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Adaptive Modulation/TDMA Scheme for Large Capacity Personal Multi-Media Communication Systems

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SUMMARY This paper proposes an adaptive modulation/TDMA scheme to achieve high capacity personal multi-media communication systems. TDMA is employed to cope with various bit rate for multi-media services. The modulation scheme is selected from 1/4-rate QPSK, 1/2-rate QPSK, QPSK, 16 QAM and 64 QAM according to the received C/I_c (power ratio of the desired signal to the co-channel interference) and the delay spread. The spectral efficiency is evaluated by using the simulated bit error rate (BER) performance as well as the cumulative distribution of the C/I_c with parameters of cell configurations. The results show that the spectral efficiency of the proposed scheme is 3.5 times higher than that of the conventional QPSK systems at the outage probability of 10%, and the effect is more remarkable at lower outage probability. The results also show that the proposed adaptive modulation is effective in improving delay spread immunity.

key words: *adaptive modulation, multi-level QAM, multipath fading, personal communication, cellular system*

1. Introduction

Recent development of digital land mobile communication techniques makes it possible to use most of the modulation techniques, such as Gaussian-filtered minimum shift keying (GMSK) [1], [2], $\pi/4$-shift quaternary phase shift keying ($\pi/4$-QPSK) [3], [4], and 16-ary quadrature amplitude modulation (16 QAM) [5], [6], and access techniques, such as time division multiple access (TDMA) [1]-[4] and code division multiple access (CDMA) [7], [8]. Consequently, the land mobile communication system engineers can flexibly design air interfaces according to the conditions in each area, such as the propagation path characteristics, traffic and the service demand.

On the other hand, the future personal communication systems, such as future public land mobile telecommunication systems (FPLMTS) require minimization of the number of air interfaces from the view points of global services and terminal portability [9]. Consequently, how to compromise the minimization of the number of air interfaces and the system flexibility according to the regional conditions is a key issue for the global personal multi-media communication systems.

Thus, we have investigated the adaptive modulation techniques [10]-[13] that select the modulation scheme from QPSK, 16 QAM, 64 QAM and 256 QAM according to the traffic and the received signal level, and found that it has the potential to increase system capacity as well as to buffer the variation of the traffic [11]-[13].

Another important issue for the adaptive modulation scheme is how to precisely compensate for fading. Thus, we have developed a pilot symbol aided fading compensation techniques for M-ary QAM in land mobile communications and confirmed by laboratory and field experiments that M-ary QAM is a practical modulation scheme for land mobile communication systems [6], [14]-[16].

Based on these results, this paper proposes an adaptive modulation/TDMA personal multi-media communication systems. In this system, TDMA is used to equivalently change the assigned bandwidth as well as to cope with various bit rate for multi-media services. The modulation scheme is selected from 1/4-rate QPSK, 1/2-rate QPSK, QPSK, 16 QAM and 64 QAM according to the required quality, the received C/I_c (power ratio of the desired signal to the co-channel interference) and the delay spread.

Although the previous papers [10]-[13] showed the potential of the adaptive modulation to improve spectral efficiency or transmission quality, evaluation of the spectral efficiency including cell configuration parameters and its delay spread immunity have not been investigated, yet. Thus, this paper evaluates the spectral efficiency of the proposed system in both flat Rayleigh and frequency selective fading conditions.

The results show that the spectral efficiency of the proposed scheme is 3.5 times higher than that of the conventional QPSK systems at the outage probability of 10%, and the improvement is more remarkable at lower outage probability. The results also show that the proposed adaptive modulation is effective in improving the delay spread immunity.

2. Concept of the Proposed Adaptive Modulation/TDMA Systems

In the cellular systems, spectral efficiency is determined by the spectral efficiency with respect to frequency (η_f) times the geographical frequency reuse factor ($1/L$: L

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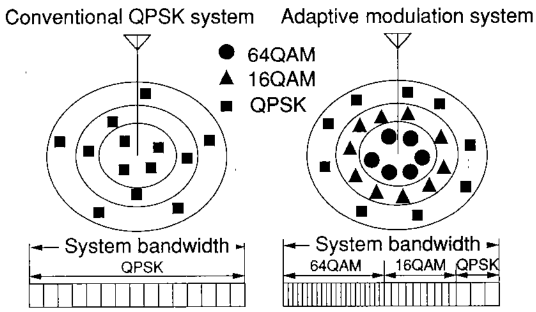

Fig. 1 Concept of the adaptive modulation systems.

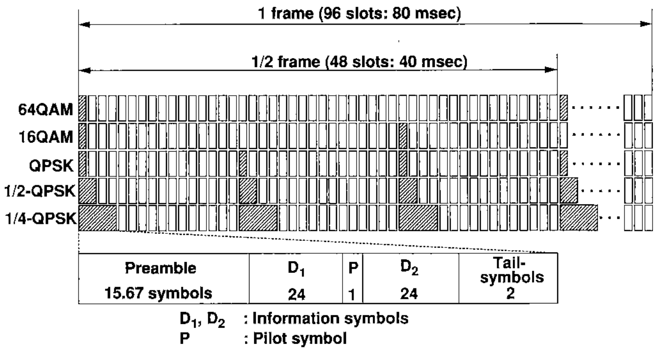

Fig. 2 Frame format for the proposed adaptive modulation systems.

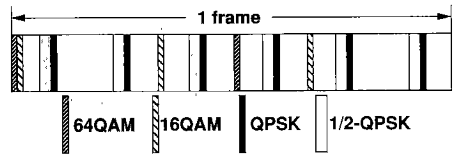

Fig. 3 Example of the slot assignment for adaptive modulation systems.

is the number of cell site in each cell cluster) [17]. When higher modulation level is applied, although η_f is linearly increased, $1/L$ is reduced due to the shorter minimum signal distance of the modulated signal. Consequently, increase in the modulation level is not always a good solution to improve spectral efficiency for cellular systems [14].

By the way, in the case of cellular systems, although C/I_c is low for the terminal at the fringe of each cell, it is very high for the terminal near the base station. Thus, if higher modulation level is assigned to the terminals near the base station and lower one is assigned to the terminals at the fringe as shown in Fig. 1, very high spectral efficiency can be expected. In this case, however, how to control bandwidth according to the modulation level is the most important issue. This paper applies TDMA because it can equivalently control the bandwidth just by changing the number of assigned slot in each TDMA frame. Furthermore, TDMA can cope with various bit rate for multi-media services.

In the proposed systems, carrier frequency, slots, modulation level and symbol rate for each terminal are initially assigned by the base station through the common control channel (CCCH) according to the traffic conditions, propagation path characteristics, and the required data-rate. When these conditions are changed during each call, they are controlled via the control channel associated with the traffic channel (associated control channel: ACCH) [18]. Although we have to solve many problems in this protocol, such as boundary switching problem, and should investigate in detail in the future, we will neglect its effect in the following.

Figure 2 shows a frame format of the proposed system. One frame consists of 96 slots and 1 frame length is 80 ms. In each slot, 48 symbols (D_1 and D_2 in Fig. 2) are used to transmit both information and the associated control signals. The preamble includes guard space as well as ramp-up and frame synchronization symbols. Tail symbols is for the ramp-down. The last symbol in the preamble, first symbol in the tail symbols and a pilot symbol (P in Fig. 2) are used to compensate for fading [19].

Symbol rate for the full-rate is 80 ksymbol/s. The modulation level is selected from 4, 16 and 64. Consequently, a burst length for the full-rate transmission is 833.3 μs (66.67 symbols).

For the voice transmission, two slots in each frame are used when 64 QAM is assigned as a modulation level. In this case, the voice signal including FEC and ACCH are transmitted at the bit rate of 7.2 kbit/s. When lower modulation level is assigned for the voice transmission, more slots in each frame are used so as to keep the bit rate of 7.2 kbit/s. That is, three slots (every 32 slots) for 16 QAM and six slots (every 16 slots) for QPSK.

When the received C/I_c is too low or the delay spread is too large, the symbol rate is reduced to half-rate (40 ksymbol/s) or quarter-rate (20 ksymbol/s). In any case, the same burst format as shown in Fig. 2 is used. That is, the burst length is 1.67 ms for the half-rate and 3.33 ms for the quarter-rate transmissions.

In this system, estimation of C/I_c is essential. Reference [20] proposes a method to estimate instantaneous energy per symbol to the noise spectral density (E_s/N_0) and delay spread using a known pseudo random noise (PN) sequence. Because this method can also be applied to the estimation of the average C/I_c, this paper assumes that the estimation of C/I_c is perfect although its accuracy should be for further study.

In each carrier, different modulation could be assigned. Figure 3 shows an example of the slot assignment for adaptive modulation systems. In this example, four subscribers with different modulation schemes are allocated in the same carrier. In the real system, system capacity greatly depends on the slot assignment algorithm. In this paper, however, we will neglect the capacity loss due to the algorithm in the following analysis. Investigation on the algorithm should be for further study.

When higher bit rate is required to transmit non-voice data, more slots in each frame will be assigned according to the required bit rate. Consequently, the maximum bit rate of 345.6 kbit/s per carrier (96 slots × 7.2 kbit/s) is available using 64 QAM.

3. Definition of the Spectral Efficiency for the Sector Cell Layout

When the modulation level is fixed, the spectral efficiency is given by [17]

$$\eta_T=\frac{l\cdot R_s\cdot F_{eff}}{f_{ch}\cdot L}\quad \text{(bit/s/Hz per number of cell sites in a cell cluster)} \tag{1a}$$

$$l=\log_2 M \tag{1b}$$

where

M : modulation level
R_s : symbol rate
f_{ch} : channel spacing
F_{eff}: frame efficiency.

On the other hand, the spectral efficiency for the adaptive modulation systems is given by

$$\eta_T=\sum_{k=1}^{k_1}\frac{1}{2^{k-2}}R_{smax}\frac{F_{eff}}{f_{ch}\cdot L}\Pr\left(\frac{1}{2^{k-1}}-\text{rate QPSK}\right)+\sum_{l=2}^{l_{max}}\frac{(2l)\cdot R_{smax}\cdot F_{eff}}{f_{ch}\cdot L}\Pr(2^{2l}-\text{QAM}) \tag{2a}$$

$$l_{max}=\log_2 M_{max} \tag{2b}$$

where R_{smax} is the symbol rate for full-rate transmission, $\Pr(\text{mod}_x)$ is a probability that a modulation (mod_x) is selected, k_1 is the number of symbol rate to be used, and M_{max} is the maximum modulation level. $k=1$, 2, and 3 correspond to full-rate QPSK, half-rate QPSK and quarter-rate QPSK, respectively, and $l=2$ and $l=3$ correspond to 16 QAM and 64 QAM. The channel spacing between each carrier is determined under the constraint that the power ratio of the desired signal to the adjacent channel interference (C/I_A) is much higher than C/I_c. When a roll-off factor of 0.5 is used for both the transmitter and receiver filters and f_{ch} is greater than $1.2R_{smax}$, this condition will be satisfied [21]. Thus, we will neglect the effect of C/I_A in the following because $f_{ch}=1.2R_{smax}$ is a very typical number for digital cellular systems, such as Japanese and North American digital cellular systems [3], [4].

In this paper, we will use the irregular parallel beam three-sector cell layout proposed by Kanai [22] because it gives very high spectral efficiency. This scheme reduces L by reducing the co-channel reuse distance in the direction orthogonal to the main beam because co-channel interference coming from this direction is very small owing to the antenna directivity. Moreover, it can take arbitrary integer number for L. In the following, we will use a directive antenna with a beam half width of 70 degree [21].

Furthermore, we will assume the followings for both the desired and interference signals.

(1) Large-scale signal variation is subject to the path loss with respect to distance (attenuation factor of 3.5) and the log-normal fading with a standard deviation of 6.0 dB.
(2) Small-scale signal variation is subject to Rayleigh fading and delay spread.

4. Spectral Efficiency in Rayleigh Fading Environments

In the following three sections, delay spread=0 will be assumed, and the effect of delay spread will be evaluated in Sect. 5.

4.1 Spectral Efficiency of the Conventional Systems

Figure 4 shows the computer simulated results of the BER vs. C/I_c performances of QPSK, 16 QAM and 64 QAM with a pilot symbol aided maximal ratio combining space diversity in Rayleigh fading environments. Gray coding with absolute phase coherent detection is employed for any modulation. Because the required BER for the voice transmission is 10^{-2} [23], and voice transmission may be the main service for personal multi-media communication systems, BER= 10^{-2} will be used to evaluate spectral efficiency in the following. From Fig. 4, the required C/I_c for BER= 10^{-2} is 9 dB for QPSK, 16 dB for 16 QAM, and 20 dB for 64 QAM.

Figure 5 shows the cumulative distribution of C/I_c (probability that C/I_c is lower than abscissa) with a

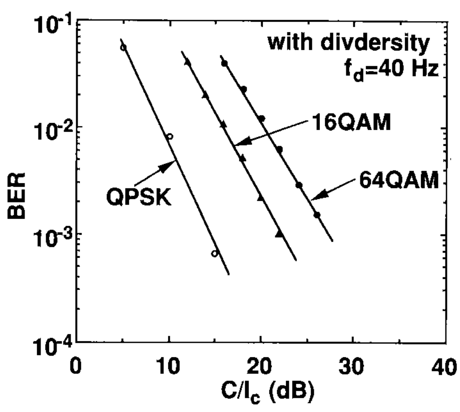

Fig. 4 BER vs. C/I_c performances for QPSK, 16 QAM and 64 QAM.

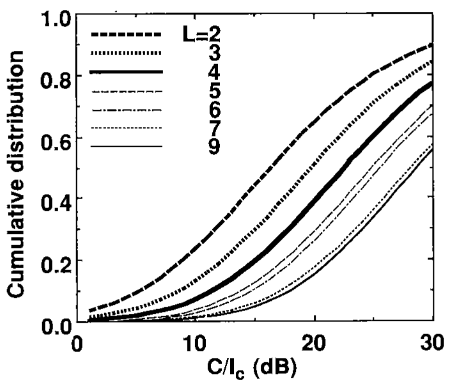

Fig. 5 Cumulative distribution of C/I_c.

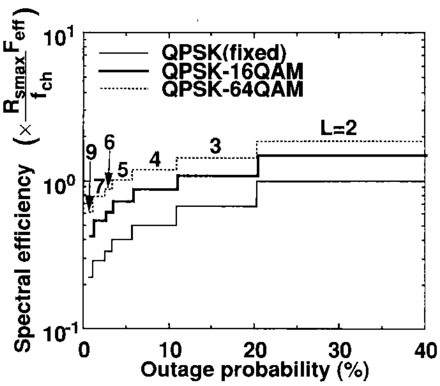

Fig. 7 Spectral efficiency vs. outage probability for the modulation level controlled adaptive modulation.

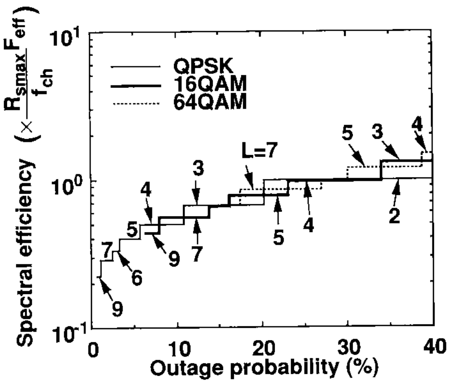

Fig. 6 Spectral efficiency vs. outage probability for QPSK, 16 QAM and 64 QAM.

parameter of L for the irregular parallel beam three-sector cell layout. When the required C/I_c for BER$=10^{-2}$ is Λ_m, L is determined to satisfy that $\Pr(C/I_c<\Lambda_m)$ is lower than an outage probability (P_0), where $\Pr(x)$ is a probability of x.

Figure 6 shows the spectral efficiency vs. P_0 for QPSK, 16 QAM, and 64 QAM. The required L for each outage probability is also shown. Spectral efficiency improvement by increasing the modulation level is very small because larger L is required although η_f is improved. This means that QPSK is considered to be the most appropriate modulation scheme when the modulation level is fixed.

4.2 Spectral Efficiency of the Modulation Level Controlled Adaptive Modulation Systems

In the case of the modulation level controlled adaptive modulation systems, outage probability is the probability that C/I_c is lower than the required C/I_c for a modulation with the smallest modulation level, i.e., QPSK ($=9.0$ dB) in this case. In this analysis, the terminal mobility is assumed to be very low. With this assumption, large scale signal variation is assumed to be constant during each call.

Figure 7 shows the spectral efficiency of the adaptive modulation with the available modulation level of 4 and 16 (QPSK-16 QAM in Fig. 7), and that with the available modulation level of 4, 16 and 64 (QPSK-64 QAM in Fig. 7). When the modulation level is selected from 4, 16 and 64, the modulation level is controlled on the following criteria.

(1) $C/I_c<16$ dB: QPSK
(2) $16\leqq C/I_c\leqq 20.0$ dB: 16 QAM
(3) 20.0 dB$<C/I_c$: 64 QAM

When the maximum modulation level is limited to 16, 16 QAM is selected whenever $C/I_c\geqq 16.0$ dB.

This figure shows that spectral efficiency is 1.8 times higher than that of the conventional QPSK systems at $P_0=10\%$ even if the maximum modulation level of the adaptive modulation system is limited to 16. When the maximum modulation level is 64, its spectral efficiency is 2.4 times higher than that of the conventional QPSK systems.

4.3 Spectral Efficiency of the Modulation Level and Symbol Rate Controlled Adaptive Modulation Systems

When symbol rate is reduced to $1/K$, the required C/I_c can be lowered by $10\log(K)$ (dB). Thus, the outage probability is the probability that the C/I_c is lower than the required C/I_c for QPSK with the lowest symbol rate.

Figure 8 shows the spectral efficiency of the modulation level and symbol rate controlled adaptive modulation systems. When the half-rate QPSK is also introduced to the adaptive modulation systems (1/2-rate QPSK-64 QAM in Fig. 8), the spectral efficiency becomes 2.8 times higher than that of the conventional QPSK systems at the outage probability of 10%. When both the half-rate and quarter-rate are introduced (1/4-rate QPSK-64 QAM in Fig. 8), spectral efficiency becomes 3.5 times higher than that of the conventional QPSK systems. Moreover, this figure shows that the improvement in spectral efficiency is more remarkable at the lower P_0. For example, spectral efficiency of the 1/4-rate QPSK-64 QAM system is 4.5 times higher than that of the conventional QPSK systems at $P_0=1\%$.

Although the adaptive modulation system shows very high spectral efficiency, it has a problem that the maximum bit rate is lowered as the distance from the base station increases. Figure 9 shows the selection ratio of each modulation vs. distance from the base station (d) normalized by the cell radius (R) in the case of 1/4-rate QPSK-64 QAM and $L=5$, in which, $P_0 < 1\%$ is satisfied. The figure shows that although the selection ratio of the lower level modulation increases with d/R, the selection ratio of 64 QAM is still 46% at the fringe area ($0.9 \leqq d/R \leqq 1.0$). In this area, P_0 was confirmed to be 1.2%. It means that muti-media services with a bit rate of 7.2–345.6 kbit/s is possible with a probability of more than 46% even at the fringe area, provided that the delay spread is very small and the traffic density is not so high. Of course, BER$=10^{-2}$ is not a sufficient transmission quality for multi-media services. Thus, forward error control (FEC), automatic repeat request (ARQ), etc. should be further applied to improve transmission quality.

5. Spectral Efficiency in Frequency Selective Fading Environments

In this section, we will discuss the spectral efficiency degradation due to delay spread. Figure 10 shows the cumulative distribution of the delay spread (τ_{rms}) at Shinjyuku and Kofu of Japan quoted from Ref. [24]. Shinjyuku is one of the typical cities surrounded by the high-rise buildings with very high traffic density, and Kofu is one of the typical cities surrounded by the mountain with moderate traffic density.

Figure 11 shows the computer simulated results of the irreducible BER (BER caused by the delay spread under noise free and slow mobility conditions) vs. delay spread performances of QPSK, 16 QAM and 64 QAM, where the delay spread is normalized by a symbol duration. This figure shows that the normalized delay spread (τ_{rms}/T_s, T_s is a symbol duration) should be smaller than 0.18, 0.13, and 0.09 for QPSK, 16 QAM and 64 QAM to achieve the irreducible BER of less than 10^{-2}.

When the modulation is fixed to QPSK, the sym-

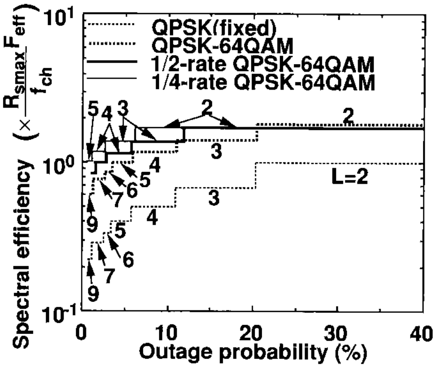

Fig. 8 Spectral efficiency vs. outage probability for the modulation level and symbol rate controlled adaptive modulation.

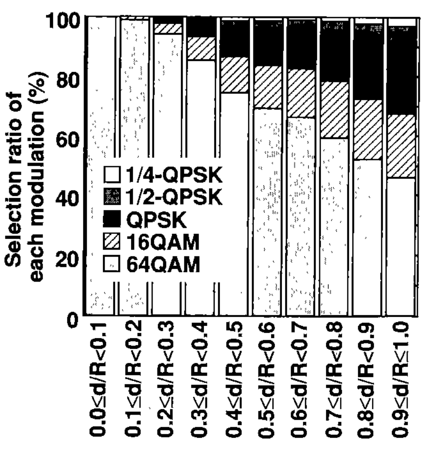

Fig. 9 Selection ratio of each modulation vs. d/R.

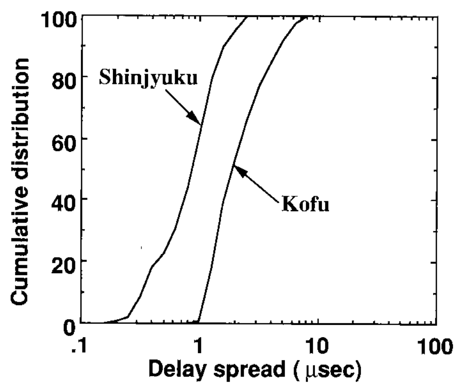

Fig. 10 Cumulative distribution of the delay spread at Shinjyuku and Kofu [23].

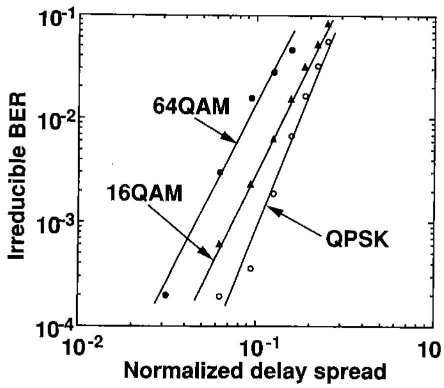

Fig. 11 Irreducible BER vs. normalized delay spread for QPSK, 16 QAM and 64 QAM.

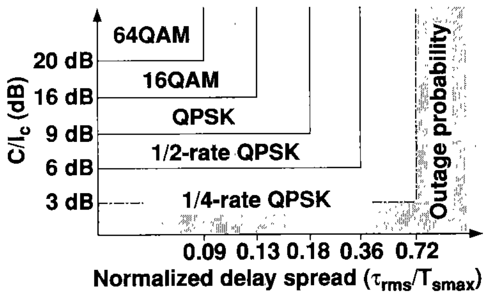

Fig. 12 Decision criteria for the adaptive modulation systems under frequency selective fading conditions.

bol rate is limited to 40 ksymbol/s to satisfy BER $=10^{-2}$ at the 90% of the area because the normalized delay spread for BER $=10^{-2}$ is 0.18 and the 90% value of the delay spread at Kofu is 4.5 μs. On the other hand, in the case of modulation level and symbol rate controlled adaptive modulation system, when the delay spread is normalized by the symbol duration of the maximum symbol rate ($T_{smax}=1/R_{smax}$), τ_{rms}/T_{smax} for 64 QAM, 16 QAM, QPSK, half-rate QPSK and quarter-rate QPSK are given by 0.09, 0.13, 0.18, 0.36 and 0.72, respectively.

For the selection of the modulation scheme in the adaptive modulation systems, BER is determined by both the average C/I_c and the average τ_{rms}/T_{smax}. Figure 12 shows the decision criteria of the adaptive modulation systems for BER $=10^{-2}$. To achieve BER $=10^{-2}$ using 64 QAM, $C/I_c \geqq 20$ dB and $\tau_{rms}/T_{smax} \leqq 0.09$ should be satisfied. Thus, the selection probability of 64 QAM is given by

$$\Pr(64\,\mathrm{QAM}) = \Pr(C/I_c \geqq 20\,\mathrm{dB}) \cdot \Pr(\tau_{rms}/T_{smax} \leqq 0.09) \quad (3a)$$

In the case of 16 QAM, BER $=10^{-2}$ is satisfied when $C/I_c \geqq 16$ dB and $\tau_{rms}/T_{smax} \leqq 0.13$. However, this condition also includes Pr(64 QAM). Thus, Pr(16 QAM) is given by

$$\begin{aligned}\Pr(16\,\mathrm{QAM}) &= \Pr(C/I_c \geqq 16\,\mathrm{dB}) \cdot \Pr(\tau_{rms}/T_{smax} \leqq 0.13) \\ &\quad - \Pr(64\,\mathrm{QAM}) \\ &= \Pr(16\,\mathrm{dB} \leqq C/I_c < 20\,\mathrm{dB}) \cdot \Pr(\tau_{rms}/T_{smax} \\ &\quad \leqq 0.13) \\ &\quad + \Pr(C/I_c \geqq 20\,\mathrm{dB}) \cdot \Pr(0.09 < \tau_{rms}/T_{smax} \\ &\quad \leqq 0.13) \end{aligned} \quad (3b)$$

With the same manner, Pr(QPSK) and Pr(1/2-rate QPSK) are given by

$$\begin{aligned}\Pr(\mathrm{QPSK}) &= \Pr(9 \leqq C/I_c < 16\,\mathrm{dB}) \cdot \Pr(\tau_{rms}/T_{smax} \leqq 0.18) \\ &\quad + \Pr(C/I_c \geqq 16\,\mathrm{dB}) \cdot \Pr(0.13 < \tau_{rms}/T_{smax} \\ &\quad \leqq 0.18) \end{aligned} \quad (3c)$$

$$\begin{aligned}\Pr(1/2\text{-rate QPSK}) &= \Pr(6 \leqq C/I_c < 9\,\mathrm{dB}) \cdot \Pr(\tau_{rms}/T_{smax} \leqq 0.36) \\ &\quad + \Pr(C/I_c \geqq 9\,\mathrm{dB}) \cdot \Pr(0.18 < \tau_{rms}/T_{smax} \\ &\quad \leqq 0.36) \end{aligned} \quad (3d)$$

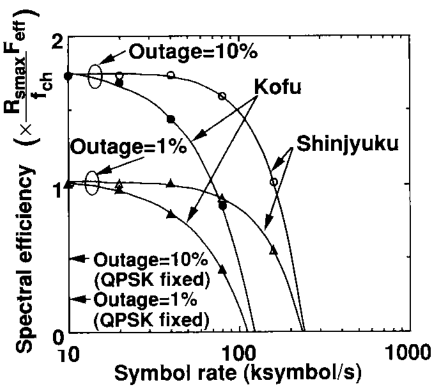

Fig. 13 Spectral efficiency vs. maximum symbol rate for the outage probability of 1% and 10% at Shinjyuku and Kofu.

1/4-rate QPSK is selected when any other modulation schemes cannot satisfy BER $=10^{-2}$. Thus, Pr(1/4-rate QPSK) is given by

$$\begin{aligned}\Pr(1/4\text{-rate QPSK}) &= \Pr(C/I_c < 6\,\mathrm{dB}) + \Pr(C/I_c \geqq 6\,\mathrm{dB}) \\ &\quad \cdot \Pr(0.36 > \tau_{rms}/T_{smax}) \end{aligned} \quad (3e)$$

P_0 is the probability that BER $=10^{-2}$ cannot be obtained even if 1/4-rate QPSK is applied. Thus, it is given by

$$\begin{aligned}P_0 &= \Pr(C/I_c < 3\,\mathrm{dB}) + \Pr(C/I_c \geqq 3\,\mathrm{dB}) \\ &\quad \cdot \Pr(\tau_{rms}/T_{smax} > 0.72). \end{aligned} \quad (4)$$

In Fig. 12, the shadowed area corresponds to the condition of the outage probability.

Figure 13 shows the spectral efficiency vs. R_{smax} for the 1/4-rate QPSK-64 QAM system at $P_0=1\%$ and 10% in Shinjyuku and Kofu areas. This figure shows that spectral efficiency is almost constant when $R_{smax} \leqq 80$ ksymbol/s at Shinjyuku area. On the other hand, the spectral efficiency for $R_{smax}=80$ ksymbol/s at Kofu is degraded by about 50% compared with the value at Shinjyuku. However, the traffic density at Kofu is not so high and its spectral efficiency is still higher than that of the conventional QPSK systems. Thus, we can apply $R_{smax}=80$ ksymbol/s at both Shinjyuku and Kofu areas.

6. Conclusion

This paper proposes an adaptive modulation/TDMA cellular systems for the personal multi-media communication systems, and evaluates its spectral efficiency and delay spread immunity. We conclude the followings.

(1) Although the modulation scheme for the adaptive modulation is selected from QPSK and 16 QAM, its spectral efficiency is 1.8 times higher than that of the conventional QPSK systems at the outage probability of 10%.

(2) When the modulation scheme for the adaptive modulation is selected from QPSK, 16 QAM and 64 QAM, its spectral efficiency becomes 2.4 times higher than that of the conventional QPSK systems.

(3) When half-rate QPSK and quarter-rate QPSK are further added to the candidates of the modulation scheme, its spectral efficiency becomes 3.5 times higher than that of the conventional QPSK systems.

(4) The effect of the modulation level and symbol rate controlled adaptive modulation is more remarkable for smaller outage probability.

(5) Even at the fringe area, 64QAM can be applied with a more than 46% of the area even at the fringe of each cell.

(6) The modulation level and symbol rate controlled adaptive modulation is also effective to improve the delay spread immunity in frequency selective fading channels.

In this paper, we have mainly discussed the spectral efficiency improvement for the voice transmission because it will be a main service for personal multimedia communication systems. However, we also have to cope with other services that require much higher transmission quality. Other than FEC and ARQ, the adaptive modulation scheme can also cope with such a requirement by preparing several decision charts like Fig. 12 for each required BER, for example, for BER$=10^{-3}$, so as to cover all the services to be supported. It will be a future problem. Moreover, the modulation control algorithm including handover and the accurate estimation scheme for C/I_c and delay spread should also be for future study.

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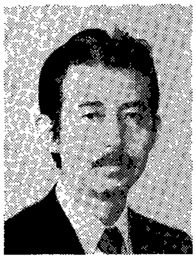

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