PAPER

Characteristics of Interference between Direct-Sequence Systems and Frequency-Hopping Systems of 2.4-GHz-Band Mid-Speed Wireless LANs

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SUMMARY 2.4-GHz-band mid-speed (1- to 2-Mbit/sec) wireless LAN systems are being widely used in offices and factories. Electromagnetic interference can occur between these systems because they use the same frequency range. In this paper, we investigate the characteristics of the interference between wireless LAN systems that use direct-sequence (DS) systems and frequency-hopping (FH) systems. The interference characteristics were measured for three DS systems and one FH system that meet the IEEE 802.11 and RCR standards and that use different modulation methods. Our results indicate that throughput depends on the system and the modulation method. We have also developed a model that can be used to calculate the interference characteristics between DS and FH systems by considering the bandwidth of their transmission signals, the dwell time of the FH system, and the time that the DS system needs to transmit a data frame. We used this model to calculate the bit error rate (BER) characteristics of the systems used in our experiment, and the results indicate that BER characteristics depend on the modulation method. The throughput characteristics of the systems used in our experiment were also calculated, and agreed with the experiment results within +/− 5 dB. The throughput characteristics of wireless LAN systems based on IEEE 802.11 were also calculated when the signal level was higher than the receiver noise level. The results show that FH systems require a D/U ratio about 7 or 8 dB higher than the ratio required in DS systems because the parameters in the standard differ between FH and DS systems.

key words: *2.4-GHz-band mid-speed wireless LAN, interference, direct-sequence, frequency-hopping*

1. Introduction

Wireless communication is playing an increasing role in information networks, and many kinds of high-data-rate wireless communication systems have been developed [1], [2]. In particular, 2.4-GHz-band mid-speed wireless LAN systems based on the spread spectrum (SS) are being widely used in offices and factories [2]. Almost all radio systems are controlled by regulations that decide the assignment of the radio frequency so that interference with other radio systems can be avoided.

The wireless medium access control layer and physical specifications of the 2.4-GHz-band mid-speed wireless LAN are standardized in IEEE 802.11 [3]. A wireless LAN system is composed of some base stations, called access points, and many personal stations. Generally, the coverage radius of an access point is about 50 m for an indoor environment, and their coverage overlaps in offices. IEEE 802.11 standardizes two kinds of systems: direct-sequence (DS) and frequency-hopping (FH) systems. Both systems are used in products on the Japanese market, but since the systems use the same frequency band at the same time interference between them can occur [3], [4]. Such interference needs to be studied to improve the performance of wireless LANs that consist of various wireless LAN systems [5]. This should be approached as an electromagnetic compatibility (EMC) problem, because the transmitters of other systems act as disturbance sources.

Interference between two or more of the same type of radio communication systems has been studied by researchers designing multiple access and radio links [6]–[8]. Studies on the performance of wireless LAN systems exposed to interference from microwave ovens [9] or Gaussian noise interference from various other sources [10] have been done. The interference characteristics between DS and DS systems [11], and between FH and FH systems [7] have been reported. However, this has not been done for the interference characteristics between DS and FH systems because DS and FH systems previously used different frequency bands.

In this paper, we investigate the interference characteristics of DS and FH systems experimentally and through theoretical analysis. Section 2 describes our measurements of the interference between DS and FH systems commonly used in offices. In Sect. 3, we develop a model to calculate the bit error rate (BER) and throughput by considering the specifications of DS and FH systems. The calculated results are compared with our measured results for the wireless LAN systems used in our experiment. Section 4 describes the interference characteristics between DS and FH systems under various conditions.

2. Measurement of Characteristics

2.1 Experimental Configuration

Figure 1 shows the experimental configuration used to measure the interference characteristics between DS and FH systems. Three DS systems (DS1, DS2, and DS3) and one FH system (FH1) were used in the measurements. Table 1 summarizes the technical parameters of these systems. Although DS1 and DS2 use almost the same PSK modulation, their physical layer (Layer 1) designs are not quite the same because they come from different manufacturers. Therefore, they cannot be connected to each other. The modulation param-

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eters of DS3 are different from those of DS1 and DS2. We measured the interference characteristics of six combinations of DS1, DS2, DS3, and FH1 systems. When the interference characteristics of the DS systems were measured, one of the three DS systems was the equipment under test (EUT) and FH1 system was a disturbance source. When that of the FH system was measured, FH1 system was an EUT and DS1, DS2 or DS3 system was a disturbance source.

The purpose of our study was to clarify the primary factors causing interference between DS and FH systems. Interference characteristics, however, are influenced by multipath fading in an indoor environment. According to Ref. [8], radio links in a fading environment can be designed by evaluating the performance in a non-fading environment and then taking into account the degradation caused by each source of multipath fading. We therefore evaluated the interference characteristics of the wireless communication systems in a non-fading environment by measuring the signal input and output with a 1-m-long coaxial cable connection.

The cable losses were about 3 dB and the insertion loss of the power splitter was about 12.5 dB. The EUT and the disturbance source were managed by the same workstation, and disturbance waves were added through a variable attenuator. This means we changed the ratio between the desired and undesired signal powers (the D/U ratio) at personal station 1. We inserted 20-dB attenuators between access point 1 and the power splitter, and between personal station 1 and the power splitter. This suppressed the effect of interference

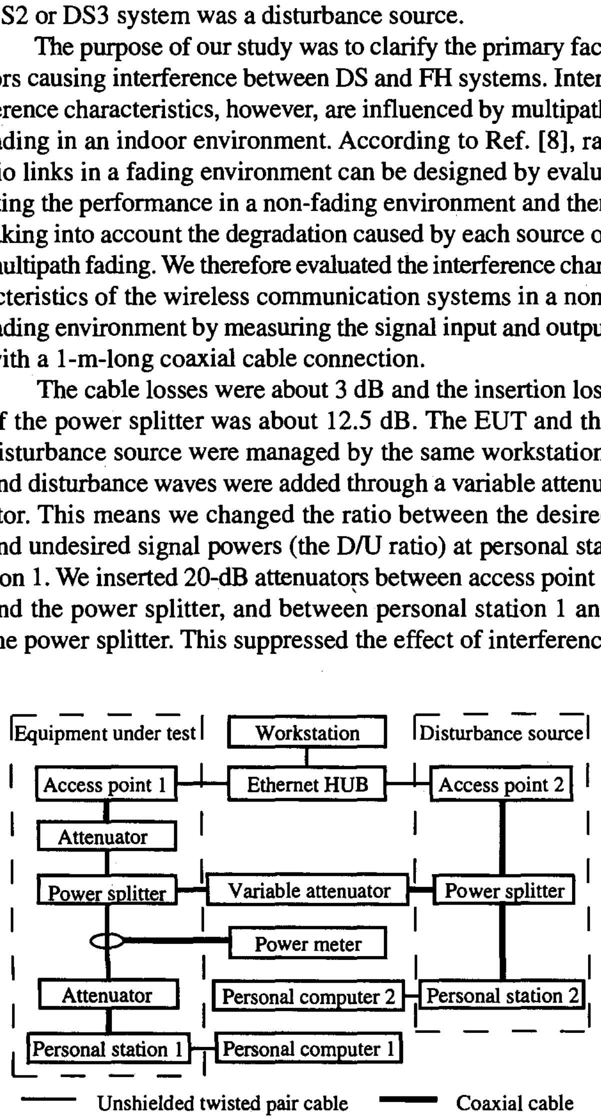

Fig. 1 Configuration for measuring interference characteristics.

Table 1 Technical parameters of wireless LAN systems.

	DS1	DS2	DS3	FH1
Spreading	DS	DS	DS	FH
Modulation	DQPSK	DQPSK	DBPSK	2 or 4 FSK
Operating frequency	2.471 - 2.497 GHz			
3 dB bandwidth	22 MHz	22 MHz	26 MHz	24 MHz
Spreading rate	11	11	13	
Hop number				23

DS : Direct sequence
FH : Frequency hopping
DQPSK : Differential quadrature phase shift keying
DBPSK : Differential binary phase shift keying
MFSK : M-level frequency shift keying

on the communication between access point 2 and personal station 2. The power of the desired and undesired signals was measured by a power meter. A 5-Mbyte file was transmitted by file transfer protocol (FTP) from the workstation to personal computers 1 and 2, and the throughput of the EUT was measured for each of the combinations.

2.2 Performance without an Undesired Signal

Wireless LAN systems are subject to thermal noise and undesired signals from various sources. Because the effects of the thermal noise and undesired signals are cumulative at the receiver input, the energy-per-bit to total-noise-power-density ratio at a receiver input γ_R is given by

$$\gamma_R = \frac{E_b}{N_0 + U_0} \tag{1}$$

where E_b is the energy-per-bit, N_0 (W/Hz) represents receiver noise power density, U_0 (W/Hz) represents undesired signal power density.

The performance of digital systems is generally evaluated in terms of the bit error rate (BER), which is a function of the energy-per-bit to total-noise-power-density ratio and is related to throughput. Therefore, to determine the effect of the undesired signal, we need to evaluate the performance when the undesired signal does not exist ($U_0 = 0$).

The relationship between throughput and E_b/N_0 ($U_0 = 0$) is shown in Fig. 2. The E_b/N_0 was normalized by the minimum E_b/N_0 required for the maximum throughput of DS1 system. This result shows that the throughput of the DS systems changed from 0 to 1 within about 3 dB. However, the throughput of FH1 system had two phases of changes when the throughput was changing from 0 to 1. The minimum E_b/N_0 of FH1 system required for the throughput of 1 was 7 dB higher than that for the throughput of 0.5. The FH systems based on the IEEE 802.11 standard (the 4FSK and 2FSK systems) have two transmission modes as shown in Table 1, and the mode is changed automatically when the energy-per-bit to total-noise-power-density ratio changes. (The mode of DS systems is not changed automatically.) To enable each sys-

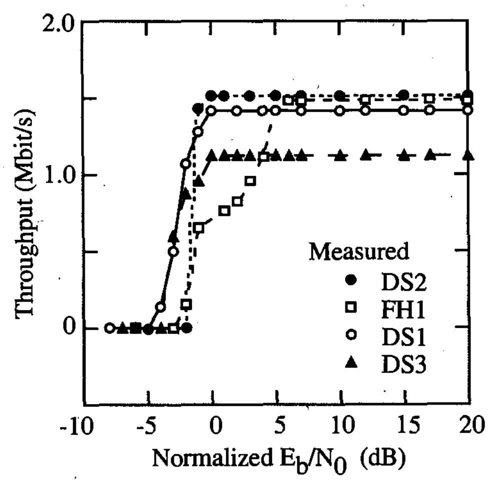

Fig. 2 Throughput characteristics for E_b/N_0.

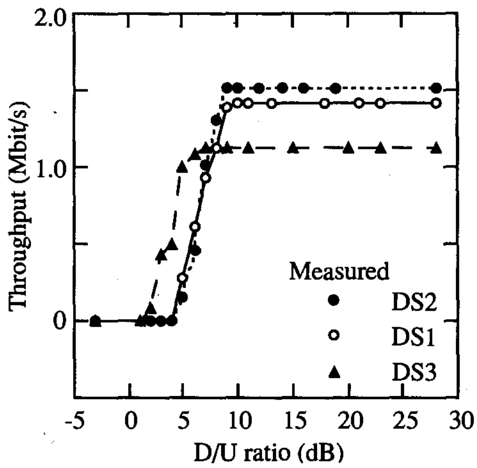

Fig. 3 Measured throughput of the DS systems with an FH1 disturbance source.

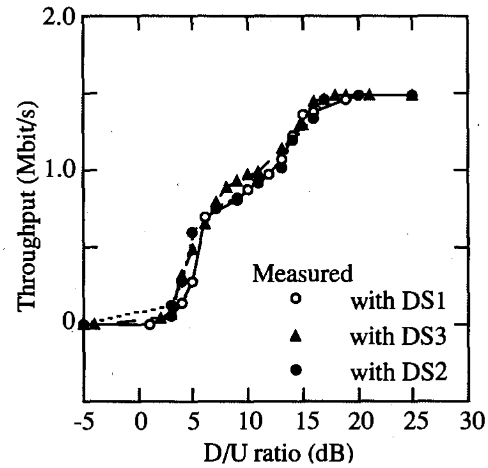

Fig. 4 Measured throughput of the FH system with a DS1, DS2 or DS3 disturbance source.

tem to realize maximum throughput, the 4FSK-FH system needs an energy-per-bit to total-noise-power-density ratio that is 7 dB higher than that of the 2FSK-FH system. This is due to the difference in the modulation index (0.32 for 2FSK, and 0.144 for 4FSK [3]), and the difference in the required E_b/N_0 can be estimated from Eq. (17) in Sect. 3. However, the transmission rate of the 2FSK system is half that of the 4FSK system at these respective ratios.

2.3 DS System

In this section, we consider the interference characteristics when the FH system is a disturbance source. For $U_0 >> N_0$, γ_R can be approximated as [12]

$$\gamma_R = E_b/U_0 = (D/U)/G_p \quad (2)$$

where D is the desired signal power (in watts), U is the undesired signal power (in watts), and G_p is the process gain. To evaluate the interference characteristics of the DS systems under the FH signal interference, we measured the throughput of each system under various D/U ratios at the receiver input while applying an FH1 disturbance source.

Figure 3 shows the measured results of throughput versus the D/U ratio. The FH system was the disturbance source, and the D/U ratio in the non-fading channel had to be above 10 dB to allow the transmission of the maximum throughput. The throughputs of DS1 and DS2 systems had almost the same characteristics, and the minimum D/U ratio required for the maximum throughput of DS3 system was about 3 dB smaller than that of DS1 and DS2 systems. Compared to the DS1 or DS2 system, the DS3 system had the advantages of DBPSK modulation and a higher spreading rate (Table 1), but had the disadvantages of stricter band-limiting and of a higher symbol rate (Table 2). As a result, the DS3 system had a D/U ratio that was 3 dB lower than for the DS1 and DS2 systems.

2.4 FH System

Using the same experimental set-up, we also measured the interference characteristics when the FH system was the EUT. Figure 4 shows the respective measured throughputs of FH1 system with a DS1, DS2 or DS3 disturbance source. These results show that each of the throughputs of FH1 system had similar characteristics because the undesired signal of DS1, DS2, and DS3 systems had almost the same bandwidth. In all three cases, the FH1 throughput had two phases of change as the throughput rose from 0 to 1; this was the same as for the FH1 system's throughput shown in Fig. 2.

Unlike the DS systems, the FH1 system could change its transmission rate in response to changes in either the D/U ratio or in the ratio of desired signal power to receiver noise power. In these cases, when the disturbance source was a DS system in a non-fading channel, the D/U ratio required for maximum FH1 throughput was above about 15 dB. To change the throughput from 0% to 100%, the required E_b/N_0 should be about 10 dB (Fig. 2), and the required D/U ratio should be about 15 dB (Fig. 4). This difference in required values indicates that the noise source was mainly thermal noise in Fig. 2, but was mainly the communication signal of a DS system in Fig. 4.

3. Theoretical Analysis

To design a communication environment that will not suffer from interference, we should estimate the interference characteristics. In this section, we calculate the characteristics of interference between DS and FH systems. We have developed a model to calculate these interference characteristics by considering that (1) the frequency bandwidth within which the FSK modulation signal of an FH system hops is almost the same frequency bandwidth as that used by the DS signal, and (2) the dwell time of an FH system is longer than the time needed by a DS system to transmit a data frame [3]. The first means that the disturbance source can be considered white

Gaussian noise when the communication signal of a DS system is the disturbance source. The second means that the disturbance source can be considered white Gaussian noise limited to one slot of the FH system bandwidth when an FH system is the disturbance source. We also made the following assumptions in order to simplify the calculation:

(1) In a non-fading environment there is a desired signal, an undesired signal, thermal noise, and no pulsed interference from any other equipment, and all individual noise sources were additive at the receiver input.
(2) The values of the thermal noise and of the noise factor remain the same for all wireless LAN systems because the systems all use almost the same operating frequency range.
(3) The transmission frame length N (bit) is the same value for all wireless LAN systems because wireless LAN systems can use a maximum frame length of 2048 bytes when the offered traffic is great.

3.1 DS System

The model to calculate the interference characteristics of the DS system under the FH signal disturbance is shown in Fig. 5. The input information signal $a(t)$ is modulated by a DBPSK or a DQPSK modulator. The modulated signal is spread by the spreading signal $b(t)$ and band-limited by a band-pass filter. The transmission signal $d_{DS}(t)$ can be expressed as

$$d_{DS}(t) = \sqrt{2D}\,a(t)b(t)\cos\left(2\pi f t+\theta(t)\right) \tag{3}$$

where D is the desired signal power (in watts), f is the carrier frequency of the DS systems, and q is the carrier phase angle. Assuming a single-carrier interference signal from an FH system $i_{FH}(t)$, it can be expressed as

$$i_{FH}(t) = \sqrt{2U}\sin\left(2\pi f_c t+\theta\right) \tag{4}$$

where U is the undesired signal power (Watts) and f_c (Hz) is the carrier frequency of the FH system.

Based on assumption 1, the transmission signal $d_{DS}(t)$ is added to the interference signal $i_{FH}(t)$ and the receiver noise

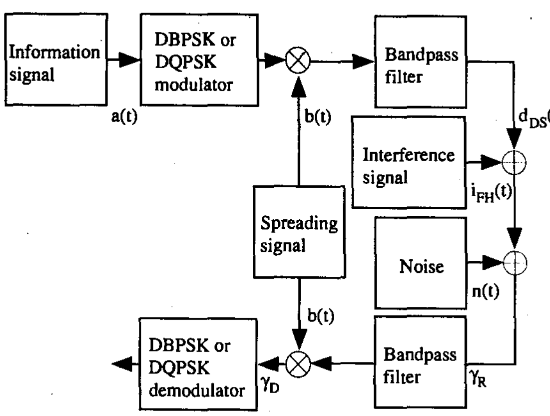

Fig. 5 Model used to simulate the DS systems.

$n(t)$, whose two-side noise spectral density is $N_0/2$, and is fed into the band-pass filter. Then, the frequency range of the received signal is narrowed by the spreading signal $b(t)$ and demodulated by a DBPSK or DQPSK demodulator.

The BER P_b of DS1 and DS2 systems (DQPSK modulation) can be written [13] as

$$P_b = \exp\left(\gamma_D\left(1-\frac{1}{\sqrt{2}}\right)\right) \tag{5}$$

and P_b of DS3 system (DBPSK modulation) is written [14] as

$$P_b = \frac{1}{2}\exp(-\gamma_D) \tag{6}$$

where γ_D represents the energy-per-bit to total-noise-power-density ratio at the demodulator input, and can be calculated from the degradation caused by band-limitting and the energy-per-bit to total-noise-power-density ratio at the receiver input γ_R.

In this analytical model, the energy-per-bit to total-noise-power-density ratio γ_R at the receiver input can be expressed as Eq. (1). At the demodulator input, the energy-per-bit of the desired signal E_b is expressed as

$$E_b = DT_b \tag{7}$$

where T_b is a bit duration (in seconds). The thermal noise power density N_0 is given by

$$N_0 = \kappa B_o \tau N_F / B_o = \kappa\tau N_F \tag{8}$$

where κ is the Boltzmann constant 1.38×10^{-23} (J/K), B_o is the operating bandwidth of 26 (MHz), and τ is the absolute temperature. τ of 300 K (room temperature) is used for the calculation . N_F is the noise factor. The undesired signal is spread by the spreading signal $b(t)$; therefore, the undesired signal power density U_0 is given by

$$U_0 = U/(G_{DS}B_{FH}) = UT_c/(B_{FH}T_s) \tag{9}$$

Moreover, the energy-per-bit to total-noise-power-density ratio of the demodulator input signal $r_{DS}(t)$ was degraded by the band-limiting of the filter and the noise factor of the receiver; therefore, the energy-per-bit to total-noise-power-density ratio at the input of the demodulator γ_D can be written as

$$\begin{aligned}\gamma_D &= \frac{\gamma_R}{L_{DS}} \\ &= \frac{E_b}{L_{DS}(N_0+U_0)} \\ &= \frac{1}{1/(E_b/N_0)/L_{DS} + 1/(D/U)(G_{DS}B_{FH}T_b/L_{DS})}\end{aligned} \tag{10}$$

where L_{DS} is the degradation of correlation output by a bandlimited filter.

We calculated the average BERs of the DS systems by substituting Eq. (10) into Eqs. (5) and (6) when the disturbance source was FH1 system (Fig. 6). The calculation used the parameters shown in Table 2, and E_b/N_0 is calculated from

Table 2 Simulation parameters.

Equipment under test	Disturbance Source	D (dBm)	T_b (ms)	T_c (ms)	T_s (ms)	B_d (MHz)	B_u (MHz)	B_{FH} (MHz)	G_{DS}	G_{FH}	ρ	L_{DS} (dB)	h_M	v (Mbit/s)
DS1	FH1	-53	0.5	1/11	1	22			11			0.45		
DS2	FH1	-51	0.5	1/11	1	22	1		11			0.45		2
DS3	FH1	-49	0.5	1/26	0.5	26			13			1.1		
FH1	DS1	-50	0.5				24				1		0.32	
FH1	DS2	-50	or		1	24	22	1		23	1		or	1 or 2
FH1	DS3	-50	1				22				1		0.14	

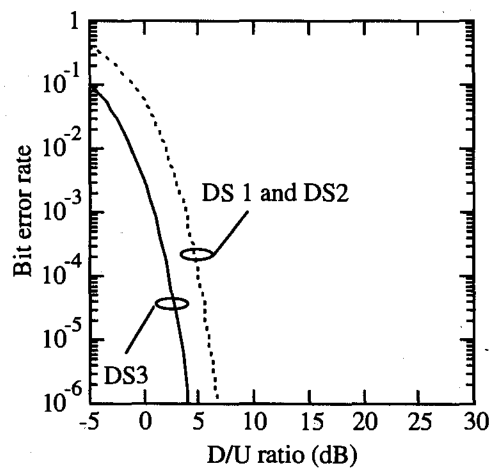

Fig. 6 Calculated bit error rates of the DS systems with an FH1 disturbance source.

Eqs. (7) and (8). L_{DS} is 0.45 dB for DS1 and DS2 systems, and 1.1 dB for DS3 system [15]. An N_F of 12 dB is used as the systems had almost the same characteristics, because they had similar modulation parameters. These BERs had a degradation of about 3 dB compared to the BER of DS3 system.

3.2 FH System

We also calculated the interference characteristics of the FH system when DS1, DS2, and DS3 system was the disturbance source. Figure 7 shows the model to calculate the interference characteristics of the FH system. This model assumes that the interference signal always disturbs the FH1 signal because it is the broadband signal of DS systems.

The input information signal $a(t)$ is modulated by an MFSK modulator. The center frequency of the modulated signal is changed by the hopping code signal $c(t)$ and the signal is band-limited by a band-pass filter. The transmission signal $d_{FH}(t)$ can be expressed as

$$d_{FH}(t) = \sqrt{2D}\cos\left(2\pi\left(f_c+\frac{-h_M((M-1)-2i)}{4T_s}\right)t\right)$$
$$= \sqrt{2D}\cos\left(2\pi\left(f_c+(-\frac{M-1}{2}+i)\Delta f\right)t\right)$$
$$(i=0, 1, ..., M-1) \quad (11)$$

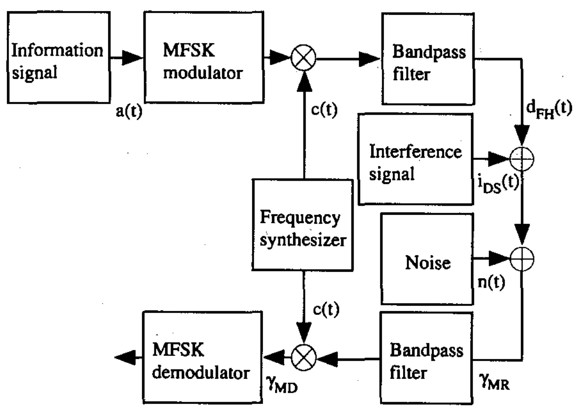

Fig. 7 Model used to simulate the FH system.

where M means the M-ary signal transmission; when the FH1 system's transmission rate is 1 or 2 Mbit/s, M is 2 or 4, respectively. Also, D is the desired signal power (in watts), T_s is the symbol duration (which is related to the bit duration T_b by $T_b = T_s/\log_2(M)$), h_M is the modulation index, Δf is the carrier deviation, and $h_M = 2\Delta f T_s$. Here, h_M is 0.32 for $M = 2$ and 0.144 for $M = 4$ [3].

Based on assumption 1, the transmission signal $d_{FH}(t)$ is added to the interference signal $i_{FH}(t)$ and the receiver noise $n(t)$ (which has a two-side spectral density of $N_0/2$), and the total received signal is fed into the band-pass filter. The center frequency of the received signal is then changed by the hopping code signal $c(t)$ and demodulated by an MFSK demodulator.

The FH1 system will then automatically enter a transmitting mode of either 2FSK-FH or 4FSK-FH depending on the energy-per-bit to total-noise-power-density ratio. The BER P_{Mb} of FH1 of 2FSK-FH ($M = 2$) and 4FSK-FH ($M = 4$) can be written [14] as follows:

$$P_{Mb} = \frac{M}{2(M-1)}\sum_{i=1}^{M-1}(-1)^{i-1}{}_{M-1}C_i\frac{1}{i+1}\exp\left(\frac{-i}{i+1}K\gamma_{MD}\right) \quad (12)$$

where the relationship between K and M is written as [14]

$$K = \log_2(M) \quad (13)$$

At the receiver input, the energy-per-bit to total-noise-power-density ratio γ_{MR} is representing in Eq. (1). At the demodulator input, the energy-per-bit of the desired signal E_b is given by

$$E_b = DT_s/K = DT_s/\log_2(M) \quad (14)$$

The noise-power-density N_0 is written as

$$N_0 = \kappa B_{FH} \tau N_F / B_{FH} = \kappa \tau N_F \quad (15)$$

where B_{FH} is the bandwidth of an instantaneous channel of the FH signal.

Since the disturbance signal of DS systems has almost the same bandwidth as the operating frequency range of an FH system, this disturbance signal is regarded as additive white Gaussian noise (AWGN) [12]. When the 3-dB bandwidth B_u of the undesired signal differs, as shown in Table 2, the fraction of the bandwidth being disturbed $\rho = B_u / B_d$ ($0 < \rho < 1$) represents the ratio of the 3-dB bandwidth of the DS disturbance signal B_u to the 3-dB bandwidth of the FH system B_d [12].

When the total hopping bandwidth and the instantaneous bandwidth are respectively denoted by B_d and B_{FH}, the process gain of FH systems G_{FH} is almost equal to B_d / B_{FH} and is equal to the hop number [14], [15]. The effective power of the disturbance signal for the instantaneous bandwidth is thus $1/G_{FH}$ of the total undesired signal power. Therefore, considering the fraction of the bandwidth being disturbed ρ and the process gain G_{FH}, the power density U_0 of the undesired signal $i_{DS}(t)$ is expressed [12] as

$$U_0 \doteqdot U/(\rho B_u) = U/(G_{FH} \rho B_{FH}) \quad (16)$$

where U is the undesired signal power (in watts), and the product of G_{FH} and B_{FH} is approximately equal to B_u.

In FH systems, when the modulation index h_M is below 1, the energy-per-bit to total-noise-power-density ratio is degraded by band-limiting. The degradation of the energy-per-bit to total-noise-power-density ratio L_{FH} is therefore dependent on the modulation index h_M and is given [16] by

$$L_{FH} = \frac{1}{3h_M^2(h_M+1)} \quad (17)$$

The energy-per-bit to total-noise-power-density ratio at the demodulator input γ_{MD} is obtained from Eqs. (1), (14), (15), (16), and (17),

$$\gamma_{MD} = \frac{\gamma_{MR}}{L_{FH}} = \frac{E_b}{L_{FH}(N_0+U_0)} = \frac{1}{1/\{(E_b/N_0)/L_{FH}\} + 1/\{(D/U)\rho G_{FH} B_{FH} T_s/(KL_{FH})\}} \quad (18)$$

From Eq. (18), the energy-per-bit to total-noise-power-density ratio for the FH system of 2FSK-FH γ_{2D} and 4FSK-FH γ_{4D} can be calculated. We can derive the BER of 2FSK-FH and 4FSK-FH by substituting Eq. (18) into Eq. (12). Moreover, when the partial band of the total hopping band is disturbed, the average BER is written [14] as

$$P_M = (1-\rho) P_{Mb}(E_b/N_0) + \rho P_{Mb}(\gamma_{MD}) \quad (19)$$

Substituting Eq. (12) into Eq. (19), we can calculate the average BERs of FH1 system with a DS1, DS2, or DS3 disturbance source (Fig. 8). These BERs had almost the same characteristics, because the disturbance signals had similar bandwidths, but the 4FSK-FH system was more easily affected by the disturbance signal than was the 2FSK-FH system.

3.3 Throughput

Many wireless LAN systems use an error correction function called Go-Back N [17]. With this form of error control, an error in any one of a group of transmitted frames causes retransmission of the group's frames starting with the frame containing the error. The throughput η (bit/s) is expressed by the average effective transmission time T_e (s) and the length N (bit) of the transmission frame as

$$\eta = N / T_e \quad (20)$$

and T_e is written as [18]

$$T_e = \sum_{i=1}^{\infty} \{ iN/v + (i-1) T_r \} P_f^{i-1} (1-P_f)^i = (N + T_r v P_f) / \{ v(1-P_f) \} \quad (21)$$

where v (bit/s) is the transmission rate, and T_r (s) is the measured average period from the time the error occurred to the time transmission of the correct frame started. In this paper, T_r is 15 ms for all wireless LAN systems because all the measured T_r results were almost the same value. The frame error rate P_f is expressed [18] by the BER P_b as

$$P_f = 1 - (1 - P_b)^N \quad (22)$$

Substituting Eqs. (5) and (6) into Eq. (21) yields the frame error rate of these DS systems, so we can calculate their throughput using Eqs. (20), (21), and (22). We can also calculate the throughput of 2FSK-FH η_{2FSK} (bit/s) and 4FSK-FH η_{4FSK} (bit/s) by substituting Eq. (19) into Eq. (22) and using Eqs. (20), (21), and (22). Here, we assume the trans-

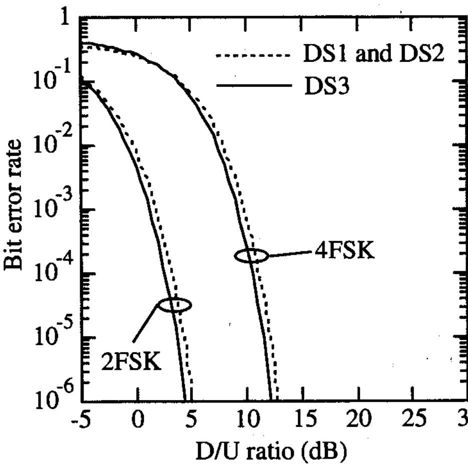

Fig. 8 Calculated bit error rates of the FH system with a DS1, DS2 or DS3 disturbance source.

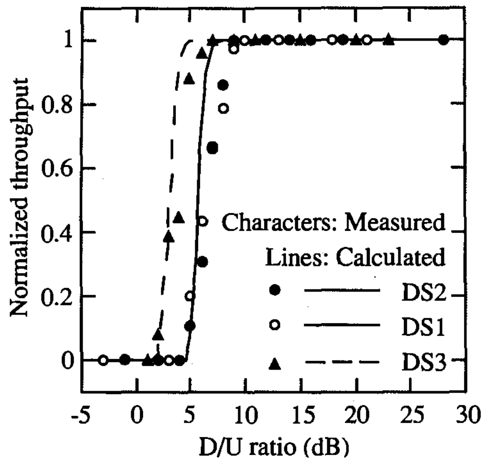

Fig. 9 Measured and calculated throughput of the DS systems with an FH1 disturbance source.

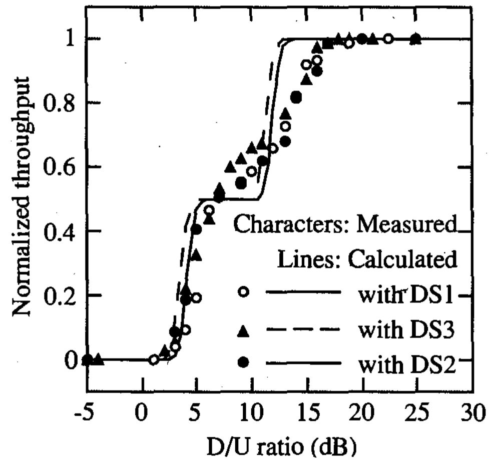

Fig. 10 Measured and calculated throughput of the FH system with a DS1, DS2, or DS3 disturbance source.

mission frame length N is a constant value of 2048 bytes (assumption 3), and do not consider carrier sense multiple access (CSMA) because we evaluate systems operated by pear-to-pear communication.

The FH1 system clearly changes its transmission rate depending on the energy-per-bit to total-noise-power-density ratio. However, an algorithm to describe how the transmission rate is changed has not been formulated. So we assumed that the average throughput of FH1 system η_{FH} (bit/s) could be written by using η_{2FSK} and η_{4FSK} as

$$\eta_{FH} = \begin{cases} \eta_{2FSK} & (\eta_{4FSK} = 0) \\ \frac{1}{2}(\eta_{2FSK} + \eta_{4FSK}) & (0 < \eta_{4FSK} < 1) \\ \eta_{4FSK} & (\eta_{4FSK} = 1) \end{cases} \quad (23)$$

Figure 9 shows the measured and calculated results of throughput versus D/U ratio when the EUT was DS1, DS2, and DS3 systems; the throughput was normalized by the maximum value of each system. Although the throughputs of DS1 and DS2 systems also had almost the same characteristics, the minimum D/U ratio required for the maximum throughput of DS3 system was about 3 dB smaller than that of DS1 and DS2 systems. The calculated results agreed well with the measured results, differing by only about 3 dB. Therefore, our calculation method can be used to predict the communication performance of DS systems when an FH system is the disturbance source.

Figure 10 shows the measured and calculated throughputs versus D/U ratio when the FH1 system was the EUT. The difference between the calculated and measured results was about ± 5 dB. This difference might have arisen because Eq. (23) is only an approximate representation, because we did not consider the effect of retransmission-error control (i.e., the transmission control protocol (TCP) congestion avoidance algorithm [20]), and/or because the DS interference signal cannot be entirely regarded as additive white Gaussian noise. Hence, we must investigate the effect of this algorithm in our future work. However, our calculation results for both DS and FH systems agreed with the measured results within a deviation of ± 5 dB.

4. Performance of DS and FH Systems Based on IEEE 802.11

Our investigation has, up to now, been based on the specifications of fojur products and on the measurement system illustrated in Fig. 1. In actual practice, the received power of the desired signal and E_b/N_0 varies. However, it is difficult to compare the performance of DS and FH systems for a targeted E_b/N_0 with this measurement system. Thus, it is difficult to change the desired signal power without risking the possibility that the desired signal will disturb the undesired signal. We therefore calculated the interference characteristics based on the IEEE 801.11 standard [3] for large and small E_b/N_0 using the calculation parameters shown in Table 3.

As an example, we calculated the interference characteristics between a DS system and an FH system when E_b/N_0 = 20 dB ($E_b > N_0$) and E_b/N_0 = 50 dB ($E_b \gg N_0$) in a non-fading channel. Here, we assumed the DS system used DBPSK (1 Mbit/s) or DQPSK (2 Mbit/s) modulation, and the FH system used 2FSK (1 Mbit/s) or 4FSK (2 Mbit/s) modulation, and that these systems change their transmission rates according to Eq. (23). The calculated throughputs are shown in Fig. 11.

Although the throughput of both DS and FH systems changed with E_b/N_0, the minimum D/U ratio of the DS system required to allow the start of communication was about 4 dB smaller than that of the FH system. The D/U ratio of the FH system required for securing its maximum throughput was about 6 dB bigger than that of the DS system. These results were mainly due to the differences in modulation method, process gain, and the degradation caused by band-limiting. The effect of the difference in modulation methods can be calculated from Eqs. (5), (12), (20), (21), and (22). The modulation method of the DS system necessitated a D/U ratio that is about 2 dB higher for maximum throughput when $E_b \gg N_0$. The ratio of the DS to FH process gain was 11/23,

Table 3 IEEE 802.11 standard parameters.

	Modulation	T_b (ms)	T_c (ms)	T_s (ms)	B_d (MHz)	B_u (MHz)	B_{FH} (MHz)	G_{DS}	G_{FH}	ρ	L_{DS} (dB)	h_M
DS (1 Mbit/s)	DBPSK	0.5	1/11	1	22	24		11			0.45	
DS (2 Mbit/s)	DQPSK	0.5	1/11	1	22	24		11			0.45	
FH (1 Mbit/s)	2FSK	1		1	24	22	1		23	22/24		0.32
FH (2 Mbit/s)	4FSK	0.5		1	24	22	1		23	22/24		0.144

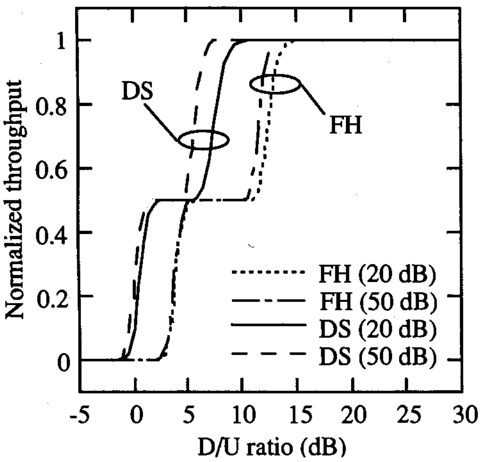

Fig. 11 Interference characteristics between DS and FH systems based on IEEE 802.11.

so the DS system also needed a D/U ratio that was a further 3 dB higher. However, the degradation caused by band-limiting meant that the FH system needed a D/U ratio that was about 11 dB higher. Therefore, the DS system performs better by about 6 dB as regards the D/U ratio, and this difference agrees with the Fig. 11 results.

To prevent interference in DS systems based on IEEE 802.11, the D/U ratio for FH interference should be above 10 dB. In FH systems, the D/U ratio required for DS interference should be above 15 dB.

5. Conclusions

In this paper, we investigated the interference characteristics of 2.4-GHz-band mid-speed wireless LANs that use direct-sequence and frequency-hopping. When an FH system was the disturbance source, the required D/U ratio was about 10 dB, and the DBPSK-DS system (DS3) performed better than the DQPSK-DS systems (DS1 and DS2). The throughput characteristics of the FH system differed from those of the DS systems in that they showed two phases of change when the throughputs rose from 0 to 1. This was because the transmission mode of the FH system changed depending on the energy-per-bit to total-noise-power-density ratio. The D/U ratio of the FH system had to be at least 15 dB to overcome DS interference.

We developed a model to calculate the characteristics of interference between DS and FH systems by considering the frequency bandwidth of the wireless systems, the dwell time of the FH system, and the time that the DS system needs to transmit a data frame. The calculated D/U ratio agreed with the measured results within ± 5 dB. This means the model can be used to calculate performance measures such as the bit error rate and throughput.

Using this model, we calculated the throughput of wireless LAN systems when the ratio of the E_b/N_0 was high enough to enable stable communication. The IEEE 802.11 specifications were used as calculation parameters. Our results indicated that the D/U ratio required in an FH system is 7 or 8 dB higher than that in a DS system when the wireless LAN systems are based on the IEEE 802.11 standard.

Under IEEE 802.11, interference between DS and DS systems should not occur because a station can detect other stations. However, this may lower the throughput of DS systems because their signal transmission will be constrained. Interference between FH and FH systems may occur, though, when two or more transmitters transmit their signals in the same frequency slot at the same time. In such cases, interference can be caused by fairly distant personal stations even though nearby personal stations will not always cause interference.

On the other hand, we found that the interference between DS and FH systems depends on the D/U ratio. That means that interference is more likely to be caused by nearby personal stations. It is difficult to determine which combination of DS and FH systems is best because there are trade-offs in performance. Therefore, the operating area of a LAN must be designed with the relative merits of the two types of system in mind.

In future work we will investigate the effect of communications control on interference (e.g., retransmission of TCP and CSMA) and performance in the fading environments.

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