Hybrid OFDM-CDMA: A Comparison of MC/DS-CDMA, MC-CDMA and OFCDM

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ABSTRACT: Due to the current trend of personal wireless communication, there are growing needs for both higher bit rate data transmission and multiple access. To fulfil these demands, a new scheme, which combines wireless digital modulation and multiple access, was proposed in the recent years, namely OFDM-CDMA (Orthogonal Frequency Division Multiplexing – Code Division Multiple Access). In general, there are three types of hybrid scheme, e.g. MC/DS-CDMA (Multi-carrier Direct Sequence CDMA), MC-CDMA (Multi-carrier CDMA) and OFCDM (Orthogonal Frequency Code Division Multiplexing). This paper compares the signal model of these three access schemes. In order to benefit from the frequency diversity of these hybrid schemes, frequency spread coding can be adopted. Thus, this paper also discusses the use of frequency spread coding.

1 Introduction

A CDMA system using direct sequence spread spectrum (DS-SS) is known to have resistance to frequency selectivity of channels. Its capacity is limited by multiple access interference (MAI), which result from the imperfection of auto-correlation and cross-correlation characteristics of spreading codes. Although zero cross-correlated orthogonal codes could result in no MAI in flat fading channels, the orthogonality will not be guaranteed in frequency selective fading channels because of inter-chip interference, which will cause MAI and degrade the system performance. One approach to suppress the effect of inter-chip interference in frequency selective fading channels is the combination of CDMA and multi-carrier modulation, such as OFDM that can achieve high spectral efficiency because the spectrum of successive sub-carriers is allowed to overlap. The combined CDMA systems with OFDM are mainly categorized into three types, i.e. MC/DS-CDMA [3],[5], MC-CDMA [4],[5],[6] and OFCDM [7],[8],[10].

In the MC/DS-CDMA scheme, the serial-to-parallel (S/P) converted data symbols are DS-SS modulated using a user specific spreading code and these signals are transmitted in parallel on different sub-carriers, or in other words, spreading in the time domain. It is guaranteed that there is no MAI in the synchronized downlink in a cell in slow frequency selective fading channels but benefits of path diversity, which is inherent in wideband transmission system, cannot be obtained because each data symbol is assigned to one of the narrow-band sub-channels and only one path is resolvable in each sub-channel [3].

In the MC-CDMA scheme, multiple copies of the same data symbol each multiplied by one chip of a user specific spreading code are transmitted on different sub-carriers in parallel over overlapping frequency in the frequency domain. Since replicas of the same data symbol are transmitted on different sub-carriers, frequency diversity can be exploited even without error-correction coding but MAI still occurs especially in downlink.

The OFCDM scheme originally based on MC-CDMA scheme exhibited better performance than the conventional DS-CDMA approach in a broadband channel, which comprises many multi-path components. It mitigates the degradation due to severe multi-path interference (MPI) occurring in such broadband channel by employing many low symbol rate sub-carriers and by making full use of the frequency diversity effect using the spread and coded signals over parallel sub-carriers. Although OFCDM achieves better throughput performance in a broadband channel, it still suffers from the degradation caused by inter-code interference due to loss of orthogonality among code-multiplexed channels. Therefore, the combining scheme to de-spread the signals in frequency domain is a key technique in order to compensate for the destruction of orthogonality, thereby achieving a high link capacity [7].

This paper shows the differences on signal model, transmitter and receiver configurations of these hybrid OFDM-CDMA schemes in downlink. This paper is organized such that Section 2 describes the transceiver structure and signal model of MC/DS-CDMA; Section 3 describes transceiver structure and signal model of MC-CDMA; Section 4 describes transceiver structure and signal model of OFCDM; and Section 5 describes the frequency spread coding and lastly draws the conclusion.

2 MC/DS-CDMA

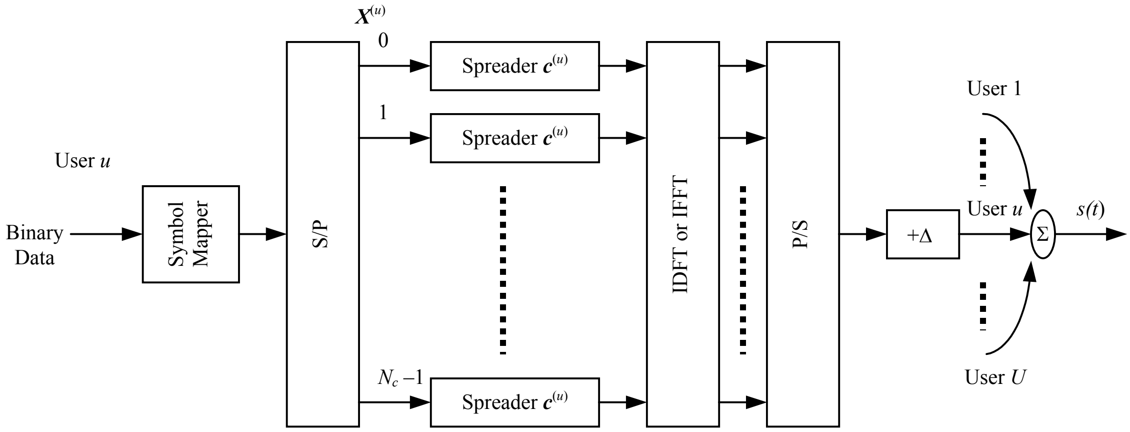


Fig. 1 MC/DS-CDMA Transmitter Model

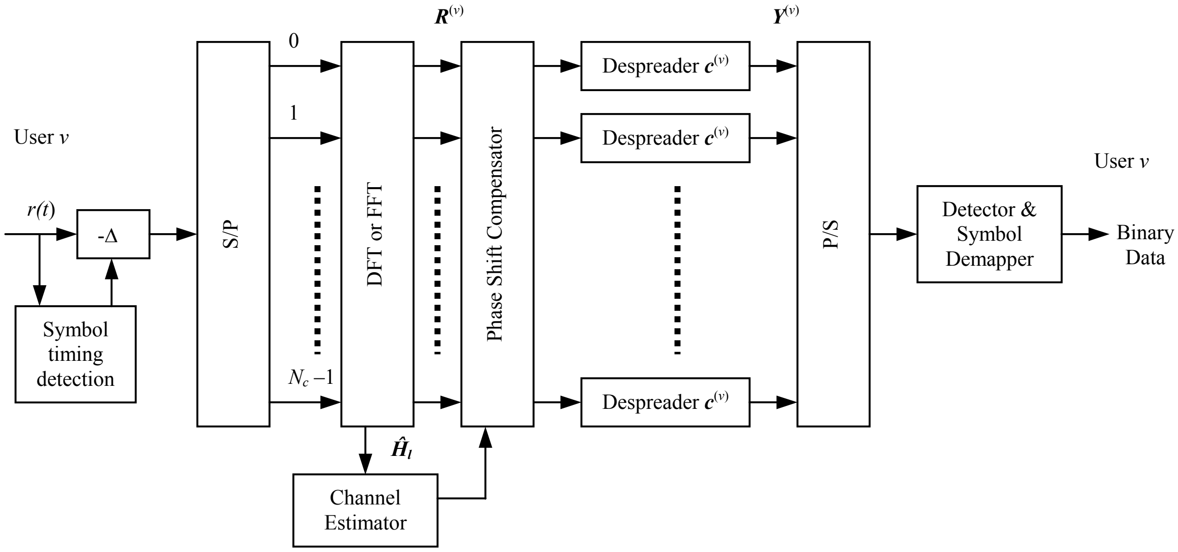


Fig. 2 MC/DS-CDMA Receiver Model

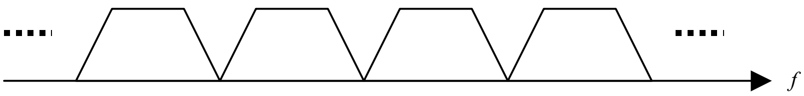


Fig. 3 Power Spectrum of MC/DS-CDMA Transmitted Signal

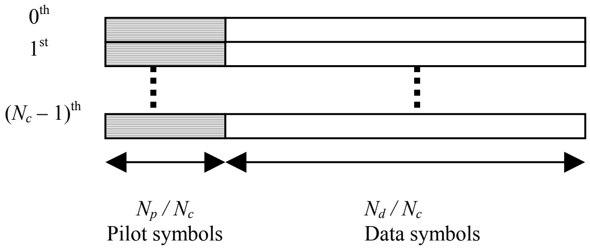


Fig. 4 Packet Structure of MC/DS-CDMA

2.1 Transmitter Model

The block diagram of a transmitter and power spectrum of a MC/DS-CDMA system are shown in Fig.1 and Fig.3 respectively. Assume that the binary data sequence of one packet is first convolutionally encoded and then QPSK (Quadrature Phase Shift Keying) modulated. The mapped symbol sequence of N_d symbols per packet, where each symbol has duration T_d, is S/P converted into N_c sub-channels and N_p/N_c pilot symbols are time-multiplexed at the beginning of each sequence, which shown in Fig.4. The new data symbol duration in each sub-channel is $T_s = NT_d$. Each sub-stream is spread by a user specific spreading code with length equals to *SF* (spreading factor) and transmitted with one of the N_c sub-carriers. The equivalent low pass transmitted signal is given by

$$s(t) = \sum_{i=0}^{(N_d+N_p)/N_c-1} \sum_{u=1}^{U} s_i^{(u)}\left(t - iT_s\right), \tag{1}$$

where U is the number of users and $s_i^{(u)}(t)$ is the i^{th} MC-DS-SS symbol waveform of user u, which is expressed as

$$s_i^{(u)}(t) = \sum_{k=0}^{N_c-1}\sum_{l=0}^{SF-1} X_{k,i}^{(u)} c_l^{(u)} e^{j2\pi f_k (t-lT_c)} p_{T_c}\left(t - lT_c\right). \qquad -\Delta \le t \le -\Delta + T_s \tag{2}$$

For explaining the notation in Eq.(2), the k^{th} sub-channel of i^{th} input sequence of user u $X_{k,i}^{(u)} = \exp\left(j\phi_k^{(u)}(i)\right)$ where the QPSK phase is defined as $\phi_k^{(u)}(i) \in \{q\pi/2; q = 0,1,2,3\}$, such that $\mathbf{X}_i^{(u)} = \left[X_{0,i}^{(u)} \quad X_{1,i}^{(u)} \quad \cdots \quad X_{N_c-1,i}^{(u)}\right]^T$; $c_l^{(u)} \in \{-1,+1\}$ is the l^{th} chip of the spreading code of user u such that $\mathbf{c}^{(u)} = \left[c_0^{(u)} \quad c_1^{(u)} \quad \cdots \quad c_{SF-1}^{(u)}\right]^T$ is used in all sub-channels in common; the frequency of sub-carrier k, $f_k = f_0 + k/t_c$ where f_0 is the lowest frequency of N_c sub-carriers; Δ is the guard interval, t_c is the observation time and $T_c = \Delta + t_c$ is the chip duration; and, $p_{T_c}(t)$ is a pulse waveform of each chip, which defined as $p_{T_c}(t) = \begin{cases} 1, & -\Delta \le t \le t_c \\ 0, & \text{otherwise} \end{cases}$.

The relationship between the symbol duration and chip duration is $T_s = SF\times T_c$, which indicates that a MC-DS-SS symbol consists of as many as *SF* chips. *SF* is also known as the processing gain. Also note that the addition of a guard interval Δ implies an increase in the actual chip rate $1/t_c$ by a factor of $(\Delta + t_c)/t_c$ if the symbol rate $1/T_s$ is kept constant [3],[5].

2.2 Channel Model

Consider a frequency selective fading channel modelled as a tapped delay line, the low pass equivalent impulse response is given by

$$h(\tau, t) = \sum_{p=1}^{P} h_p(t)\delta(\tau - \tau_p), \tag{3}$$

where P is number of paths, τ_p is the propagation delay for the p^{th} path and $h_p(t)$ is the complex envelope of the signal received on the p^{th} path.

2.3 Receiver Model

The block diagram of a MC/DS-CDMA receiver is shown in Fig.2. The transmitted signal $s(t)$ propagated via a wireless channel is disturbed by multi-path fading and additive white Gaussian noise (AWGN). The received signal is given by

$$r(t) = s(t) \otimes h(\tau;t) + n(t) = \int_0^{\infty} s(t-\tau)h(\tau;t)d\tau + n(t), \tag{4}$$

where $n(t)$ is a complex Gaussian noise with double sided power spectral density $N_0/2$.

On the received signal $r(t)$, the inverse operation, which comprises removal of guard interval, S/P conversion and Discrete or Fast Fourier Transform (DFT or FFT). The output of the k^{th} sub-carrier branch at time $iT_s + lT_c$ (i^{th} input sequence, l^{th} chip) is expressed as

$$R_{k,l,i} = \frac{1}{t_c} \int_{iT_s + lT_c}^{iT_s + lT_c + t_c} r(t) \exp\left(-j2\pi f_k (t - iT_s - lT_c)\right) dt. \tag{5}$$

Let τ_{max} be the maximum delay spread and f_D be a maximum Doppler frequency. On the assumption that $\Delta > \tau_{max}$ and $T_c << 1/f_D$, thus no inter-chip interference exists and the channel parameters are constant over several consecutive chip intervals, each sub-channel acts like a slow flat fading channel. Rewrite Eq.(5),

$$R_{k,l,i} = H_{k,l,i} \sum_{u=1}^{U} X_{k,i}^{(u)} c_l^{(u)} + N_{k,l,i}, \tag{6}$$

where $N_{k,l,i}$ is a zero mean Gaussian random variable with variance $N_0/2$ and $H_{k,l,i}$ is the channel response at a sub-carrier frequency f_k, which given by

$$H_{k,l,i} = \sum_{p=1}^{P} h_p(iT_s + lT_c)\exp\left(-j2\pi f_k \tau_p\right). \tag{7}$$

After the phase shift compensating and de-spreading operations, the de-spread data symbol of user v on the k^{th} sub-channel is expressed as

$$Y_{k,i}^{(v)} = \sum_{l=0}^{SF-1} \frac{\hat{H}_{k,l,i}^{*}}{\left|\hat{H}_{k,l,i}\right|} R_{k,l,i} c_l^{(v)} , \tag{8}$$

where $\hat{H}_{k,l,i}$ is an estimate of the channel response.

3 MC-CDMA

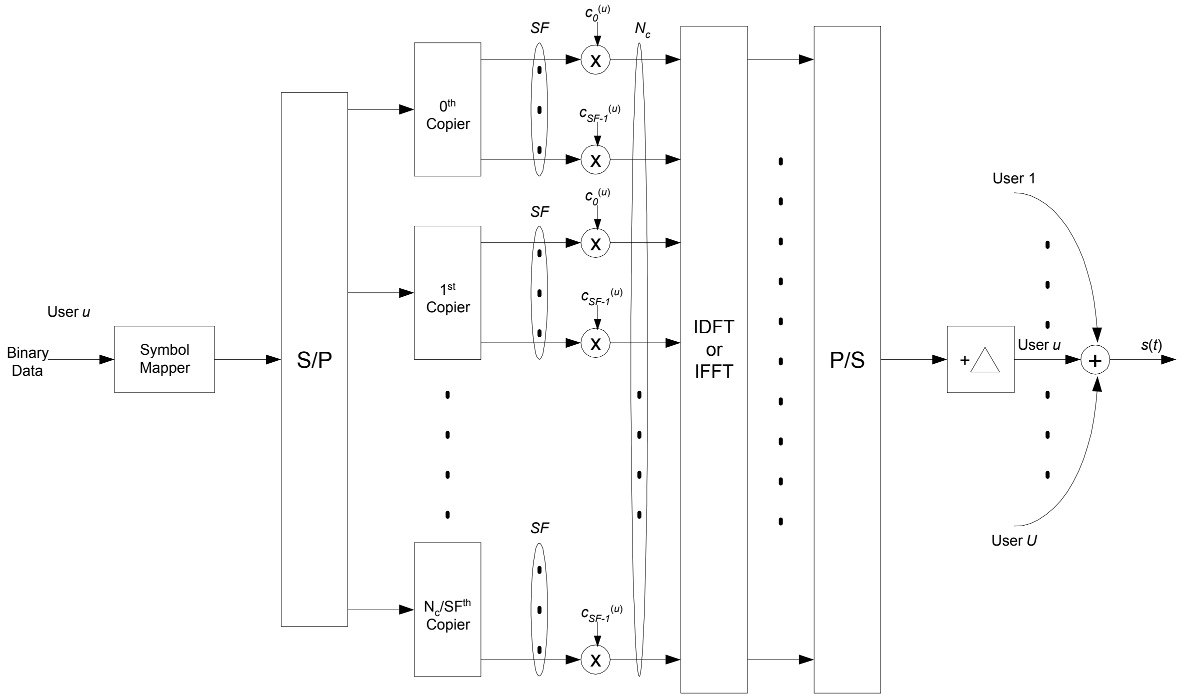


Fig. 5 MC-CDMA Transmitter Model

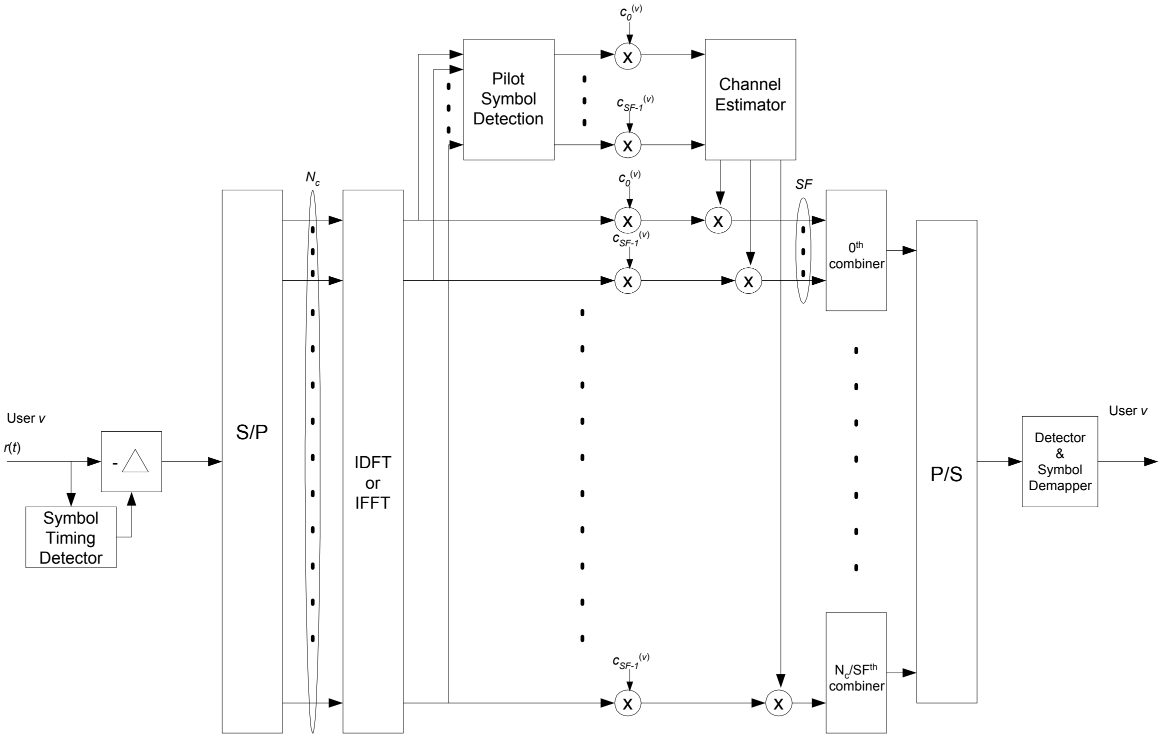


Fig. 6 MC-CDMA Receiver Model

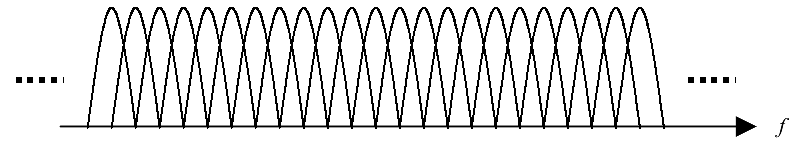


Fig. 7 Power Spectrum of MC-CDMA Transmitter Signal

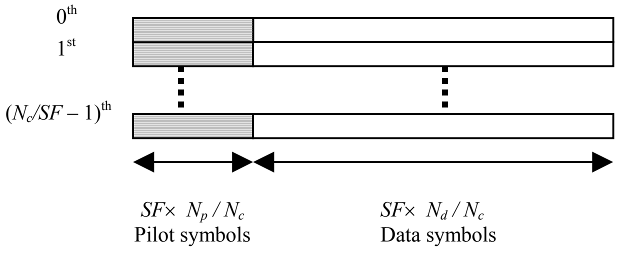


Fig. 8 Packet Structure of MC-CDMA

3.1 Transmitter Model

The block diagram of a transmitter and power spectrum of a MC-CDMA system are shown in Fig.5 and Fig.7 respectively. Assume that the binary data sequence of one packet is first convolutionally encoded and then QPSK (Quadrature Phase Shift Keying) modulated. N_p pilot symbols are appended at the beginning of the sequence. The resulting sequence of symbol duration of T_d is S/P converted into N_c/SF parallel sequences, which indicates that N_c/SF is the number of symbols transmitted simultaneously by one user where N_c is the total number of sub-carriers and SF is the spreading factor. The transmitted packet frame of MC-CDMA is shown in Fig.8. The new data symbol duration after S/P conversion is $T_s'=(N_c/SF)T_d+\Delta$, where Δ is guard interval. Each of the sub-channels is spread by a user specific spreading code with length of SF and scrambled by a long pseudo random code in the frequency domain. The base-band transmitted signal is given by

$$s(t)=\sum_{i=0}^{\frac{(N_d+N_p)}{N_c/SF}-1}\sum_{k=0}^{\frac{N_c}{SF}-1}\sum_{u=1}^{U}s_{i,k}^{(u)}\left(t-iT_s'\right), \qquad (9)$$

where U is the number of users and $s_{i,k}^{(u)}(t)$ is the i^{th} symbol waveform of the k^{th} sub-channel of user u, which is expressed as

$$s_{i,k}^{(u)}(t)=\sum_{m=0}^{\frac{N_c}{SF}-1}\sum_{l=0}^{SF-1}X_{m,i}^{(u)}c_l^{(u)}e^{j2\pi f_k t}p_{T_s'}(t). \qquad -\Delta\le t\le -\Delta+T_s' \qquad (10)$$

For explaining the notation in Eq.(10), the m^{th} parallel sequence of i^{th} input sequence of user u is $X_{m,i}^{(u)}=\exp\left(j\phi_k^{(u)}(m)\right)$ where the m^{th} parallel sequence of QPSK phase is defined as $\phi_k^{(u)}\left(i\times(N_c/SF)+\left\lfloor k/(N_c/SF)\right\rfloor\right)\in\{q\pi/2;q=0,1,2,3\}$, such that the input data sequence is expressed as, $\mathbf{X}_i^{(u)}=\left[X_{0,i}^{(u)}\quad X_{1,i}^{(u)}\quad\cdots\quad X_{N_c/SF-1,i}^{(u)}\right]^T$; $c_l^{(u)}\in\{-1,+1\}$ is the l^{th} chip of the spreading code of user u such that $\mathbf{c}^{(u)}=\left[c_0^{(u)}\quad c_1^{(u)}\quad\cdots\quad c_{SF-1}^{(u)}\right]^T$ is used in all parallel sequence in common; the frequency of sub-carrier *k*, $f_k = f_0 + {(m \cdot SF + l)}/{T'_s}$ where f_0 is the lowest frequency of N_c sub-carriers; Δ is the guard interval; and, $p_{T'_s}(t)$ is a pulse waveform of each chip, which defined as $p_{T'_s}(t) = \begin{cases} 1, & -\Delta \le t \le T'_s \\ 0, & \text{otherwise} \end{cases}$.

3.2 Channel Model

Consider the same channel model as Section 2.2, with the channel impulse response given as Eq.(3).

3.3 Receiver Model

The block diagram of a MC-CDMA receiver is shown in Fig.6. The transmitted signal *s*(*t*) propagated via a wireless channel is disturbed by multi-path fading and additive white Gaussian noise (AWGN). The received signal is given by

$$r(t) = s(t) \otimes h(\tau;t) + n(t) = \int_0^{\infty} s(t-\tau)h(\tau;t)d\tau + n(t), \tag{11}$$

where *n*(*t*) is a complex Gaussian noise with double sided power spectral density $N_0/2$.

On the received signal *r*(*t*), the inverse operation, which comprises removal of guard interval, S/P conversion and DFT (or FFT). The output of the $k^{\text{th}}(k = m \cdot SF + l)$ sub-carrier branch at time iT'_s (i^{th} input sequence) is expressed as

$$R_{m,l,i} = \frac{1}{(N_c/SF)T_d} \int_{iT'_s}^{iT'_s + (N_c/SF)T_d} r(t)\exp(-j2\pi f_k (t - iT'_s))dt. \tag{12}$$

Assume each sub-channel acts like a slow flat fading channel. Rewrite Eq.(12),

$$R_{m,l,i} = H_{m,l,i} \sum_{u=1}^{U} X_{m,i}^{(u)} c_l^{(u)} + N_{m,l,i}, \tag{13}$$

where $N_{m,l,i}$ is a zero mean Gaussian random variable with variance $N_0/2$ and $H_{m,l,i}$ is the channel response at a sub-carrier frequency f_k, which given by

$$H_{m,l,i} = \sum_{p=1}^{P} h_p(iT'_s)\exp(-j2\pi f_k \tau_p). \tag{14}$$

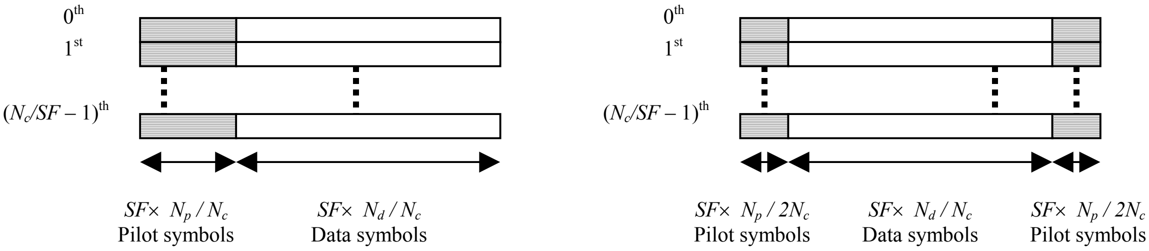
After the channel estimation, all sub-channels are combined and de-spreaded into N_c/SF parallel sequences. The m^{th} parallel-received symbol of user *v* is expressed as

$$Y_{m,i}^{(v)} = \sum_{l=0}^{SF-1} \frac{\hat{H}_{m,l,i}^*}{\left|\hat{H}_{m,l,i}\right|} R_{m,l,i} c_l^{(v)}, \tag{15}$$

where $\hat{H}_{m,l,i}$ is an estimate of the channel response.

4 OFCDM

In [7] and [8], OFCDM is proposed with variable spreading factor (VSF), which changes *SF* of OFCDM corresponding to the cell structure and radio link conditions such as delay spread, including the special no-spreading mode with $SF = 1$ (OFCDM becomes OFDM).



(a) Forward Pilot only (b) Forward & Backward Pilot

Fig. 9 Packet structure of OFCDM

Since OFCDM is based on MC-CDMA, thus it has the same transceiver model as a MC-CDMA system (Refer to Fig.5 & 6). The transmitted packet frame of OFCDM is shown in Fig.9 where the common pilot symbols are time-multiplexed at (a) only the beginning of a packet or (b) both the beginning and end of a packet.

5 Frequency Spread Coding

With frequency spread coding (FSC), *Q* low-rate data symbols of one user given by a S/P conversion are superimposed with code division multiplexing (CDM) using codes of length *Q* and then a sequence of resulting superimposed chips is S/P into *Q* frequency sub-channels as shown in Fig.10. So, each data symbol is spread over *Q* frequency sub-channels.

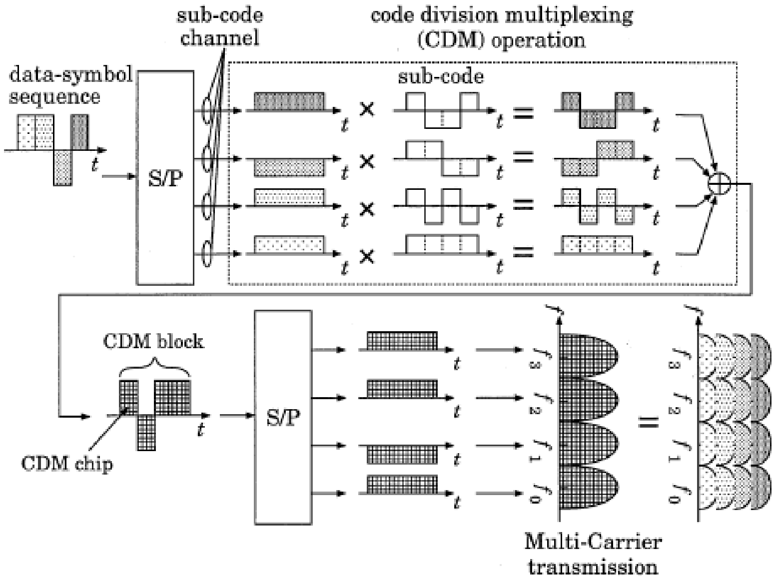


Fig. 10 Principle of Frequency Spread Coding

If the sub-channels experience frequency selective fading, a diversity gain can be obtained because *Q* replicas per data symbol would be observed as shown in Fig.11. In notation wise, the sub-channel carrying *Q* replica of the same data symbol is denoted as sub-code channel and the code that specifies the sub-code channel is denoted as sub-code. In order to apply the concept of FSC into the three hybrid schemes, the data sequence after the first S/P conversion should be going through the CDM operation before any spreading operation in time or frequency domain.

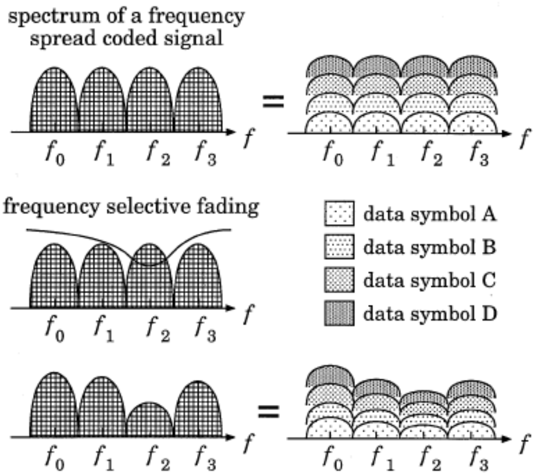


Fig. 11 Power Spectrum of Frequency Spread Coding

There are a few possible choices for sub-code that is going to be used in the CDM operation, note that this sub-code should be an orthogonal code. One of the examples of an orthogonal code is the Walsh-Hadamard code. This code consists of +1 and –1. The Hadamard matrix $\mathbf{H}_{2n}$ is a $2n \times 2n$ matrix such that the first row of the matrix contains all +1's and the other rows contains n of +1's follow by n of –1's. The rows of the Hadamard matrix are then mutually orthogonal. Fundamental unit of Hadamard matrix,

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

A recursive matrix operation is required to produce the Walsh-Hadamard codes of length $2n$,

$$\mathbf{H}_{2n} = \begin{bmatrix} \mathbf{H}_n & \mathbf{H}_n \\ \mathbf{H}_n & -\mathbf{H}_n \end{bmatrix}, \tag{16}$$

where the matrix $\mathbf{H}_{2n}$ is formed by using matrix $\mathbf{H}_n$ recursively until matrix $\mathbf{H}_2$. This code fulfils completely the orthogonality between each other.

6 Conclusion

This paper compared the signal models of the three hybrid OFDM-CDMA schemes essentially apply to the downlink. As an alternative for exploiting frequency diversity, frequency spread coding has been considered. Further computer simulations on determining the Signal-to-Noise Ratio and Bit Error Rate on each scheme are required in order to comment on their performances. Nevertheless, each of these schemes has their potential to be chosen as the next generation of mobile communication system.

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