Delay-time/code division multi-access in frequency-selective channel

F. Adachi and K. Takeda

A new hybrid multi-access technique, called delay-time/code division multi-access (DT/CDMA), is proposed. Multiplexing is accomplished in both the delay-time domain and code domain. Delay-time division multiplexing is achieved by assigning different cyclic time delays to the same spreading sequence. At a receiver, frequency-domain equalisation, despreading, and demultiplexing are performed simultaneously in the frequency domain. The bit error rate performance when using the proposed DT/CDMA in a frequency-selective Rayleigh fading channel is evaluated by computer simulation.

Introduction: Direct-sequence code division multi-access (DS-CDMA) with coherent rake combining is adopted in third generation (3G) mobile communication systems [1]. Rake combining can take advantage of the frequency selectivity of the channel to improve bit error rate (BER) performance by separating different propagation paths in the despreading process and then coherently combining them. In the fourth generation (4G) mobile communication systems [2], there is demand for broadband data services that require a much wider bandwidth, e.g. 100 MHz, than the 3G systems (which use the 1.25–5 MHz bandwidth). The wireless channel for 4G systems may become severely frequency selective owing to the presence of many propagation paths which causes the BER performance to degrade when employing coherent rake combining. To overcome this problem, multi-carrier CDMA (MC-CDMA) [3, 4] has recently attracted much attention. More recently, it was shown [5] that frequency-domain equalisation (FDE) based on the minimum mean square error (MMSE) criterion improves the BER performance of nonspread single-carrier transmission. MMSE-FDE can also be applied to DS-CDMA to replace coherent rake combining in order to achieve much improved BER performance [6]. This is true for the case of the DS-CDMA downlink (base-to-mobile). However, in the DS-CDMA uplink (mobile-to-base) case, the orthogonality among different user spread signals is severely distorted since different user signals pass through different channels. The resulting multi-access interference (MAI) limits the uplink BER performance even if MMSE-FDE is used. This Letter proposes a new hybrid multi-access technique that suppresses MAI while taking advantage of the channel frequency selectivity to improve BER performance.

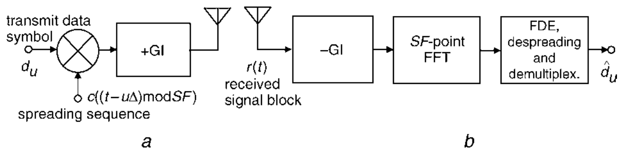

Fig. 1 *Transmitter/receiver structure*

a Transmitter
b Receiver

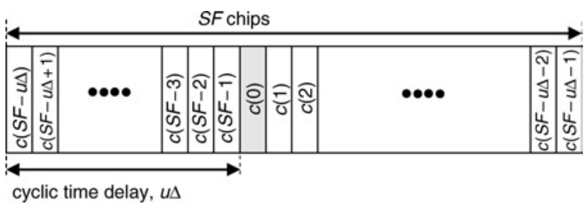

Fig. 2 *Cyclic time delay*

Operation principle of DT/CDMA: A long pseudo-noise (PN) sequence, $\{c(t)=\pm1\}$, is used as a spreading sequence. U users transmit their data to a base station. For the spreading factor, SF, U users share the same partial sequence, $\{c(t);t=n\cdot SF\sim(n+1)\cdot SF-1\}$, to spread their nth data-modulated symbols, but the uth user, $u=0\sim U-1$, is assigned a cyclic time delay of $u\Delta$ chips to the partial sequence, where Δ is set to the maximum time delay difference of the channel. Below, without loss of generality, we consider the transmission of the $n=0$th data symbol and omit symbol index n for simplicity. The transmitter and receiver structures are illustrated in Fig. 1. The uth user data-modulated symbol, d_u, is spread by $c((t-u\Delta)\mathrm{mod}SF)$, $t=0\sim SF-1$, as shown in Fig. 2. Before the transmission of the spread signal, the insertion of a guard interval (GI) of Δ chips is necessary to carry out FDE at the receiver [6]; however, in the following explanation, the GI insertion/removal operation is omitted for simplicity. Throughout this Letter, a discrete-time signal representation is used.

The uth user transmit signal, $s_u(t)$, $t=0\sim SF-1$, is expressed using the lowpass equivalent representation as

$$s_u(t)=\sqrt{2S_u}d_uc((t-u\Delta)\mathrm{mod}SF) \tag{1}$$

where S_u is the average transmit power and $E[|d_u|^2]=1$ with $E[.]$ representing the ensemble average operation. The channel is assumed to be composed of L distinct paths, each having an integer multiple of chip length T_c. Superposition of U user signals is received at the base station, which can be expressed as

$$\begin{aligned}r(t)=&\sum_{u=0}^{U-1}\sqrt{2S_u}d_u\sum_{l=0}^{L-1}h_{u,l}c((t-\tau_{u,l}-u\Delta)\mathrm{mod}SF)\\&+\eta(t),\ t=0\sim F-1\end{aligned} \tag{2}$$

where $h_{u,l}$ and $\tau_{u,l}$ are the complex path gain and time delay of the lth path, respectively. Term $\eta(t)$ is a zero-mean noise process having variance $2N_0/T_c$ due to the additive white Gaussian noise (AW and T_c is the chip length). The received signal, $\{r(t);\ t=0\sim SF-1\}$, is transformed by applying the SF-point fast Fourier transform (FFT) to frequency-domain signal $\{R(k);\ k=0\sim SF-1\}$. Term $R(k)$ is given as (its derivation is omitted for the sake of brevity)

$$\begin{aligned}R(k)&=\sum_{t=0}^{SF-1}r(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\\&=\sum_{u=0}^{U-1}\sqrt{2S_u}d_uH_u(k)\left\{C(k)\exp\left(-j2\pi k\frac{u\Delta}{SF}\right)\right\}+\Pi(k)\end{aligned} \tag{3}$$

where $C(k)$, $H_u(k)$, and $\Pi(k)$ are Fourier transforms of partial sequence $\{c(t);t=0\sim SF-1\}$, the channel impulse response, and noise, respectively. These are given by

$$\left\{\begin{aligned}C(k)&=\sum_{t=0}^{SF-1}c(t)\exp\left(-j2\pi k\frac{t}{SF}\right),H_u(k)\\&=\sum_{l=0}^{L-1}h_{u,l}\exp\left(-j2\pi k\frac{\tau_{u,l}}{SF}\right)\\\Pi(k)&=\sum_{t=0}^{SF-1}a(t)\exp\left(-j2\pi k\frac{t}{SF}\right)\end{aligned}\right. \tag{4}$$

The uth user is considered to be a desired user. FDE is carried out as $\hat{R}_u(k)=w_u(k)R(k)$, where $w_u(k)$ is the equalisation weight. The frequency-domain signal, $\{\hat{R}_u(k);\ k=0\sim SF-1\}$, is transformed by SF-point inverse FFT (IFFT) into delay-time domain signal $\{y_u(\tau);\tau=0\sim SF-1\}$. Below, we derive the MMSE weight such that $y_u(\tau)$ is as close to $d_u\ \delta(\tau)$ as possible. This means that $y_u(0)$ becomes the decision variable, $\hat{d}_u$. We have

$$\hat{d}_u=y_u(0)=\frac{1}{SF}\sum_{k=0}^{SF-1}w_u(k)R(k) \tag{5}$$

FDE, despreading, and demultiplexing can be simultaneously performed in the frequency domain. The Fourier transform of $d_u\delta(\tau)$ is d_u for $k=0\sim SF-1$ and the equalisation error $e(k)$ is defined as $e(k)=\hat{R}_u(k)-d_u$. Since data symbols of different users are independent, solving $\partial E[|e(k)|^2]/\partial w_u(k)=0$ gives the following MMSE weight

$$w_u(k)=\frac{\{C(k)H_u(k)\exp(-j2\pi k(u\Delta/SF))\}^*}{(|C(k)|^2/SF(\sum_{u'=0}^{U-1})S_{u'}T_c/N_0)|H_{u'}(k)|^2+1} \tag{6}$$

Simulation results: Quaternary phase shift keying (QPSK) is used for data modulation. The fading channel is a chip-spaced $L=16$-path frequency-selective block Rayleigh channel with a uniform power delay profile (i.e. $E[|h_{u,l}|^2]=1/L$ and $\tau_{u,l}=l$ for all u). The spreading factor is set to $SF=64$. The GI length is set to $\Delta=16$ chips; therefore, the maximum number of users to be multiplexed is $SF/\Delta=4$. A long PN sequence with the repetition period of 4095 chips is used as the spreading sequence, $c(t)$. Partial sequence $\{c(t);\ t=nSF\sim(n+1)SF\}$ is used to spread the nth data-modulated symbol for users $u=0$–3. If U users exceeds four but is less than eight, we use $\{c(t);\ t=(n+1)$

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$SF\sim(n+2)SF\}$ to spread the nth data-modulated symbol for users $u=4$–7. Ideal timing recovery and channel estimation are assumed.

Fig. 3 plots the uplink average BER performance of the proposed DT/CDMA against the average received signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 $(=0.5(ST_c/N_0)(SF+\Delta))$, where we assume $S_u=S$ for all u (i.e. the signal-to-interference power (SIR) per user is 0 dB). For comparison, the results of conventional DS-CDMA with MMSE-FDE are plotted. DT/CDMA cannot completely remove the MAI since the orthogonality among different users is distorted to some extent owing to MMSE-FDE and therefore the achievable BER performance degrades owing to residual MAI as U increases. However, the proposed DT/CDMA provides better BER performance than the conventional DS-CDMA. Fig. 4 shows how the achievable BER performance degrades as SIR per user decreases when $U=4$. The $u=0$th user is the desired user and the other three users, $u=1$–3, are interfering users. The Figure clearly shows that the proposed DT/CDMA is very insensitive to the power difference among users compared to DS-CDMA.

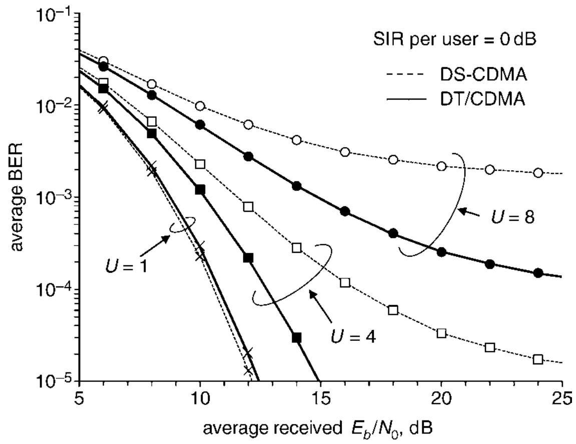

Fig. 3 *Average BER performance with SIR per user = 0 dB*

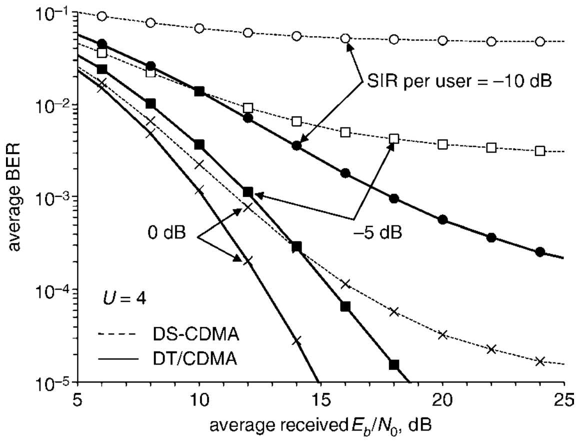

Fig. 4 *Impact of interference power on BER performance*

Conclusion: We propose a new hybrid multi-access technique that utilises both the delay-time domain and code domain. Frequency-domain equalisation, despreading, and demultiplexing are simultaneously performed in the frequency domain. The achievable BER performance of the proposed DT/CDMA was evaluated by computer simulation to confirm its advantage over DS-CDMA.

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