cdot\sin[(\theta_1-\theta_2)/2]|. \quad (9)$$

In the case of parallel arrival of e_1 and e_2, $\theta_1-\theta_2=2n\pi$, where n=0, 1, 2, 3,…(see Figure 5(b)). In the case of symmetrical arrival relative to the direction of vehicle motion, $\theta_1+\theta_2=2n\pi$ (see Figure 5(c)). In this case the spatial period of fade takes a maximum value of $\Lambda_{max}=\infty$. In the case of symmetric arrival relative to the perpendicular to the direction of vehicle motion, $\theta_1+\theta_2=(2n+1)\pi$ (see Figure 5(d)). For this last case Eq.(9) becomes a minimum and is expressed as:

$$\Lambda_{min}=\lambda/|2\cdot\sin[(\theta_1-\theta_2)/2]|. \quad (10)$$



(a)



(b) (c) (d)

Fig.5 Conditions fo maximum and minimum period of fade:
(a) two-ray model; (b),(c) maximum conditions; (d) minimum condition.

In this case, where the angle made by the two incident waves is $\theta_1-\theta_2=(2n+1)\pi$, i.e., the signals arrive parallel to the direction of vehicle motion but in opposite directions, the spatial period of fade takes a minimum value of $\lambda/2$.

The value of the spatial period of fade of the received signal envelope obtained from experimental measurement, when compared to the theoretical value, can be used to judge whether or not the two-ray model is a good approximation in the actual urban conditions.

3.2 RF Doppler Spectrum of Random Model

The RF Doppler spectrum $S_r(f)$ represents the energy of the received signal, r, in the frequency interval (f, f+df) and is expressed as follows[12]:

$$S_r(f)=\frac{1}{f_m\sqrt{1-f^2/f_m^2}} \cdot[g(\theta)\cdot p(\theta)|_{\theta=\cos^{-1}(f/f_m)} + g(\theta)\cdot p(\theta)|_{\theta=-\cos^{-1}(f/f_m)}], \quad (11)$$

where θ is the arrival angle of the plane waves incident on the antenna, $g(\theta)$ is the antenna's azimuthal power gain function, and $p(\theta)$ is the Rayleigh density function.

The most common case is that of a vertical monopole antenna which has a constant azimuthal gain function, say $g(\theta)=1$. Assuming that $p(\theta)$ is uniform for all angles throughout the range $-\pi$ to π, i.e., assuming the random propagation model, $p(\theta)=1/2\pi$. Therefore, the RF Dopper spectrum at the antenna terminal is:

$$S_r(f)=\frac{1}{\pi f_m\sqrt{1-f^2/f_m^2}} \tag{12}$$

$S_r(f)$ has a finite value for frequencies in the range $\pm f_m$ around the carrier frequency f_c, and is zero outside that range, as shown in Figure 6.

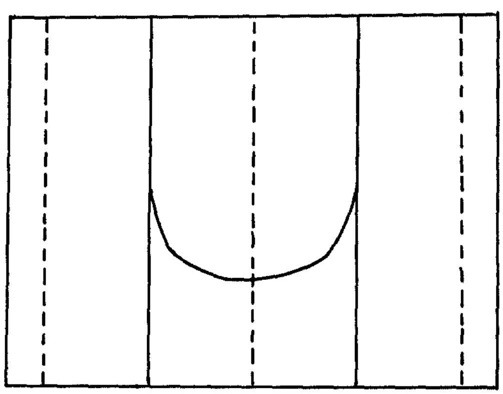


Fig.6 RF spectrum of random model.

3.3. Field Measurements of RF Spectrum

To investigate whether the RF spectrum in an urban area is such as predicted by the random model, a field test was conducted in an urban area (Kyoto, Japan) to measure the RF spectrum.

The variations in the signal strength and phase, and the RF spectra measured in this test are shown in Figure 7. In the case of a road nearly parallel to the incident wave direction, the RF spectrum shows a concentration on the maximum Doppler shift frequencies, $f_c \pm f_m$ (see Figure 7(a)). This, plus the direction pattern of the signal strength as measured by a directional antenna and the period of variation of the measured signal strength, all indicate that two dominant waves arrive parallel to vehicle motion but in opposite directions. Vehicle motion is nearly parallel to the incident wave direction, thus the conditions for fading due to regular standing wave pattern (see Figure 4(b)) are approximated.

In the case of a road perpendicular to the incident wave direction, the RF spectrum of the received signal is concentrated about the carrier frequency f_c, as shown in Figure 7(b). This, plus the direction pattern of the received signal strength, indicate that the received waves are usually confined to the direction of the incident wave from the transmitting station.

4. FIELD MEASUREMENTS OF DELAY TIME

Investigations of time delays in urban areas have been done using short pulses or bandpass impulse response measurements[13,14,15]. Another method of predicting time delay is proposed using the envelope correlation between two radoio frequencies. This is called the frequency correlation method. The propagation model assumed in this method is the random model or two-ray model.

4. 1 The Principle of Estimation Delay Time

In the case of the random propagation model, the correlation of the envelopes of the signals

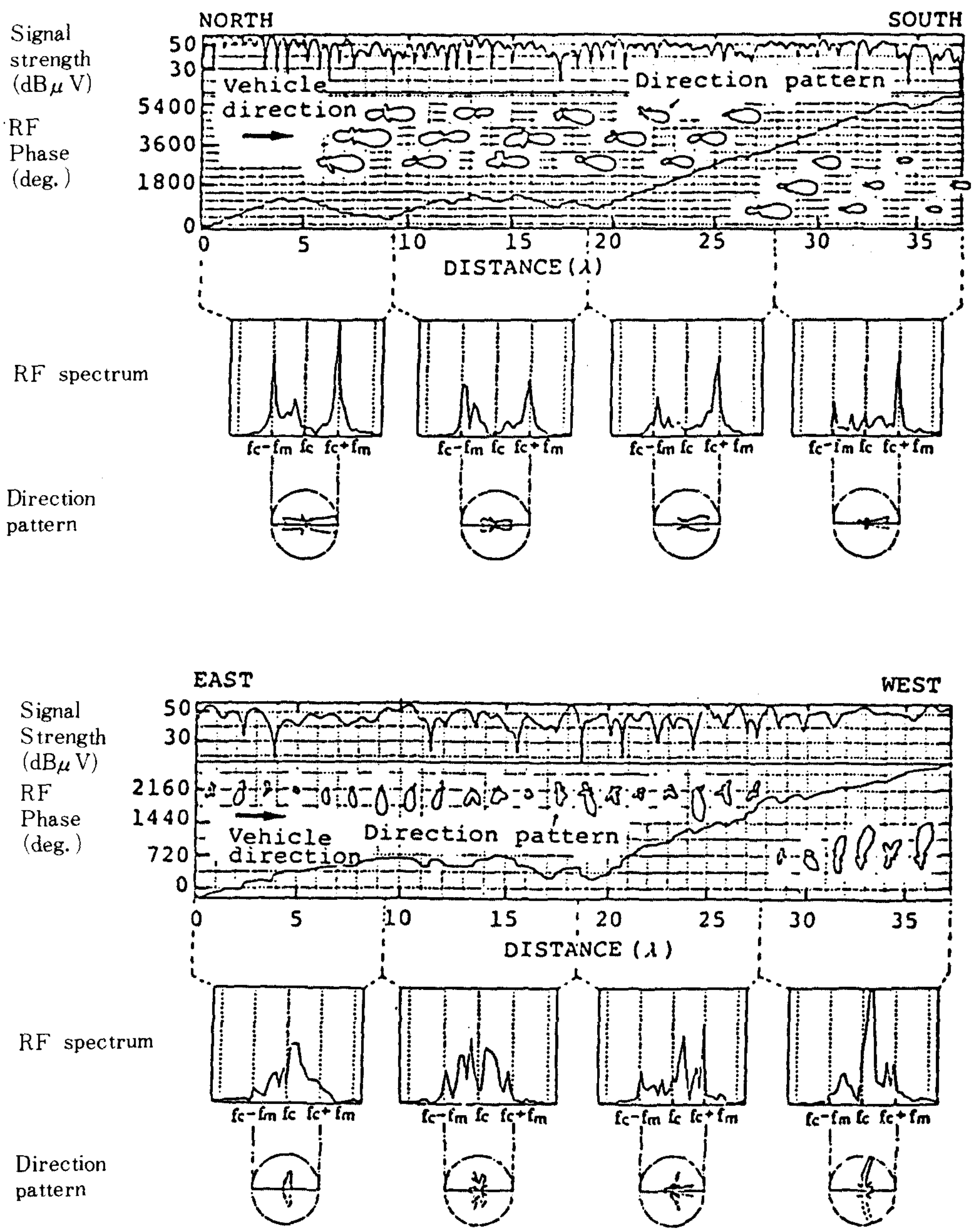


Fig.7 An example of measured signal strength, phase, direction pattern and RF spectrum in an urban area:
(a) meausred data on North-South Street;
(b) measured data on East-West Street,
where the transmitting station is located South of the data-gathering point.

at the two frequencies is expressd as follow [16]:

$$\rho_r = \frac{1}{1 + (2\pi\Delta f \cdot \sigma_l / c)^2} \tag{13}$$

where Δf is the frequency interval of the two radio waves, σ_l is the standard deviation of the path difference spread (or delay spread), and c is the light speed. From the Eq.(13), the theoretical formula of the delay spread in random model can be derived as follow:

$$\sigma_l = \frac{c}{2\pi\Delta f} \sqrt{\frac{1}{\rho_r} - 1} \tag{14}$$

We see from the Eq.(13) that the frequency correlation coefficient ρ_r decreases with increasing frequency separation Δf or delay spread σ_l, as one would expect.

We now consider that the propagation model is the two-ray propagation model. Assuming that the amplitude ratio of the two waves is R and the path length difference is l, the received power P of a radio wave with the frequency f can be expressed as follow:

$$P = 1 + R^2 + 2R \cdot \cos\left(2\pi f \cdot \frac{l}{c}\right) \tag{15}$$

Thus, the received power P_1, P_2 of the two waves with the frequency f_1 and $f_2 = f_1 + \Delta f$ can be rewritten as follow, respectively:

$$P_1 = 1 + R^2 + 2R \cdot \cos\left(2\pi f_1 \cdot \frac{l}{c}\right)$$

$$P_2 = 1 + R^2 + 2R \cdot \cos\left(2\pi f_1 \cdot \frac{l}{c} + 2\pi\Delta f \cdot \frac{l}{c}\right) \tag{16}$$

Therefore, in the case of the two-ray propagation model, the frequency correlation coefficient ρ_t can be calculated as follow:

$$\rho_t = \frac{\langle (P_1 - \langle P_1 \rangle) \cdot (P_2 - \langle P_2 \rangle) \rangle}{\sqrt{\langle (P_1 - \langle P_1 \rangle)^2 \rangle \langle (P_2 - \langle P_2 \rangle)^2 \rangle}}$$

$$= \cos(2\pi\Delta f \cdot l/c), \tag{17}$$

where the symbol ⟨ · ⟩ means the ensemble average. From the Eq.(17), the theoretical formula of the delay time can be also derived as follow:

$$l = \frac{c}{2\pi\Delta f} \cdot \cos^{-1} \rho_t. \tag{18}$$

We can see from the Eq.(17) that the frequency correlation coefficient takes repeatedly the value from -1 to 1 in accordance with the variation of path length difference and the frequency separation.

Figure 8 shows the theoretical curves of frequency correlation vs. path length difference (two-ray model) or path difference spread corresponding to the delay spread (random model), for frequency separation of 100 and 375KHz. We can see from this Figure 8 that the delay spread (or delay time) can be derived from the frequency correlation coefficient

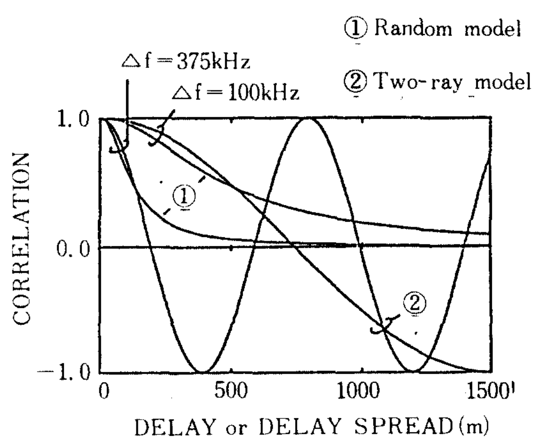


Fig.8 Theoretical curves of frequency correlation vs. delay or delay spread.

(i.e., using the Eq.(13) and(17)). Especially, in the case of the frequency separation is 1 00KHz the path length difference can be estimated to the value of 500 meters with a negligible error between the above mentioned two propagation models. In this method, the frequency correlation coefficient can be calculated from the measured two signal strengths with each different frequency.

4.2 Field Tests of Delay Time

The frequency correlation method was tested in a specific urban area (Kyoto, Japan), and delay time were measured along the streets for 400MHz waves at two frequencies separated by 100KHz. A schematic diagram of the measuring system for signal strengths and test frequencies are given in Figure 9. The map of the test area is shown in Figure 10.

The radio waves(400MHz band), transmitted from Kyoto Minami Station about 7Km south-south-west of the test area, and radio waves were received by an omni-directional antenna(turn-stile antenna; Gain-1. 9dB) and a directive antenna(Gain 4dB, front-to-back ratio 14~17dB, half-power beamwidth 65degrees) mounted on the roof top(about 3m above the ground) of a mobile labortory turned to the north and south. The measured data using the omni-directional antenna were analysed for estimating the time delays in the random propagation model and the data using the directive antenna were analysed for the two-ray propagation model. The output voltage of the field strength meter was recorded by a data recorder together with a "distance pulse" which was generated by a distance sensor every 2.6cm while the mobile lab was moving. The signal strength was converted to a signal power after the A / D conversion using by the distance pulse as a sampling pulse. And then, the frequency correlation coefficients were calculated from the signal power with the distance interval of 10.5 meters and the time delays were estimated from those data.

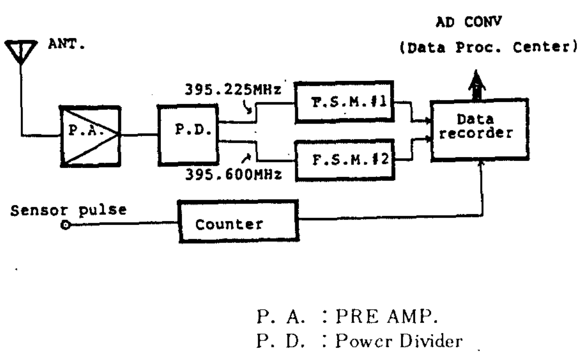


Fig.9 Measuring system for signal strengths.

The delay obtained from the frequency correlation are shown in Figure 11. The obtained delays, which give the average approximate values, are about 100~500 meters in most points with the negligible error between the two models, but exceed 500 meters sometimes up to 1000 meters or more. A tendency is seen that the delay is larger on a street nearly paralllel to the incident wave direction than on a street nearly perpendicular.

The results show that multipath waves with delay time of about 1 microsecond always exist at receiving points on the urban streets.

5. SUMMARY

To investigate the models and characteristics

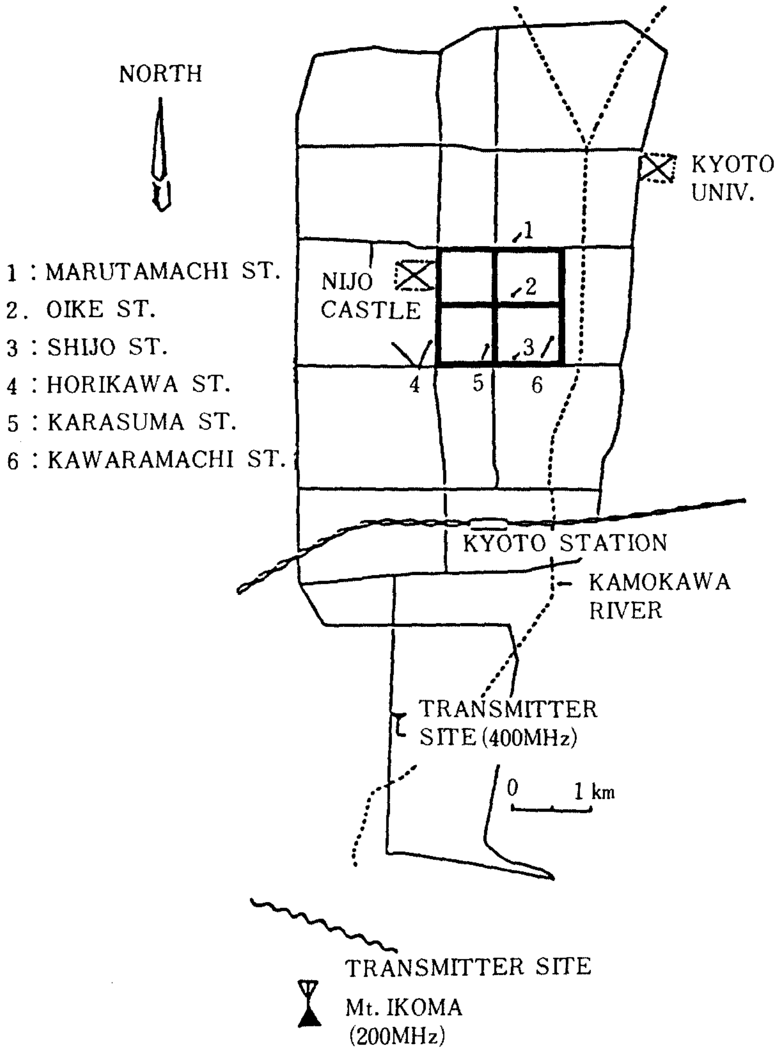


Fig.10 Map of test area(the broad lines on the map indicate the measuring course.)

of multipath propagation in an urban area both the theoretical and experimental analysis were made in relation to the RF spectrum, the measured direction pattern of the signal strength and the period of variation of signal strength. In addition, the field tests were conducted to measure the time delays based on the envelope correlation between two radio frequencies, assuming both the random and two-ray propagation model.

From the experimental results, it can be seen that the theoretical RF Doppler spectrum for the random model is different from the actual measured RF spectrum in the urban test areas. From this it can be inferred that the random model is not always appropriate in an urban

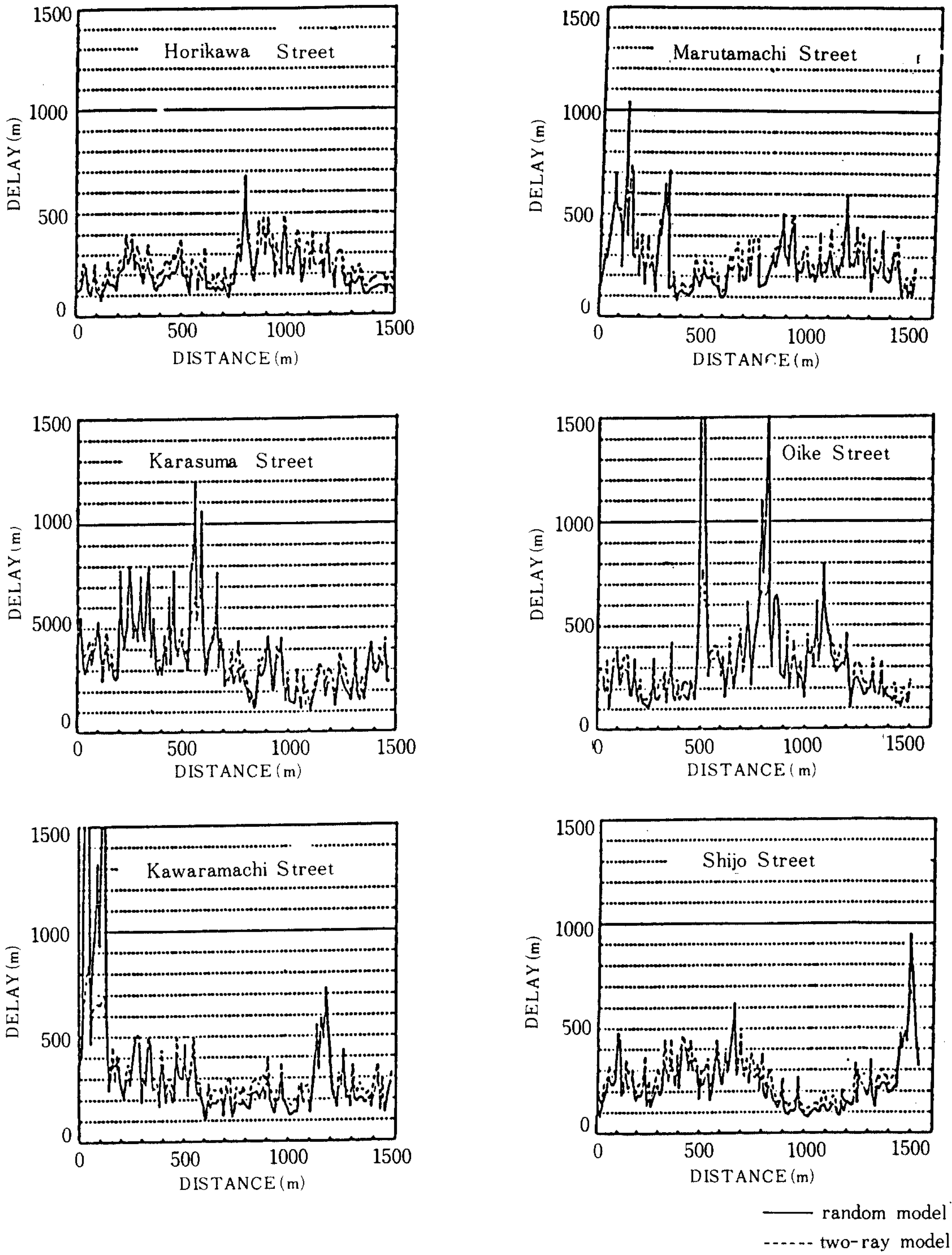


Fig.11 Delay vs. distance on main streets of Kyoto:
(a) North-South streets (i.e., parallel to incident wave direction);
(b) East-West streets (i.e., perpendicular to incident wave direction).

area.

The measured direction patterns of the signal strength are also different from that caused by the random model. It was found that two principal rays are dominant on most parts of urban streets, for an ideal city structure of regularly laid out buildings of same height.

From the estimated time delays of radio waves in a specific urban area(i.e., the city structure is regularly laid out buildings of same height and the road is nearly parallel or perpendicular to the incident wave), it can be seen that time delays are nearly same values in both case of the two-ray model and random model. Therefore, in this specific urban area it can be inferred that the two-ray model is good approximation model to study the propagation characteristics and estimate the time delays of mutipath-propagated waves.

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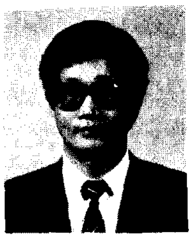

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