Correlation Coefficients of Received Signal I and Q Components in a Domain with Time and Frequency Axes under Multipath Mobile Channel with LOS and NLOS

Shigeru Kozono, Kenji Ookubo, Takeshi Kozima and Tomohiro Hamashima

Department of Electrical, Electronics and Computer Engineering,
Chiba Institute of Technology
2-17-1 Tsudanuma, Narashino-shi, 275-0016, Japan

1. Introduction

To support realtime multimedia communication, future mobile communications will require a high-bit-rate transmission system with high utilization of the frequency spectrum in very rich multipath channels [1]. Systems capable of fulfilling this requirement, with features such as orthogonal frequency division multiplexing (OFDM) [2], [3] and multiple-input multiple-output (MIMO) [4]–[7], have been studied extensively. Furthermore, the use of M-ary quadrature amplitude modulation (M-ary QAM) with coherent detection helps to meet the transmission requirements. Such systems overcome frequency selective fading by using a narrowband multiple-carrier signal called a sub-channel. Those systems use sophisticated and refined techniques and several of those techniques are usually combined in one system. To make full use of the techniques in the system design and achieve high-quality transmission, we must design a system taking into consideration wide and detailed multipath properties in a domain with time and frequency axes. OFDM works best with a lot of narrow bands for the sub-channel. MIMO also requires multipath properties between the antennas composing the MIMO antenna, and it requires a low correlation coefficient. M-ary QAM detection also requires the device to compensate accurately for both the in-phase and quadrature (I and Q) components of the sub-channel for the ever-changing multipath channel associated with terminal movement, and this is achieved by putting a pilot signal in the information data [8].

Figure 1 shows an example of the sub-channel state of the I and Q components and phase $\psi$ ($\tan^{-1}(Q/I)$) as movement in a multipath channel, and Fig. 2 shows the signal state diagram at the moment. With movement, the I, Q, and the phase $\psi$ change irregularly as shown by solid lines in Fig.1, so we cannot use the sub-channel as a transmission line. Therefore, the sub-channel needs to be a stable state with compensation by a pilot signal. The states of the sub-channel compensated every $10T_{sy}$ ($T_{sy}$: symbol length) in information data, which
corresponds to a $0.1\lambda$ [m] running distance, are shown by broken lines in Fig. 1, the I and Q components become stable, and the sub-channel can then be used as a transmission line. This phenomenon in Fig. 2 appears as concentrated points in a small broken circle, so it is possible that a received signal with M-ary QAM is detected. The pilot signal is inserted at a fixed interval in information data: in particular the pilot signal in a combined system with OFDM and M-ary QAM is allocated in a domain with time and frequency axes and there must be a high correlation coefficient between pilot signals. This signal allocation is very important because it influences transmission efficiency and bit error rate (BER).

Fig. 1. Example of sub-channel variations with movement
Fig. 2. Signal state diagram with I and Q components in Fig. 1

What the wireless system design requires in terms of basic multipath properties seems to be the correlation of the sub-channel’s I and Q components in a domain with time and frequency axes. Many theoretical and experimental studies have been performed on the correlation of received signal amplitudes [9]–[12], but the correlation of the I and Q components has hardly been studied at all [9]. Furthermore, the ordinary formula for amplitude correlation given by Jakes [10] is derived on the basis of the I and Q components with a random Gaussian variable in the non-line-of-sight (NLOS) condition. With this in mind, we paid attention to the delay profile with actual multipath data in a mobile channel and developed an analysis model with a domain having time, frequency, and space (delay time) axes to investigate the correlation using the profile [13]. Furthermore, we derived a correlation formula for various profile types for the line-of-sight (LOS) and NLOS conditions and also verified the theory by computer simulation.

This chapter is organized as follows. Section 2 describes a propagation model and analysis model. Section 3 covers the theoretical study. First, we derive the general correlation formula for the I and Q components using a delay profile for LOS or NLOS. Next as examples, we derived formulas for delay profiles when the arriving wave has an exponentially decreasing amplitude and a random amplitude. Section 4 covers simulation. The simulation method and parameters are described and the simulation results are presented. The simulation was done for autocorrelation and for frequency correlation on time and frequency axes for LOS and NLOS and also done in the domain for those profiles. Then, the correlation formulas were evaluated. Finally, section 5 summarizes the results.

2. Propagation model and analysis model

A. Propagation model

In a mobile radio channel, numerous waves arrive at a receiving point via multiple paths, with each wave having a certain amplitude, a certain delay time, and a random arrival angle. Consequently, the arriving waves interfere with each other and standing waves are
produced. Thus, the received signal amplitude varies with terminal movement and has a Rayleigh or Nakagami-Rice distribution. An example of the delay profile is shown in Fig. 3 for the following conditions.

![Figure 3. Example of delay profile](image)

i. The number of arriving waves is $N+1$, the waves are independent of each other, and the $i$th arriving wave is denoted by subscript $i$, where $i=0$ means a directive wave and $i \geq 1$ means no directive waves.

ii. The waves have an excess delay time $\tau_i$ relative to the directive wave and a maximum excess delay time $\tau_{\text{max}}$. The $\tau_i$ values are random from $\tau_0$ to $\tau_{\text{max}}$.

iii. The amplitude is $h_i$, the power ratio of the directive and nondirective waves is denoted by $k$ ($K$ in dB), and $k=0$ ($K=-\infty$ dB) means NLOS. Furthermore, the nondirective wave’s power is normalized to 1.

iv. The arrival angle is $\xi_i$, the initial phase is $\phi_i$, and the values are random from 0 to $2\pi$ rad.

**B. Multipath channel**

Under the above conditions, the envelope $E(t, f_c)$ of a received signal is given by (1), where $I(t, f_c)$ and $Q(t, f_c)$ express the in-phase (real) and quadrature (imaginary) components of $E(t, f_c)$, respectively.

$$ E(t, f_c) = \sum_{i=0}^{N} h_i e^{j\theta_i} $$

$$ = I(t, f_c) + jQ(t, f_c) \quad (1) $$

$$ I(t, f_c) = \sum_{i=0}^{N} h_i \cos \theta_i \quad (2-a) $$

$$ Q(t, f_c) = \sum_{i=0}^{N} h_i \sin \theta_i \quad (2-b) $$
Here, $\theta_i$ is the path phase of the $i$th arriving wave, $f_c$ is the radio frequency, and $f_m$ is the maximum fading frequency calculated as $v/\lambda$, where $v$ is the moving speed and $\lambda$ is the wavelength. As shown by (2) and (3), the I and Q components are functions of variable $\theta_i$, which is a function of $f_c$, $t$, and $v$, for a given delay profile. When the sub-channel bandwidth of the system, such as an OFDM system, is $f_0$, we have $f_c >> f_0$ since we treat a narrowband channel in a multipath environment. Therefore, we treat the frequency separately from $f_c$ as $\Delta f = nf_0$ ($n$: integer). Figure 4 shows an example of an OFDM channel with a lot of sub-channels in a domain with time ($vt$) and frequency ($nf_0$): each sub-channel amplitude $|E(t, f_c)|$ changes severely and deeply in the domain.

\[
\theta_i = 2\pi(f_c \tau_i - f_m t \cos \xi_i) + \phi_i
\]

**C. Analysis model**

As shown (2), the $I(t, f_c)$ and $Q(t, f_c)$ depend on $\theta_i$ by (3) for a given delay profile and the $\theta_i$ is a function of $f_c \tau_i$ and $f_m t$. Therefore, we study the correlation of $I(t, f_c)$ and $Q(t, f_c)$ by using the variables of $f_m T_s$ (normalized maximum Doppler frequency) on the time axis and $\Delta f \sigma$ ($\sigma$: delay spread) on the frequency axis. For example, $T_s$ is absolute time $t$ minus relative time $T_0$ for a directive wave arriving at the receiving point, i.e., $T_s = t - T_0$; $\Delta f$ is the frequency separation from the radio frequency $f_c$, i.e., $\Delta f = f - f_c$. Furthermore, to simplify the expression of those variables, we introduce $x = f_m T_s + \Delta f \sigma$ as a variable of time and frequency. Moreover, we choose the origin $P_0(0,0)$ and the point under consideration for the correlation $P_1(f_m T_s, \Delta f \sigma)$ to correspond to $x=0$ and $x=\Delta x$, respectively. Consequently, those points are expressed by $P_0(0)$ and $P_1(\Delta x)$, and we can calculate the correlation coefficient $\rho(\Delta x)$ as the correlation between $P_0(0)$ and $P_1(\Delta x)$. We denote the correlation coefficients for the I and Q components using the

![Graph showing an example of an OFDM channel in multipath condition](image-url)
symbols $\rho(\Delta x)$ and $\rho_Q(\Delta x)$, respectively. The path phases of the $i$th arriving wave $\theta_i$ given by (3) at $P_0(0)$ and $P_1(\Delta x)$ are also represented by (4-a) and (4-b), respectively.

$$\theta_i(0) = 2\pi f_c \tau_i + \phi_i, \quad \text{(4-a)}$$

$$\theta_i(\Delta x) = 2\pi((f_c + \Delta f)\tau_i - f_m T_s \cos \xi_i) + \phi_i \quad \text{(4-b)}$$

### 3. Derivation of correlation coefficients

#### A. General formula derivation

We start by studying the correlation coefficient of the I component. With the variable $x$, the correlation coefficient of the I component is generally expressed by

$$\rho_i(\Delta x) = \frac{\langle (I(0)) \langle I(\Delta x) \rangle - \langle I(0) \rangle \langle I(\Delta x) \rangle \rangle}{\sqrt{\langle (I(0))^2 \rangle - \langle I(0) \rangle^2} \langle (I(\Delta x))^2 \rangle - \langle I(\Delta x) \rangle^2}^{1/2}. \quad (5)$$

Here, the symbol $\langle \rangle$ means an ensemble average. Under the conditions of the propagation model in 2-A and assuming that $N$ is a large number, we can start to calculate each term in (5).

First, we calculate the terms $\langle I(0) \rangle$ and $\langle I(\Delta x) \rangle$. Because $\tau_i$, $\xi_i$, and $\phi_i$ have random values, the ensemble averages at $x=0$ and $\Delta x$ become zero when (4-a) and (4-b) are used to substitute for $\theta_i$ in (2-a), so these terms become

$$\langle I(0) \rangle = \langle I(\Delta x) \rangle = 0. \quad (6)$$

Second, we calculate $\langle I(0)^2 \rangle$ and $\langle I(\Delta x)^2 \rangle$. Though the ensemble averages for the product of different $i$th arriving waves vanish since $\tau_i$, $\xi_i$, and $\phi_i$ have random values, those of the same $i$th arriving waves remain as the power, and we get

$$\langle I(0)^2 \rangle = \langle I(\Delta x)^2 \rangle = \frac{1}{2} \sum_{i=0}^{N} h_i^2. \quad (7)$$

Next, we calculate the term $\langle I(0)I(\Delta x) \rangle$. When we consider $\tau_i$, $\xi_i$, and $\phi_i$ to be random values and take an odd function of sine, this term becomes as follows (see appendix A).

$$\langle I(0)I(\Delta x) \rangle = \frac{1}{2} \left\langle \sum_{i=0}^{N} a_i \cos(2\pi f_c \tau_i) \cos(-2\pi f_m T_s \cos \xi_i) \right\rangle \quad (8)$$

Through (6) to (8), we can calculate the denominator and numerator in (5). Both $\langle I(0)^2 \rangle - \langle I(0) \rangle^2$ and $\langle I(\Delta x)^2 \rangle - \langle I(\Delta x) \rangle^2$ in the denominator are $\frac{1}{2} \langle \sum_{i=0}^{N} h_i^2 \rangle$ by (7) minus (6), so the denominator is $\frac{1}{2} \langle \sum_{i=0}^{N} h_i^2 \rangle$. On the other hand, the numerator becomes

$$\frac{1}{2} \langle \sum_{i=0}^{N} a_i \cos(2\pi f_c \tau_i) \cos(-2\pi f_m T_s \cos \xi_i) \rangle$$

by (6) and (8). Finally, we can rewrite correlation coefficient $\rho_i(\Delta x)$ in (5) as (9).
Correlation Coefficients of Received Signal I and Q Components

\[ \rho_i(\Delta x) = \frac{\frac{1}{2} \left( \sum_{i=0}^{N} h_i^2 \cos(2\pi f_i T_c) \cos(-2\pi f_i' T_c \cos(\xi_i)) \right)}{\sum_{i=0}^{N} h_i^2} \]

(9)

Equation (9) represents a general correlation coefficient formula for the I component, and it is applicable to a delay profile for both LOS and NLOS conditions.

Next, we study the correlation coefficient of the Q component. It is easy to understand that the correlation coefficient of the Q component is given by the same formula (9) as that for the I component. The reason is as follows. Since (9) does not contain \( \phi \), we can replace \( \phi \) in (3) by \( \phi + \pi/2 \) and substitute \( \phi + \pi/2 \) for \( \phi \) in \( \theta \) in (2-b). Consequently, the term \( \sin \theta \) becomes \( \cos \theta \) analytically, and the properties of \( Q(t, f_c) \) then become statistically similar to those of \( I(t, f_c) \). Thus, since we can calculate the correlation coefficients of both the I and Q components by using the I component, from here on we treat only the I component, which we denote simply as \( \rho(\Delta x) \).

B. Correlation coefficient in given delay profile

i) Type 1: Delay profile with exponential distribution

We first calculate correlation coefficient \( \rho(\Delta x) \) in (9) for a delay profile with an exponential distribution, as shown in Fig. 5(a). It has a directive wave with amplitude \( h_0 \) and excess delay time \( \tau_0 = 0 \) and also has a lot of nondirective waves for which \( h_i \) decreases exponentially according to (10) as excess delay time \( \tau_i \) increases.

\[ h_i = h \exp(-\tau_i/\tau_{aw}) \]

(10)

where \( h \) is the amplitude at \( \tau = 0 \) and \( \tau_{aw} \) is the average excess delay time. Under this condition and for the propagation model in 2-A, we analytically derive the correlation coefficient formula on the basis of \( \rho(\Delta x) \) in (9). The denominator in (9) is \( k+1 \) because the power of the nondirective wave was normalized to 1. Furthermore, since \( \tau_i \) and \( \xi_i \) are independent, the numerator in (9) can be separated into two parts, \( A_1 \) and \( B_1 \), as in (11).

\[ A_1 B_1 = \left( \frac{1}{2} \sum_{i=0}^{N} h_i^2 \cos(2\pi f_i T_c) \right) \left( \sum_{i=0}^{N} \cos(-2\pi f_i' T_c \cos(\xi_i)) \right) \]

(11)

When \( N \) is a large number, \( \tau_{\text{max}} \) is large, and \( h_i \) decreases according to (10), the first term \( A_1 \) can be calculated by integrating with respect to \( \tau \). As shown in appendix B, it becomes

\[ A_1 = \left( \frac{1}{2} h_0^2 \right) + \frac{1}{2} \int_{\tau_{\text{max}}}^{\tau_{aw}} h^2 \exp(-2\tau/\tau_{aw}) \cos(2\pi f \Delta f \tau) d\tau \]

\[ = k + \frac{1}{1 + (2\pi f \Delta f)^2 (\tau_{aw}/2)^2} \]

(12)

Concerning the second part, \( B_1 \), it is well-known that \( B_1 = J_0(2\pi f_m' T_s) \), where \( J_0(\bullet) \) is a zeroth-order Bessel function of the first kind and \( f_m' \) is the maximum fading frequency at \( f_c + \Delta f \). Moreover, the value of \( \tau_{aw}/2 \) in (12) is equal to delay spread \( \sigma \) when \( \tau_{\text{max}} \) is very large and \( h_i \) becomes very small at \( \tau_{\text{max}} \). Replacing \( 2\pi f \Delta f \) by \( s \), we finally get the correlation coefficient \( \rho(\Delta x) \).

\[ \rho(\Delta x) = \frac{k + \frac{1}{1 + s^2/\sigma^2}}{k+1} J_0(2\pi f_m' T_s) \]

(13)
ii) Type 2: Delay profile with random distribution

Next, we calculate the correlation $\rho(\Delta x)$ for a delay profile with a random distribution, as shown in Fig. 5(b). It has a directive wave and a lot of nondirective waves like Fig. 5(a), but $h_i$ and $\tau_i$ of the nondirective waves are independent. Excess delay time $\tau_i$ has maximum value $\tau_{\text{max}}$ and is random between $\tau_{\text{min}}$ (close to 0) and $\tau_{\text{max}}$. In a similar way to that for type 1, the denominator in (9) is also $k+1$, and the numerator in (9) can also be separated into $A_2$ and $B_2$; moreover, $A_2$ separates into directive and nondirective waves, as shown in (14).

$$A_2 B_2 = \left( \frac{1}{2} h_0^2 + \frac{1}{2} \sum_{i=1}^{N} h_i^2 \cos(2\pi f T) \right) \sum_{i=0}^{N} \cos(-2\pi f T \cos \xi_i)$$

(14)

In the first ensemble average in (14), the power of a directive wave is $k$ and that of a nondirective one is 1; moreover, $h_i$ and $\tau_i$ are independent. Therefore, $A_2$ becomes (15) by a similar integration to that for type 1 (see appendix C).

$$A_2 = \langle k + \sum_{i=1}^{N} \cos(2\pi f T) \rangle = k + \frac{\sin(2\pi f T \tau_{\text{max}})}{2\pi f T \tau_{\text{max}}}$$

(15)
B_2 in (14) also becomes J_0(2\pi f_m T_s). From the above description, the correlation coefficient \( \rho(\Delta x) \) becomes

\[
\rho(\Delta x) = \frac{k + \sin(2\pi \Delta f \tau_{\text{max}})}{k + 1} J_0(2\pi f \tau_{\text{max}}).
\]

From (13) and (16), the autocorrelation on the time axis is independent of the delay profile and always seems to be a zeroth-order Bessel function of the first kind, \( J_0(\bullet) \), whenever arriving angle \( \xi_i \) has a uniform distribution over 0 to 2\( \pi \). However, the frequency correlation on the frequency axis depends on whether the delay profile is for LOS or NLOS and whether it is dependent on or independent of \( h_i \) and \( \tau_i \).

4. Simulation

A. Simulation method

A computer simulation was performed to verify the correlation coefficient formula derived in 3-B. The simulation parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ( f_c )</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Number of arriving waves ( N + 1 )</td>
<td>10+1</td>
</tr>
<tr>
<td>Nakagami-Rice factor ( K )</td>
<td>(-\infty, 5 \text{ dB})</td>
</tr>
<tr>
<td>Average excess delay time ( \tau_{\text{av}} )</td>
<td>1 ( \mu \text{s} ) (type 1)</td>
</tr>
<tr>
<td>Maximum excess delay time ( \tau_{\text{max}} )</td>
<td>2 ( \mu \text{s} ) (type 2)</td>
</tr>
<tr>
<td>Effective amplitude ( h_i )</td>
<td>-20 dB</td>
</tr>
</tbody>
</table>

Table 1. Simulation parameters

Simulation was done to confirm (13) for type 1 with an exponential distribution and (16) for type 2 with a random distribution, and it mainly simulated correlations such as autocorrelation on the time axis, frequency correlation on the frequency axis, and correlation in a domain with time and frequency axes. The correlation was simulated by using the delay profile in actually and frequently encountered environments within the propagation model in 2-A, such that \( N = 10 \), the effective amplitude of arriving wave was -20 dB relative to the maximum for a nondirective wave, and the \( K \) factor took values of \(-\infty \) and 5 dB. For type 1, the average delay time \( \tau_{\text{av}} \) was 1 \( \mu \text{s} \) when the statistical delay spread \( \sigma \) was about 0.42 \( \mu \text{s} \) at \( K = -\infty \) dB. For type 2, the maximum delay time \( \tau_{\text{max}} \) was 2 \( \mu \text{s} \) and \( \sigma \) was 0.50 \( \mu \text{s} \). The simulation was performed on the basis of (2) and (5). Each simulated value of \( \rho(\Delta x) \) was calculated from an ensemble average for more than \( 10^6 \) delay profiles. Thus, we performed a statistical analysis in the simulation.

B. Simulation results and considerations

i) Type 1: Delay profile with exponential distribution

Figure 6 shows the correlation coefficient simulated using a delay profile with exponential distributions of \( K = -\infty \) and 5 dB denoted by symbols \( \times \) and \( \blacksquare \), respectively. Figures 6(a) and
(b) are the correlations on the time and frequency axes, i.e., the well known autocorrelation and frequency correlation, respectively. In Fig. 6(a), the fine line is the theoretical value of $\rho(\Delta x)$ obtained from (13) by putting $\Delta f=0$ or $\rho(\Delta x)=J_0(2\pi f_m T_s)$. The simulated autocorrelations for both $K=\infty$ and 5 dB have almost the same features and agree with the theoretical value. This shows that the autocorrelation is independent of the $K$ factor and is expressed by $J_0(2\pi f_m T_s)$. In Fig. 6(b), the fine and broken lines are theoretical values of $\rho(\Delta x)$ obtained from (13) by putting $f_m T_s=0$ or $f_m T_s=\frac{k + 1/\sqrt{(1+s^2\sigma^2)}}{k+1}$. Here, we note that delay spread $\sigma$ was calculated for NLOS without any directive waves. The frequency correlations for $K=\infty$ and 5 dB have different features, so the correlation depends on the $K$ factor. The simulated

Fig. 6. Correlation coefficient (Type 1: exponential distribution)
Fig. 7. Correlation coefficient in a domain with time and frequency axes (Type 1: exponential distribution, \( K = -\infty \text{ dB} \))
correlation for $K = -\infty$ dB is slightly lower than the theoretical one. We suppose that the
difference is due to different conditions between the theoretical and simulation models for
the delay profile, such as the number of waves $N$ and the counted effective amplitude in $h_i$.
Therefore, we repeated the simulation, changing from $N=10$ and effective amplitude of -20
dB to $N>100$ and effective amplitude of less than -50 dB. As a result, the correlation became
close to the theoretical one. The above results show that the autocorrelation is independent of
the $K$ factor, while the frequency correlation depends on the $K$ factor. The correlation
coefficient in a domain with time and frequency axes for NLOS is shown in Fig. 7. Figure
7(a) is a bird’s-eye view of $\rho(\Delta x)$ obtained from (13), which makes it easy to comprehend the
overall $\rho(\Delta x)$. We can see that $\rho(\Delta x)$ has a peak $\rho(0)=1$ at the origin $\Delta x = 0$ and that $\rho(\Delta x)$
becomes smaller with increasing $\Delta x$ or as $f_m T_s$ and $\Delta f \sigma$ become larger. Furthermore, $\rho(\Delta x)$
decreases in a fluctuating manner on the time axis, but decreases monotonically on the
frequency axis. The high area of $\rho(\Delta x)$ needed to allocate the pilot signal in coherent
detection, such as $\rho(\Delta x) >0.8$, is very small in the domain, whereas the low area needed to
design the diversity antenna, such as $\rho(\Delta x) <0.5$, is spread out widely. Figure 7(b) also shows
a bird’s-eye view of the simulated correlation; Figs. 7(a) and (b) both exhibit almost the same
features. Figure 7(c) shows the loci of the theoretical and simulated correlations in a small
area up to 0.3 on both axes, with contour lines of $\rho(\Delta x)$. It is easy to compare them. The
theoretical value on the time axis agrees well with the simulated one, but the theoretical
value on the frequency axis is slightly higher than the simulated one. The reason for this is a
different model for the delay profile, as described earlier. We can see from Fig. 7(c) that the
theoretical value agrees roughly with the simulated one. Furthermore, we note that in Fig.
7(c), the locus of the correlation coefficient $\rho(\Delta x)$ seems to be an ellipse with its major axis on
the time axis and its origin $\Delta x=0$ in the domain.

ii) Type 2: Delay profile with random distribution

Figure 8 shows the correlation coefficient for a delay profile with random distributions of
$K=-\infty$ and 5 dB. The values plotted by symbols of $\times$ and $\triangle$ in Figs. 8(a) and (b) were
simulated in a similar way to Fig. 6, and the fine and broken lines show the theoretical
value of $\rho(\Delta x)$ obtained from (16) by putting $\Delta f =0$ for autocorrelation or $\rho(\Delta x)=\int_0^{2\pi/s} f_m T_s$
and by putting $f_m T_s=0$ for frequency correlation or $\frac{\sin(2\pi/\Delta f \tau_{\text{max}})}{2\pi/\Delta f \tau_{\text{max}}}$. As shown
in Fig. 8(a), the simulated autocorrelations for both $K=-\infty$ and 5 [dB] have almost the same
features and agree well with the theoretical values, so the correlation seems to be independent of the $K$ factor. On the other hand, the simulated frequency correlations for
$K=-\infty$ and 5 dB in Fig. 8(b) have different features that also depend on the $K$ factor. The
simulated and theoretical values agree well.

The correlation coefficient in a domain with time and frequency axes for NLOS is shown
in Fig. 9 by a similar method to that for Fig. 7. Figure 9(a) is a bird’s-eye view of the
theoretical value of $\rho(\Delta x)$ obtained from (16). We can also see that $\rho(\Delta x)$ has a peak $\rho(0)=1$
at the origin $\Delta x = 0$, and $\rho(\Delta x)$ becomes smaller with increasing $\Delta x$. However, in this case,
$\rho(\Delta x)$ decreases in a fluctuating manner not only on the time axis, but also on the
frequency axis. The high area of $\rho(\Delta x)$ in the domain, such as $\rho(\Delta x) >0.8$, is larger than that
for an exponential distribution; the low area, such as $\rho(\Delta x) <0.5$, is spread out widely.
Figure 9(b) is the simulated correlation, which exhibits similar features to the theoretical one in Fig. 9(a). Figure 9(c) shows the loci of the theoretical and simulated correlations. The theoretical value in the domain agrees well with the simulated ones. For a delay profile with random distribution, the locus of correlation coefficient $\rho(\Delta x)$ is also an ellipse in the domain.

Fig. 8. Correlation coefficient (Type 2 : random distribution)
Fig. 9. Correlation coefficient in a domain with time and frequency axes
(Type 2: random distribution, $K = -\infty$ dB)
5. Conclusion

An analysis model having a domain with time, frequency, and space axes was prepared to study the correlation coefficients of the I and Q components in a mobile channel, which are needed in order to allocate a pilot signal with M-ary QAM detection, such as in an OFDM system, and to compose antennas in the MIMO technique. For a multipath environment, the general correlation coefficient formula was derived on the basis of a delay profile with and without a directive wave, and as examples, the formulas for delay profiles with exponential and random distributions were then derived. The formulas exhibit some interesting features: the autocorrelation on the time axis is independent of the $K$ factor and is expressed by $J_0(2\pi f_m T_s)$, but the frequency correlation depends on the $K$ factor and delay profile type. The locus of a fixed value correlation is an ellipse in the domain with time and frequency axes. The correlations were also shown in the domain using bird’s-eye views for easy comprehension. Furthermore, computer simulation was performed to verify the derived formulas and the theoretical and simulated values agree well. Therefore, it is possible to estimate logically the pilot signal allocation of M-ary QAM in OFDM and antenna construction for MIMO in the domain.

6. Appendix

6.1 Appendix A derivation of (8)

Under the conditions of the propagation model in 2-A and assuming that $N$ is a large number, $<I(0)I(\Delta x)>$ is analyzed as follows. It is separated into terms of the same $i$th and other $i$th arriving waves, as shown in (17).

$$<I(0)I(\Delta x)> = \left(\sum_{i=0}^{N} h_i \cos(2\pi f_c \tau_i + \phi_i)\right)\left[\sum_{i=0}^{N} h_i \cos(2\pi((f_c + \Delta f)\tau_i - f_m T_s \cos \xi_i) + \phi_i)\right]$$

$$= \left(\sum_{i=0}^{N} h_i^2 \cos(2\pi f_c \tau_i + \phi_i)\right)\cos(2\pi((f_c + \Delta f)\tau_i - f_m T_s \cos \xi_i) + \phi_i)$$

$$+ \sum_{i=0}^{N} \sum_{j=0}^{N} h_i h_j \cos(2\pi f_c \tau_i + \phi_i)\cos(2\pi((f_c + \Delta f)\tau_j - f_m T_s \cos \xi_j) + \phi_j),$$

where $i \neq j$ on $\sum_{i=0}^{N} \sum_{j=0}^{N}$.

Eq. (17) = $\frac{1}{2}\sum_{i=0}^{N} h_i^2 \cos(2\pi(\Delta f \tau_i - f_m T_s \cos \xi_i)) + \cos(2\pi((2f_c + \Delta f)\tau_i - f_m T_s \cos \xi_i) + 2\phi_i)]$ (18)
In the first term $A_1$ in (11), we change $A_1$ to (21) because the directive wave's amplitude $h_0$ is usually much larger than that of the nondirective one and because $\tau_i=0$. Moreover, the amplitude $h_i$ of the $i$th arriving wave depends on excess delay time $\tau_i$ according to (10). So by substituting (10) for $h_i$, we can rewrite (21) as (22).

$$A_1 = \left\langle \frac{1}{2} h_0^2 + \sum_{i=1}^{N} h_i^2 \cos(2\pi A f \tau_i) \right\rangle$$

$$= \left\langle \frac{1}{2} h_0^2 \right\rangle + \left\langle \sum_{i=1}^{N} \left[ h \exp(-\tau_i / \tau_{aw}) \right]^2 \cos(2\pi A f \tau_i) \right\rangle$$

(22)

We try to calculate by replacing the ensemble average of the second term in (22) by integration with respect to $\tau$ assuming a large $N$. As a result, we get (23) assuming $\tau_{\min}$ is close to 0 and $\tau_{\max}$ is large.

$$A_1 = \left\langle \frac{1}{2} h_0^2 \right\rangle + \frac{h_0^2}{2} \int_{\tau_{\min}}^{\tau_{\max}} \exp(-2\tau / \tau_{aw}) \cos(2\pi A f \tau) d\tau$$

$$= \left\langle \frac{1}{2} h_0^2 \right\rangle + \frac{h_0^2 \tau_{aw} / 4}{1 + (\tau_{aw} / 2)^2 (2\pi A f)^2}$$

(23)

Furthermore, we need to adjust $h$ in (23) to a normalized power of 1 when $N$ and $\tau_{\max}$ are large, so we get

$$\sum_{i=1}^{N} \frac{1}{2} h_i^2 = \frac{1}{2} \sum_{i=1}^{N} \left[ h \exp(-\tau_i / \tau_{aw}) \right]^2$$

$$= \frac{h_0^2}{2} \int_{\tau_{\min}}^{\tau_{\max}} \exp(-2 \tau / \tau_{aw}) d\tau$$

$$= \frac{1}{4} h_0^2 \tau_{aw} = 1.$$

(24)

Consequently, the numerator of the second term in (23) should be 1. Furthermore, considering $\left\langle \frac{1}{2} h_0^2 \right\rangle$, we get (25).

$$A_1 = k + \frac{1}{1 + (\tau_{aw} / 2)^2 (2\pi A f)^2}$$

(25)
6.3 Appendix C derivation of (15)
We calculate the ensemble average of $A_2$ in (14) in a similar manner to that for (23) by integrating with the probability density function $1/\tau_{\text{max}}$ of $\tau$. Considering the independence of $h_i$ and $\tau$ and the power of the directive and nondirective waves, or $k$ and 1, we get (26).

$$A_2 = \left\langle \frac{1}{2} h_0^2 + \frac{1}{2} \sum_{i=1}^{N} h_i^2 \cos(2\pi f \tau_i) \right\rangle$$

$$= k + \left\langle \frac{1}{2} \sum_{i=1}^{N} h_i^2 \right\rangle \left\langle \sum_{i=1}^{N} \cos(2\pi f \tau_i) \right\rangle$$

$$= k + \frac{1}{\tau_{\text{max}}} \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} \cos(2\pi f \tau) d\tau$$

$$= k + \frac{\sin(2\pi f \tau_{\text{max}})}{2\pi f \tau_{\text{max}}}$$

(26)

7. References


This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:
