Technologies and Services of Digital Broadcasting (9)

MODULATION Systems (part 2)

1. OFDM (Orthogonal Frequency Division Multiplex)

1.1 OFDM signal

Orthogonal frequency-division multiplexing is a multicarrier digital modulation system that has been employed as a modulation system for terrestrial digital broadcasting. Compared with single-carrier digital modulation, OFDM can lengthen the symbol period while maintaining the same error-rate characteristics and band efficiency. It can also add a redundant signal period called a guard interval. For these reasons, OFDM features little deterioration of transmission characteristics with respect to multipath distortion, the main type of disturbance on a terrestrial transmission path.

The OFDM signal multiplexes multiple digitally modulated waves that are mutually orthogonal in a certain signal interval. Referring to Figure 1, if, for baseband frequencies, we let carrier-1 be the base wave and arrange subsequent carriers at integral multiples of 2, 3, and so on of the base frequency, then any set of these carriers will be mutually orthogonal within one period of the basic wave. Varying the amplitude and phase of each of these carriers by digital modulation and then adding them together (frequency multiplexing them) results in an OFDM signal. In addition, performing a Fourier transform on this OFDM signal in one base-wave period makes it possible to uncover the amplitude and phase information of each carrier. This operation is none other than OFDM demodulation.

Digital modulation of individual carriers is normally performed using QPSK or QAM, and particular modulation systems are referred to as QPSK-OFDM, 64QAM-OFDM, etc. The QPSK-OFDM and 16QAM-OFDM systems are used on transmission paths characterized by severe disturbances such as in mobile communications where automobiles and other objects come into play. On the other hand, for fixed reception by an antenna installed on a roof as in ordinary television reception, 64QAM-OFDM is used so that as much data as possible can be transmitted within a limited frequency bandwidth.

Transmit symbols in OFDM consist of effective symbols and guard intervals. Data allocated to the carriers are transformed collectively by an inverse discrete Fourier transform into symbols each within the effective symbol period Tu. A guard interval is formed for each effective symbol period by taking a section of waveform data from the end of the symbol in question and simply attaching it

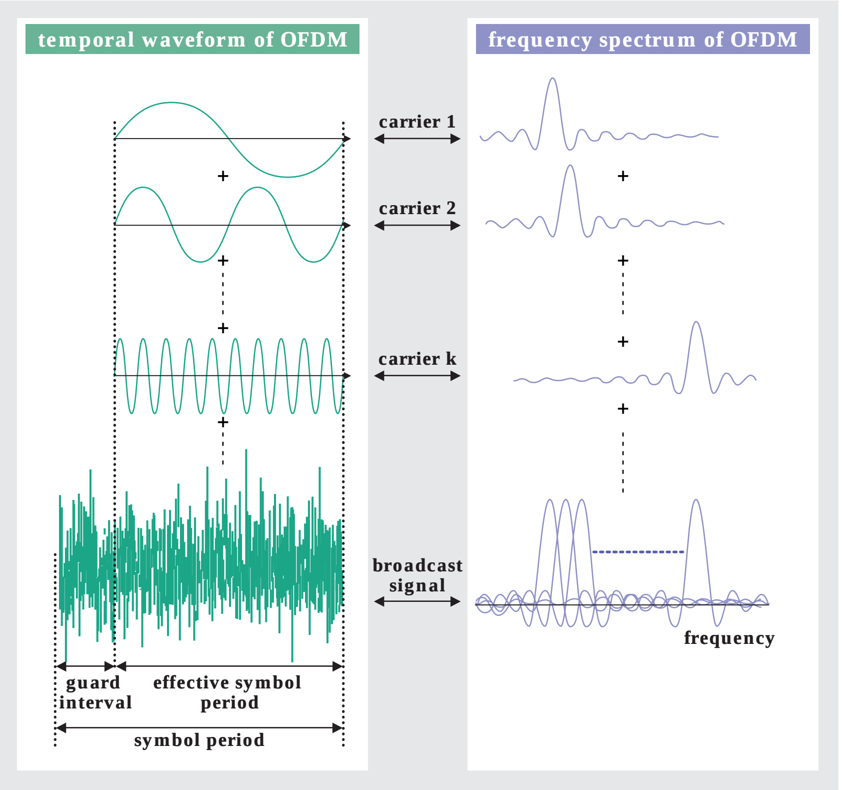

Figure 1: OFDM time spectrum and frequency spectrum

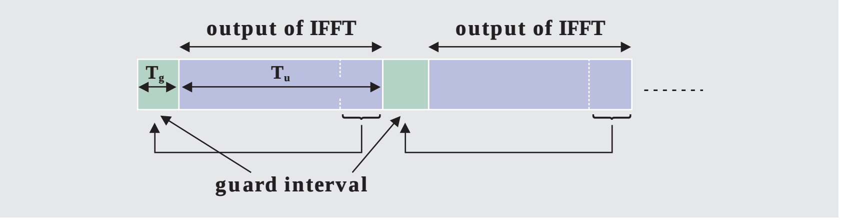

Figure 2: Attaching a guard interval

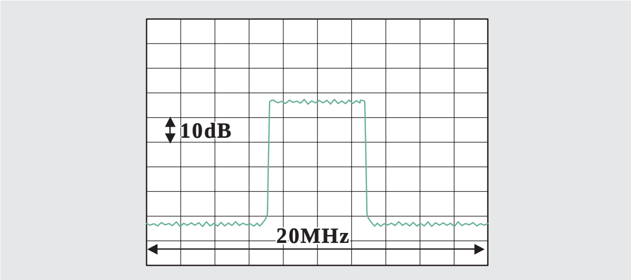

Figure 3: OFDM transmission spectrum

to the front of the symbol, as shown in Figure 2. Transmit symbols of period Tu+Tg are obtained in this way.

The OFDM carrier interval is the inverse of the base-wave period (effective symbol period) shown in Figure 1.

$$\Delta f = 1 / T_u \quad (1)$$

For example, for an effective symbol period T_u = 1 msec, the carrier interval Δf = 1 kHz.

Each OFDM carrier has a small spectral width because of the low-speed modulation, and the OFDM transmission spectrum that groups together these individual spectrums takes on a nearly rectangular shape, as shown in Figure 3. If the number of carriers K is large (several hundred or more), the occupied bandwidth B can be approximated as follows.

$$B \approx K\Delta f \quad (2)$$

Letting $C(l, k)$ denote transmit data corresponding to symbol number l and carrier number k, the OFDM transmit signal $S(t)$ can be expressed as follows.

$$S(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{l=-\infty}^{\infty} \sum_{k=0}^{K-1} C(l,k)\Psi(l,k,t) \right\} \quad (3)$$

Here:

$$\Psi(l,k,t) = \begin{cases} e^{j2\pi \frac{k-Kc}{Tu}(t-Tg-lTs)} & lTs \le t < (l+1)Ts \\ 0 & t < lTs, (l+1)Ts \le t \end{cases}$$

The symbols in the above expressions have the following meanings.

k: carrier number (carrier at the lower end of the band is 0)

l: Symbol number

K: Number of carriers

T_s: Length of symbol period (T_g+ T_u)

T_g: Length of guard-interval period

T_u: Length of effective symbol period

fc: Center frequency of RF signal

Kc: Carrier number corresponding to center frequency of RF signal

$C(l,k)$: Complex transmit data corresponding to symbol number l and carrier number k

$S(t)$: RF signal

1.2 OFDM modulation/demodulation and Fourier transforms

Modulation and demodulation in an OFDM system can be performed for all carriers collectively by using an inverse discrete Fourier transform (IDFT, IFFT) and a discrete Fourier transform (DFT, FFT). On the transmit side, the transmit bit stream is input data for the IFFT.

As an example, consider the case of 16QAM-OFDM modulation. As shown in Figure 4, each carrier is divided into 4-bit units. If the four bits allocated to symbol number l and carrier number k happen to be 1001, the I-axis value will be 1 and the Q-axis value -3 in the 16QAM constellation. Accordingly, data C(l,k) input to the IFFT can be expressed as complex data in the following manner.

$$\begin{aligned} C(l,k) &= A(l,k) + jB(l,k) \\ &= 1 + j(-3)c \end{aligned} \quad (4)$$

This input-data conversion is performed for multiple carriers and the result is subjected to the IFFT: this constitutes the 16QAM-OFDM modulation process. The output from one IFFT pass constitutes the temporal waveform data of one (effective) symbol. On the receive side, the inverse operations of those on the transmit side are performed to obtain the received bit stream. The above forms the basis for OFDM modulation/demodulation using FFTs.

Using only the above processes, however, does not result in a transmittable OFDM signal expressed by Equation (3), and on the OFDM receive side, simply extracting the FFT output does not enable the original transmit bit stream to be decoded.

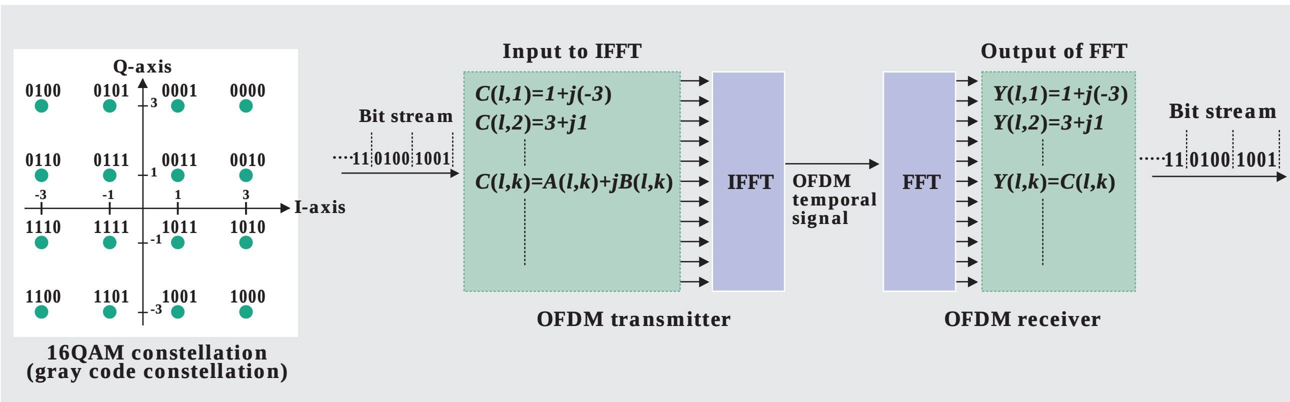

Figure 4: OFDM transmit signal (case of 16QAM-OFDM)

1.3 Transmission and reception of the OFDM signal

The OFDM transmit signal is generated by the process shown in Figure 5. In this process, the system transforms complex-number data on the frequency axis to signals on the time axis by IFFT one symbol at a time, passes the baseband temporal waveform data so obtained through D/A converters, and performs frequency conversion with an orthogonal modulator. The receiver in this system performs a frequency conversion to the baseband followed by an FFT on the resulting signal waveform so that the data from each carrier can be determined.

The following discusses OFDM signal generation in more detail, focusing on the effective symbol period of one symbol. The output $S(i)$ of an $N(=2^L)$-point IFFT with respect to input complex data $C(n)$ can be expressed as follows.

$$S(i) = \sum_{n=0}^{N-1} C(n) e^{j\left(2\pi \frac{n-Kc}{N} i\right)} \tag{5}$$

The system outputs the real part and imaginary part of $S(i)$ as I-axis and Q-axis data, respectively. Note here that if $K<N$ and $n>k-1$, $C(n)=0$.

Next, within the effective symbol period T_u, the system samples the real part and imaginary part of $S(i)$ at T_u/N intervals, where sample time t is expressed as follows.

$$t = i\frac{T_u}{N} \qquad (i = 0, 1, 2, \cdots, N-1) \tag{6}$$

Then, after performing D/A conversion, the system passes the results through LPFs and obtains the following as the OFDM baseband signal $S_b(t)$.

$$S_b(t) = \sum_{n=0}^{N-1} C(n) e^{j\left(2\pi \frac{n-Kc}{T_u} t\right)}$$

$$\mathrm{Re}(S_b(t)) = \sum_{n=0}^{N-1} \left[A(n)\cos\left(2\pi \frac{n-Kc}{T_u} t\right) - B(n)\sin\left(2\pi \frac{n-Kc}{T_u} t\right) \right]$$

$$\mathrm{Im}(S_b(t)) = \sum_{n=0}^{N-1} \left[A(n)\sin\left(2\pi \frac{n-Kc}{T_u} t\right) + B(n)\cos\left(2\pi \frac{n-Kc}{T_u} t\right) \right] \tag{7}$$

Finally, to obtain a transmittable OFDM signal, the system converts the baseband signals to transmission frequencies. In this process, a cosine wave and -sine wave of frequency fc are applied to the I-axis and Q-axis baseband signals, respectively, to perform orthogonal modulation. The resulting OFDM signal $S(t)$ is expressed as follows.

$$S(t) = \mathrm{Re}(S_b(t)).\cos(2\pi f_c t) - \mathrm{Im}(S_b(t)).\sin(2\pi f_c t)$$

$$= \mathrm{Re}\left[e^{j2\pi f_c t} \sum_{n=0}^{N-1} C(n) e^{j\left(2\pi \frac{n-Kc}{T_u} t\right)} \right]$$

$$= \sum_{n=0}^{N-1} \left[A(n)\cos\left(2\pi\left(f_c + \frac{n-Kc}{T_u}\right)t\right) - B(n)\sin\left(2\pi\left(f_c + \frac{n-Kc}{T_u}\right)t\right) \right] \tag{8}$$

Because the transmit complex data $C(k)$ is zero when the carrier number K is less than the number of IFFT points N and $K-1<k<N$, it can be seen that Eq. (8) represents one effective symbol period of the transmit signal $S(t)$ of Eq. (3) if we replace n by k and N by K. In addition, K_c in the above equation is a correction value assuming that the center carrier of the OFDM signal has frequency fc.

At the receiver, the system performs inverse processing with respect to the transmit side. Specifically, the system first performs carrier and clock recovery in the synchronization circuit section. It then performs orthogonal demodulation on the received OFDM signal by using the recovered carrier frequency fc as a local signal, and converts the result to the baseband frequency. The system next performs an A/D conversion on these baseband signals by using the recovered clock and then executes an FFT to enable the receive data from each carrier to be determined.

After A/D conversion, N instances of complex data $R(i)$ within the effective symbol period T_u are input to an N-point FFT. Its output $Y(n)$ is as follows.

$$Y(n) = \frac{1}{N}\sum_{i=0}^{N-1} R(i) e^{-j\left(2\pi \frac{i}{N}(n-Kc)\right)} \tag{9}$$

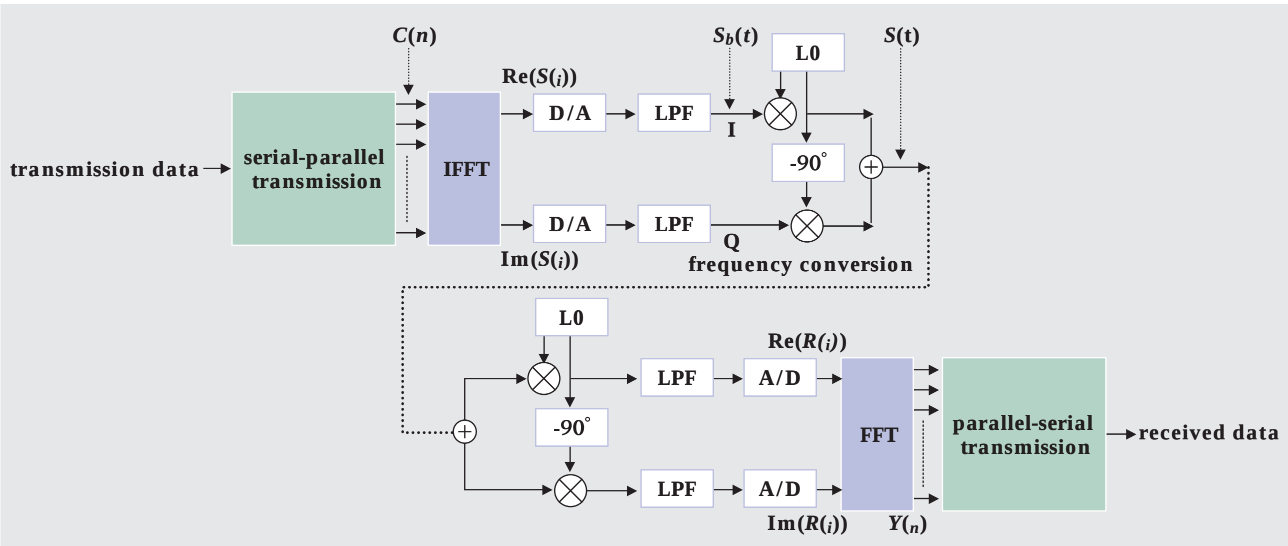

Figure 5: OFDM transmit/receive system

Assuming, for the time being, that the IFFT output $S(i)$ on the transmit side is obtained as FFT input data $R(i)$ on the receive side, the FFT output data $Y(n)$ would be expressed as follows and the transmit data would be determined.

$$Y(n) = \frac{1}{N}\sum_{i=0}^{N-1}\left[\sum_{k=0}^{N-1} C(k) e^{j\left(2\pi \frac{k-Kc}{N} i\right)}\right] e^{-j\left(2\pi \frac{i}{N}(n-Kc)\right)}$$
$$= C(n) \qquad (10)$$

The transmitted data, however, cannot normally be directly obtained from the FFT data $Y(n)$ at the receiver. This is because the signal is subjected to multipath distortion and other disturbances on the transmission path such that the OFDM signal exhibits frequency characteristics within the band in question. In other words, the amplitude and phase of each carrier of the received OFDM signal will be altered due to distortion on the transmission path. For this reason, demodulation of transmit data requires that changes in the amplitude and phase be detected and compensated for in each carrier. Actual OFDM demodulation is described in the next section.

1.4 OFDM demodulation

As stated above, the transmitted signal exhibits a frequency response within the signal bandwidth if multipath distortion or other disturbances exist on the transmission path. This means that the amplitude and phase of each carrier of the received OFDM signal will be altered according to this frequency response. It therefore becomes necessary in OFDM demodulation to detect and compensate for the frequency response components associated with the transmission path using the FFT output data at the receiver.

The above discussion leads us to the following equation for the FFT output $Y(l,k)$ for symbol number l and carrier number k at the OFDM receiver (see also the illustration in Figure 6). Here, $C(l,k)$ is the transmit data, $H(l,k)$ is the frequency response of the transmission path for carrier number k, and $N(l,k)$ is the noise component.

$$Y(l,k) = C(l,k)H(l,k) + N(l,k) \qquad (11)$$

Considering, for example, a transmission path having multipaths with a DU ratio of $20\log(\gamma)$ and delay time τ, its frequency response $H(f)$ would be expressed as follows.

$$H(f) = 1 + \gamma \cdot e^{-j2\pi f\tau} \qquad (12)$$

$H(l,k)$ can be interpreted as the frequency response $H(f)$ of frequency f corresponding to carrier number k.

Now, for all OFDM carriers, we assume that the frequency response $H(l,k)$ of the transmission path can be correctly estimated. The OFDM demodulated data $Z(l,k)$ can then be obtained by performing complex division on the FFT output data using the estimated $H(l,k)$.

$$Z(l,k) = Y(l,k) / H(l,k)$$
$$= C(l,k) + N(l,k) / H(l,k) \qquad (13)$$

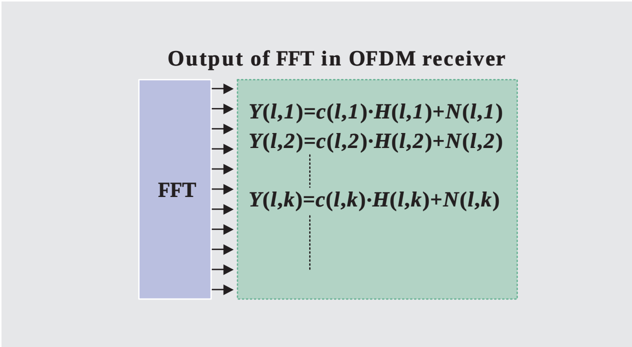

Figure 6: Output of FFT in OFDM receiver (frequency response *H* (*l*,*k*) in transmission path with noise *N* (*l*,*k*))

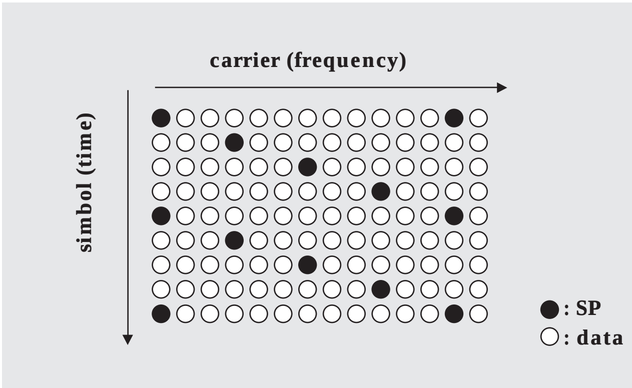

Figure 7: Scattered pilots (SP) constellation

The above equation tells us that if the CN ratio of the OFDM signal is sufficiently large and the noise component is of negligible magnitude, the transmit data $C(l,k)$ will be demodulated without error.

We therefore see that an OFDM signal can be demodulated provided that the frequency response of the transmission path can be determined for each carrier. In this regard, we describe a method for estimating the frequency response for each carrier and performing demodulation, taking Japan's ISDB-T (Integrated Services Digital Broadcasting System for Terrestrial) as an example.

OFDM as used in ISDB-T adopts a transmission scheme in which pilots are inserted in specific carriers within a symbol. Such pilots are commonly called "scattered pilots" (SPs). Figure 7 shows how SPs are assigned to specific carriers of an OFDM symbol in ISDB-T. Denoting carriers assigned with SPs as $k = k_p$, k_p with respect to symbol number l is expressed as follows.

$$k_p = 3 \times (l \bmod 4) + 12p \qquad (14)$$

p=0, 1, 2, 3, 4, ……

Scattered pilots are arranged on the I-axis at L times or $-L$ times the RMS value of the modulation level of C(l,k) transmit data. In ISDB-T, the value of L is 4/3. As shown in Figure 8, the RMS value of the modulation level for 16QAM modulation is $\sqrt{10}$ so that the SP is placed at ($4/3\sqrt{10}$, 0) or ($-4/3\sqrt{10}$, 0). For 64QAM modulation, the SP is placed at ($4/3\sqrt{42}$, 0) or ($-4/3\sqrt{42}$, 0). Which of the two points to place the SP is decided beforehand for each carrier so that the receiver can know the arrangement and

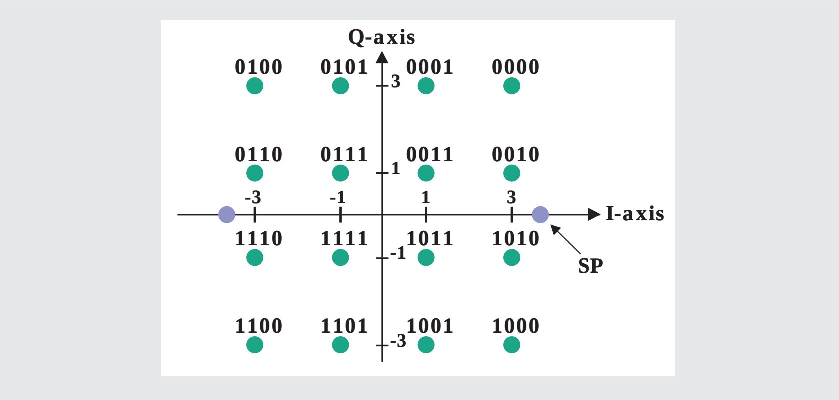

Figure 8: Sp data of 16QAM-OFDM (for the RMS value $\sqrt{10}$ in 16QAM, SP is placed at (+L $\sqrt{10}$, 0) or (-L $\sqrt{10}$, 0))

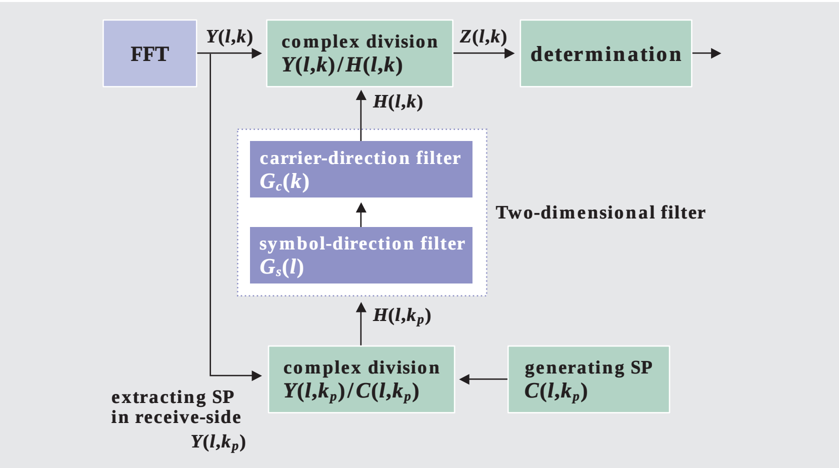

Figure 9: Demodulation process using SPs

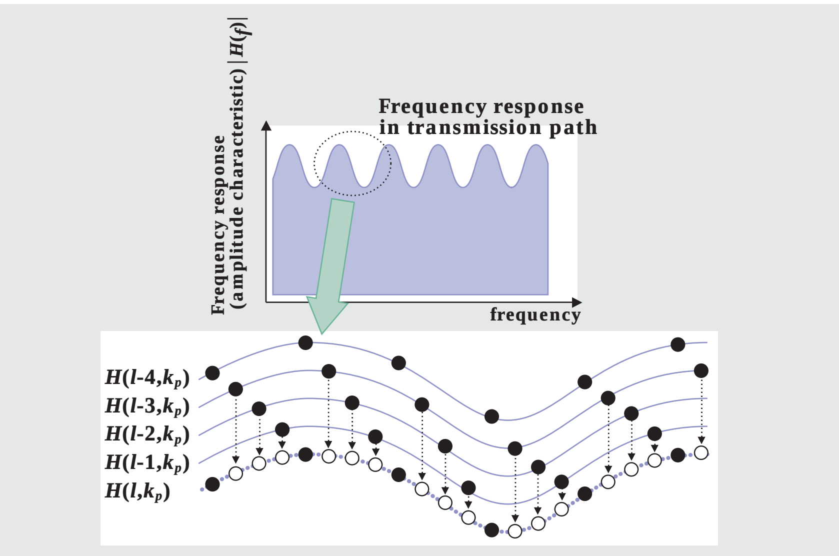

Figure 10: SP and frequency response in transmission path

demodulate the OFDM signal using the received SP.

The demodulation process using SPs is shown in Figure 9. First, from among the FFT output data, the system extracts the received SP data $Y(l,k_p)$ from carrier k_p with the SP inserted. It then performs complex division on that data with a receive-side generated $C(l,k_p)$ equivalent to the transmit SP so as to obtain an estimate of transmission-path frequency response $H(l,k_p)$ for the SP only.

Next, the system inserts the SP frequency response $H(l,k_p)$ by interpolation using a two-dimensional filter $G(l,k)$ consisting of a symbol-direction filter $Gs(l)$ and carrier-direction filter $Gc(k)$ and consequently obtains an estimate of the transmission-path frequency response $H(l,k_p)$ for all carrier symbols.

$$H(l,k) = H(l,k_p) * G(l,k)$$
$$= H(l,k_p) * G_s(l) * G_c(k) \qquad (15)$$

$Z(l,k)$ of Eq. (13) can be obtained by dividing the FFT output data $Y(l,k)$ by the $H(l,k)$ estimate of Eq. (15).

A symbol filter can be easily achieved. One method (Figure 10) is to save the value of $H(l,k_p)$ (● in the figure) determined from an SP inserted every four symbols in the carrier k_p until the next SP appears (○ in the figure). In this way, $H(l,k_p)$ will be interpolated for one in three carriers (● and ○ in the figure) after passing through the symbol filter. It will then be possible to obtain the estimated frequency response $H(l,k)$ for all carriers (●, ○, and small ● in the figure) by using a subsequent carrier filter composed of an FIR filter or similar having rectangular low-pass characteristics.

Linear interpolation between ● and ○ in the carrier filter is also possible. We note here that only amplitude characteristics are shown in Figure 10 for the sake of clarity and that processing with complex numbers is normally required.

The OFDM demodulation described here is coherent demodulation such as 16QAM-OFDM and 64QAM-OFDM under the assumption that carrier recovery and clock recovery as well as symbol-timing recovery for coherent demodulation operates in an ideal manner.

Differential modulation is also possible in OFDM, through phase modulation such as DQPSK. In differential modulation, transmit data $C(l,k)$ is differentially coded between adjacent symbols on the same carrier in a process that is performed beforehand on the transmit side for each carrier. This differentially coded data $D(l,k)$ is used as IFFT input data.

$$D(l,k) = D(l-1,k) \cdot C(l,k) \tag{16}$$

FFT output data at the OFDM demodulator is consequently given as follows.

$$Y(l,k) = D(l,k) \cdot H(l,k) + N(l,k) \tag{17}$$

OFDM differentially modulated data $Z(l,k)$ is obtained by performing complex division on the FFT output $Y(l,k)$ of the current symbol with the FFT output $Y(l-1,k)$ of the immediately prior symbol. If we here consider that the frequency response of the transmission path is invariable between symbols and that the noise component can be ignored, we get the following expression for $Z(l,k)$.

$$\begin{aligned} Z(l,k) &= Y(l,k) / Y(l-1,k) \\ &\approx D(l,k) / D(l-1,k) \\ &= C(l,k) \end{aligned} \tag{18}$$

This is the OFDM differential demodulation.

1.5 Guard intervals and multipath distortion

A digital signal affected by a multipath disturbance as in Figure 11(a) will suffer from distortion as adjacent symbols

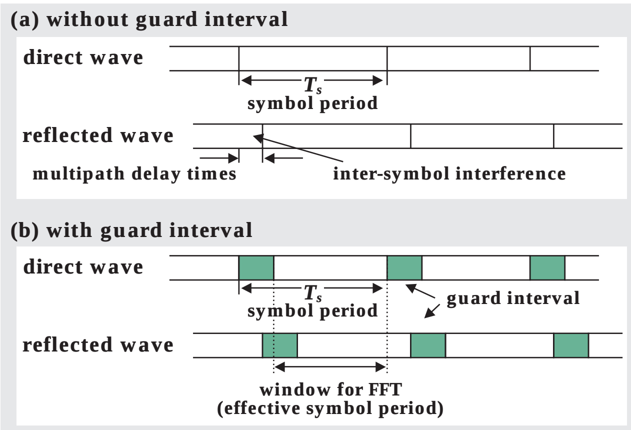

Figure 11: Guard intervals and multipath distortion

will overlap. This inter-symbol interference can be a major source of demodulation errors. Compared with single-carrier digital modulation of an identical bit rate, OFDM with K carriers can lengthen the effective symbol period by K times. This means that selecting an appropriate value for K can sufficiently lengthen the OFDM effective symbol period and minimize inter-symbol interference even for the multipath delay times that are common in terrestrial transmissions (0 to several 10 μ sec).

OFDM can also add guard intervals to minimize effects from adjacent symbols. Referring to Figure 11(b), inter-symbol interference from adjacent symbols will not occur if the interval of overlapping adjacent symbols is within the guard interval. This is because the period demodulated by the FFT will enclose only the overlap of the same symbol signal. As a result, fewer errors because of multipath distortion will occur than in single-carrier digital modulation.

Nevertheless, OFDM will still suffer from deterioration due to multipath distortion. As shown in Figure 10, a transmission path with multipath features will exhibit a frequency response corresponding to the delay time and DU ratio of that path. As a result, the received OFDM signal will possess frequency characteristics within the signal band and dips will occur. A carrier whose CN ratio has dropped because of dips will experience dramatic deterioration in its error rate compared with other carriers. It thus adversely affects the average error rate for all OFDM carriers.

1.6 OFDM transmission characteristics

Figure 12 shows the Gaussian noise characteristics for DQPSK-OFDM and 64QAM-OFDM. The transmission parameters in both cases are a carrier interval of 3.968 (=250/63) kHz, a carrier number of 1405 (bandwidth 5.57 MHz), an effective symbol length of 252 μ sec, and a guard interval of 31.5 μ sec. The characteristic curves marked in black represent the BER after OFDM

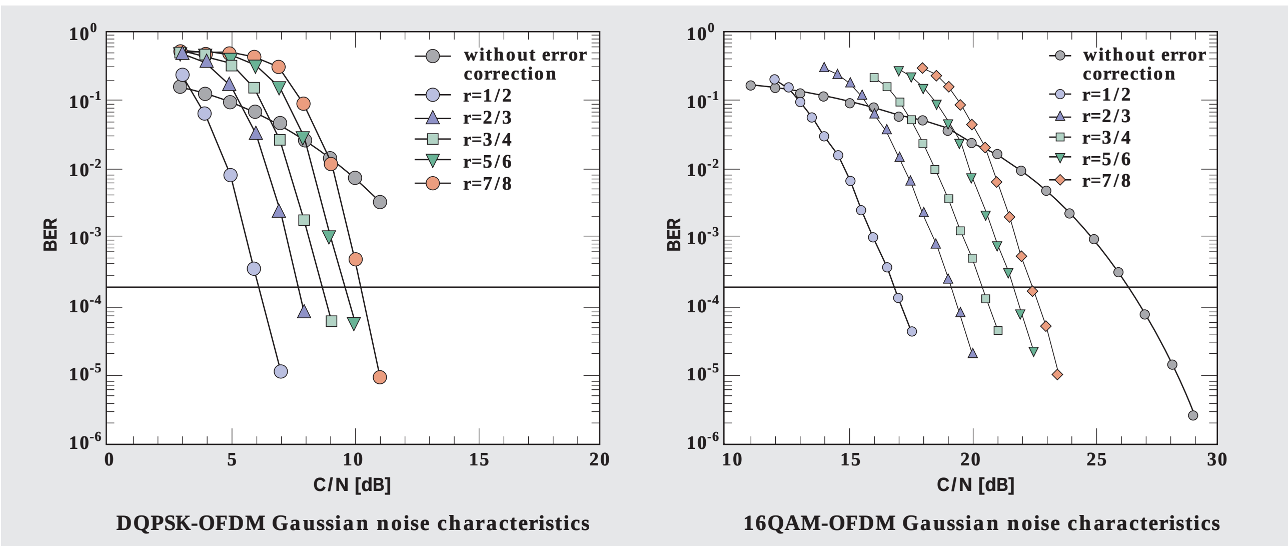

Figure 12: OFDM Gaussian noise characteristics

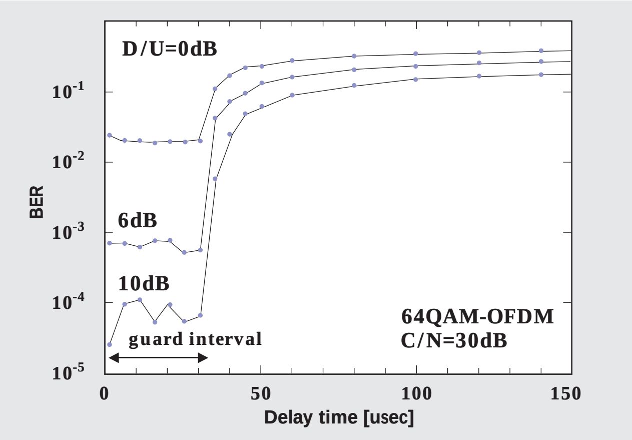

Figure 13: Multipath characteristics (delay time vs. BER)

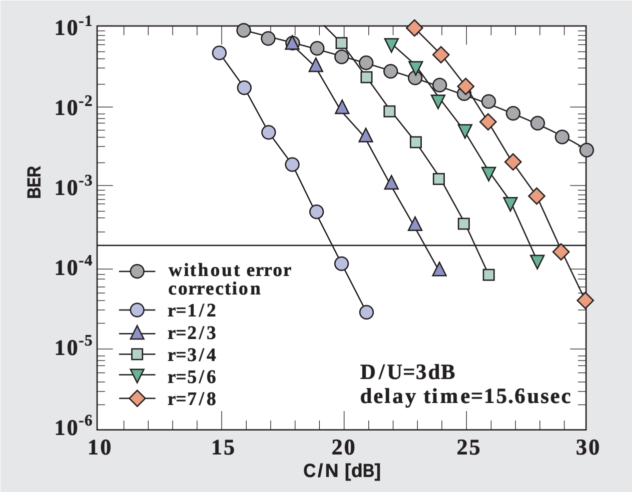

Figure 14: Multipath characteristics (C/N vs. BER)

demodulation. The curves marked with white symbols represent the BER after error correction of OFDM demodulation data by Viterbi soft-decision decoding for convolutional coding rates of *r* = 1/2, 2/3, 3/4, 5/6, and 7/8. We point out here that the BER of MPEG2 video data is usually 2×10^{-4} after Viterbi decoding (but before Reed-Solomon decoding), which is generally considered to be the error-free level. Accordingly, the CN ratio at the point where a characteristic curve crosses a BER of 2×10^{-4} becomes the required CN ratio.

Let us now examine the OFDM multipath characteristics. Figure 13 plots BER versus OFDM multipath delay time. The transmission parameters are the same as those of the above case for Gaussian noise characteristics. It can be seen that, for the same DU ratio, the BER is nearly constant for delays within the guard interval but that it deteriorates for delays greater than the guard interval. Figure 14 shows multipath characteristics caused by a simple echo corresponding to a DU ratio of 3 dB. These results show that reception is possible even under strong multipath interference having a DU ratio of 3 dB if the CN ratio is sufficiently large. However, comparing these results with those of Figure 12 for Gaussian noise characteristics tells us that the CN ratio to enable reception increases.

(Shunji Nakahara)