COMPLEMENTARY-CODE-DIVISION MULTIPLEXING FOR FUTURE GENERATION WLAN AND MOBILE COMMUNICATIONS

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Abstract—**This paper proposes a novel spread spectrum data transmission scheme, called complementary-code-division multiplexing (CCDM), which makes use of asymptotic Gaussian distributed complementary code spread signals to achieve high-speed and variable rate data transmission for future generation wireless local area networks (WLAN) and mobile communications.**

I. INTRODUCTION

The fundamental laws of data compression and transmission established in Claude Shannon's famous work [1] have been shown to be the bases of our modern information and communication technologies [2]. In Theorem 17 of [1], Shannon obtained the capacity limit for a bandwidth and power limited signal perturbed by white Gaussian noise and asserted that "to approximate this limiting rate of transmission the transmitted signals must approximate, in statistical properties, a white noise". According to this Theorem, using white Gaussian noise like signals for communications is the best way to achieve the channel capacity limit. In addition to high-speed data transmission, future generation communication systems are also required to provide high mobility and robust performance in severe channel environments. These goals can be achieved by adaptive transmission techniques to allow for variable processing gains and/or variable date rates under different channel conditions.

In this paper, a novel spread spectrum data transmission scheme, called complementary-code-division multiplexing (CCDM), is proposed based on complementary codes (or sequences) [3-6]. Due to its resemblance to white Gaussian noise and its ability to provide variable rate data transmission, CCDM signal is extremely suitable for future high-speed and adaptive communication applications such as wireless local area networks (WLAN) and mobile communications.

II. COMPLEMENTARY CODE SPREADING AND DESPREADING

According to the complementary property [3,4] of a set of complementary codes, $\{c_i[n]\}$, the sum of their respective autocorrelation functions is zero at any non-zero offset, i.e.,

$$\sum_{i=0}^{K-1}\phi_{c_i,c_i}[m]=\begin{cases}KN, & m=0\\ 0, & m\neq 0\end{cases}, \tag{1}$$

where N is the code length, K is the set size, and $\phi_{c_i,c_i}[m]=\sum_{n=0}^{N-1}c_i[n]c_i[n+m]$ is the autocorrelation function of code $c_i[n]$. Denoting $\{w_i(t)\}$ as a set of K time waveforms of duration T, which form an orthogonal waveform set satisfying

$$\int_0^T w_i^*(t)w_j(t)dt=\begin{cases}1, & i=j\\ 0, & i\neq j\end{cases}, \tag{2}$$

a coded waveform of duration NT associated with $c_i[n]$ and $w_i(t)$ can be generated as $\sum_{n=0}^{N-1}c_i[n]w_i(t-nT)$. Adding all K coded waveforms together, a waveform associated with the complementary set $\{c_i[n]\}$ and the orthogonal waveform set $\{w_i(t)\}$ is obtained as

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$$s(t)=\sum_{i=0}^{K-1}\sum_{n=0}^{N-1}c_i[n]w_i(t-nT), \quad (3)$$

which is called the complementary code spreading signal with the property that its autocorrelation function is zero at any time offset (an integer multiple of T) except for zero offset, i.e.,

$$\phi_{s,s}(t)=\int_0^{NT}s^*(\tau)s(\tau+t)d\tau=0, \qquad \text{for } t=-(N-1)T,\ldots,-T,T,\ldots,(N-1)T. \quad (4)$$

There are three typical types of orthogonal waveform sets: 1. time-division orthogonal waveform set, in which each waveform is a gate function of duration T_c, called chip time and related to the waveform duration by $T=KT_c$, located in one of the K different time slots; 2. code-division orthogonal waveform set, in which each waveform is a binary coded waveform such as one of the Walsh-Hadamard functions; and 3. frequency-division orthogonal waveform set, in which each waveform is a sinusoidal function with one of K orthogonal frequencies.

The complementary code spreading signal can be used to modulate data symbols to form a spread spectrum signal for data transmission. The modulation is realized by passing the date symbol sequence $\{a_n\}$ with symbol interval T_s, which is an integer multiple of T, through a filter with the complementary code spreading signal $s(t)$ as the impulse response, resulting in a complementary code spread signal $\sum_{n=-\infty}^{\infty}a_n s(t-nT_s)$. We refer to this modulation as complementary code spreading. For signal demodulation, the complementary code spread signal is received by the matched filter $s^*(-t)$ and then sampled at symbol interval. We refer to this demodulation as complementary code despreading. Due to the unique autocorrelation property of $s(t)$ as expressed in (4), the transmitted symbols will be recovered at the sampling points without intersymbol interference.

Some characteristics of complementary code spreading are of interest. Firstly, the amplitude of the complementary code spread signal demonstrates an asymptotic Gaussian distribution. When time-division orthogonal waveform set is used, for example, the probability density function (pdf) of the normalized (i.e., unity variance) complementary code spread signal is found to be

$$p_n(x)=2^{-n-1}\sqrt{n}\sum_{k=0}^{n}\frac{n!}{(n-k)!k!}\delta\left(x-\frac{2k-n}{\sqrt{n}}\right), \quad (5)$$

where n is the ratio of the spreading signal duration NT over symbol interval T_s. Fig. 1 shows the comparison between $p_n(x)$ and the Gaussian pdf with unity variance. We see that, when $n\geq 16$, $p_n(x)$ approaches the Gaussian distribution. Secondly, the complementary code spreading enables variable rate data transmission using the fixed-length complementary code spreading signal instead of the conventional variable-length spreading codes [7]. And thirdly, the complementary code spreading can realize both direct sequence (when time-division or code-division orthogonal waveform set is used) and multicarrier (when frequency-division orthogonal waveform set is used) spread spectrum systems.

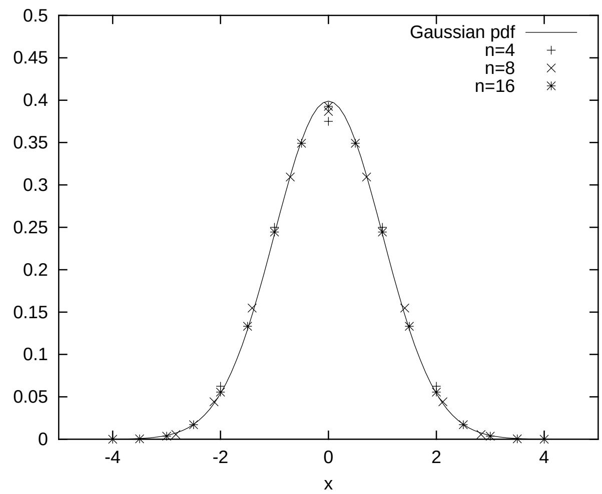

Fig. 1. $p_n(x)$ for $n=4$, 8, and 16 versus Gaussian pdf.

III. COMPLEMENTARY-CODE-DIVISION MULTIPLEXING

For a set of complementary codes of size K, a collection of K mutually orthogonal complementary code sets can be also constructed [4,5]. Denoting these mutually orthogonal complementary code sets as $\{c_i^{(k)}[n]\}$, $k=0,\ 1,\ \ldots,\ K-1$, we have the following complementary property

$$\sum_{i=0}^{K-1}\phi_{c_i^{(k)},c_i^{(l)}}[m]=\begin{cases}KN, k=l, m=0\\0,\quad k=l, m\neq 0\\0,\quad k\neq l, \text{all}\, m\end{cases}, \tag{6}$$

where $\phi_{c_i^{(k)},c_i^{(l)}}[m]=\sum_{n=0}^{N-1}c_i^{(k)}[n]c_i^{(l)}[n+m]$ is the autocorrelation function of $c_i^{(k)}[n]$ when $k=l$, or, the cross-correlation function of $c_i^{(k)}[n]$ and $c_i^{(l)}[n]$ when $k\neq l$. Using the same method described in previous section, K orthogonal complementary code spreading signals can be constructed as

$$s^{(k)}(t)=\sum_{i=0}^{K-1}\sum_{n=0}^{N-1}c_i^{(k)}[n]w_i(t-nT),\qquad \text{for } k=0,\ 1,\ \ldots,\ K-1, \tag{7}$$

and they will demonstrate the following property

$$\phi_{s^{(k)},s^{(l)}}(t)=\int_0^{NT}s^{(k)*}(\tau)s^{(l)}(\tau+t)d\tau=\begin{cases}0, \text{ for } t=-NT,\ldots,-T,T,\ldots,NT \text{ and } k=l\\0, \text{ for } t=-NT,\ldots,-T,0,T,\ldots,NT \text{ and } k\neq l\end{cases}, \tag{8}$$

where $\phi_{s^{(k)},s^{(l)}}(t)$ is the autocorrelation function of $s^{(k)}(t)$ when $k=l$, or, the cross-correlation function of $s^{(k)}(t)$ and $s^{(l)}(t)$ when $k\neq l$. Exploring this property, K different data streams with symbol duration T_s can be spread by the K orthogonal complementary code spreading signals respectively, transmitted through a common channel, and received without intersymbol interference and inter-data-stream interference, as shown in Fig. 2. We call this data transmission scheme as complementary-code-division multiplexing (CCDM). Accordingly, we refer to the sum of spread signals generated respectively by orthogonal complementary code spreading signals as the CCDM signal, which also demonstrates an asymptotic Gaussian distribution in its amplitude. Furthermore, assuming an ideal Nyquist pulse shaping, the power spectral density of the CCDM signal is shown to be white within its bandwidth. Therefore, a CCDM signal statistically resembles a band-limited white Gaussian noise, which is perfect for communication according to Shannon's theorem [1].

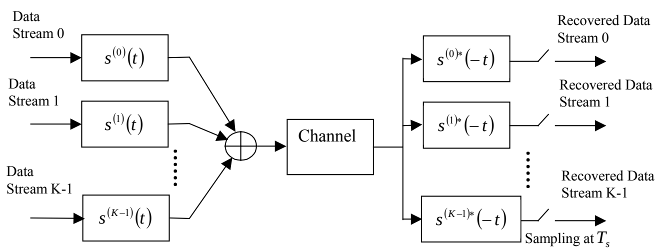

Fig. 2. Complementary-code-division-multiplexing.

CCDM enables high-speed data transmission since it can achieve the data rate of one symbol per chip when $T_s=T$. Assuming M-QAM date symbol, CCDM have the spectral efficiency (also referred to as normalized system capacity) $\log_2 M$ (bits per second per Hz). Using the M-QAM bit error probability formula [8] in AWGN channel, the normalized system capacity of CCDM as a function of the average signal-to-noise ratio (SNR) per symbol at different bit error rate P_e can be drawn in Fig. 3. Although the capacity of CCDM is definitely lower than Shannon capacity limit (also shown in Fig. 3), it is the highest a practical system could achieve.

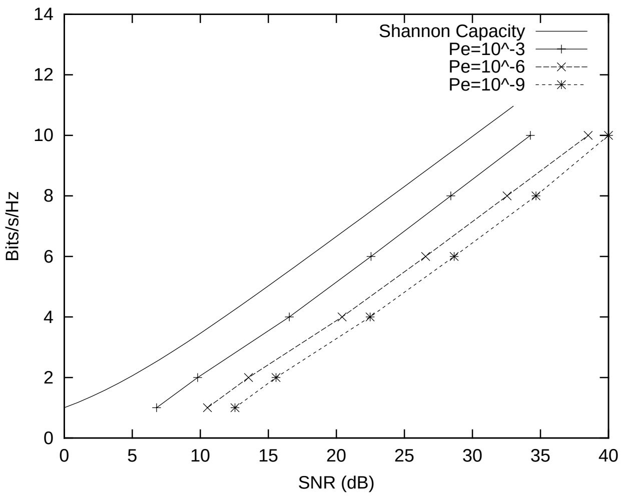

Fig. 3. Normalized system capacity of CCDM using M-QAM symbol.

IV. CCDM APPLICATIONS

CCDM is applicable for any spread spectrum system, whether a continuous wave narrowband or an impulse ultra-wideband system, a single carrier or a multicarrier system. This section only describes the possible CCDM applications to high speed WLAN and mobile communication systems.

For WLAN application, CCDM can replace the orthogonal frequency division multiplexing (OFDM) used in current high-speed WLANs such as IEEE 802.11a/g with higher data rate and lower complexity. Assuming the same chip rate of 20 Mega chips per second and the same 64-QAM symbol, i.e., one symbol represents 6 bits, the date rate of CCDM (uncoded) can be as high as 120 Mega bits per second (Mbps), whereas the data rate of OFDM is only 54 Mbps. Furthermore, the fast correlation of complementary codes [5,6,9,10] in CCDM will be simpler than fast Fourier transform (FFT) used in OFDM, since no multiplication will be involved.

For mobile communication application, CCDM can be easily extended into a complementary-code-division multiple access (CCDMA) system. In this system, each user is assigned a complementary code spreading signal from an orthogonal spreading signal set and communicates with a base station. The complementary code spreading signals (with cyclic prefixes inserted) constructed using frequency-division orthogonal waveform set will be particularly useful in this application, resulting in a multicarrier CCDMA system to mitigate multiple access interference (MAI) and solve the low system capacity problem encountered with conventional asynchronous code-division multiple access (CDMA) system [11]. Although this MAI mitigation technique is similar to that used in conventional mulaticarrier CDMA system [12], the multicarrier CCDMA system has the advantage of easily providing variable data rates to cope with different channel conditions.

V. CONCLUSIONS

It has been shown that a set of complementary codes can be used to construct different complementary code spreading signals in conjunction with different orthogonal waveform sets. A complementary code spreading signal can be used to generate spread spectrum signal with asymptotic Gaussian distribution and with variable spreading ratio. Making use of a set of orthogonal complementary code spreading signals, the CCDM data transmission scheme is formed, which is particularly suitable for future generation high-speed, variable rate WLAN and mobile communications.

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