Exploiting Data Correlation to Reduce the Power Variance for Forward-link CDMA Sequences

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This paper investigates the effect of interactions between the Walsh codes and data sequences on the statistical moments of the forward-link CDMA signal. Of primary interest is the normalized fourth-order moment, which is referred to as the "power variance". Several techniques for reducing the power variance of the CDMA signal are discussed that are based on Walsh code selection and data encoding. Results illustrate the effects of data correlation, and demonstrate the reduction in the power variance afforded by two novel approaches referred to as "channel hopping" and "data bit reversal".

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Abstract

This paper investigates the effect of interactions between the Walsh codes and data sequences on the statistical moments of the forward-link CDMA signal. Of primary interest is the normalized fourth-order moment, which is referred to as the "power variance". Several techniques for reducing the power variance of the CDMA signal are discussed that are based on Walsh code selection and data encoding. Results illustrate the effects of data correlation, and demonstrate the reduction in the power variance afforded by two novel approaches referred to as "channel hopping" and "data bit reversal".

IEEE keywords: multi-access communication, intermodulation distortion.

1.0 Introduction

CDMA, or Code Division Multiple Access, is a modulation format that uses spread spectrum to transmit multiple channels over a common bandwidth [16], [18]. It is generally accepted that a CDMA system is limited by the interference from other users [6], [7]. However, if the transmit portion of a base-station (referred to as the "forward-link") contains nonlinear components, such as power amplifiers, intermodulation distortion becomes an additional source of interference [4]. In general, it is the AM component of the input signal that is converted by nonlinearities into intermodulation distortion. Thus, methods of reducing the amplitude variations in the signal are of interest.

In this paper, we investigate how Walsh code selection and data encoding can be used within the CDMA modulation format to reduce the "power variance" of the input signal, prior to any nonlinear devices, while it is still in a digital form. The proposed methods exploit correlations between data sequences within specific groups of Walsh codes to minimize the power variance.

Walsh code selection has an additional effect when the CDMA signal is bandlimited; however, this topic is beyond the scope of this paper and is discussed in [2].

The remainder of the introduction describes the digital baseband portion of a forward-link CDMA signal, and introduces the power variance as a measure of the signal's sensitivity to non-linearities. An outline for the paper is found at the end of this section.

The generation of a forward-link CDMA signal is shown as a block diagram in Figure 1. For the purpose of analyzing the digital baseband portion of the forward-link, there are three key signals: Walsh-coded signal $x_{AM}(nT)$; sampled CDMA signal $x(nT)$; and output signal $z(nT)$. The Walsh-coded signal, $x_{AM}(nT)$, is a bipolar sequence which contains the amplitude information. It is QPSK modulated to form the sampled CDMA signal, $x(nT)$. The output signal, $z(nT)$, is a distorted version of the sampled CDMA signal after it has passed through a nonlinear device.
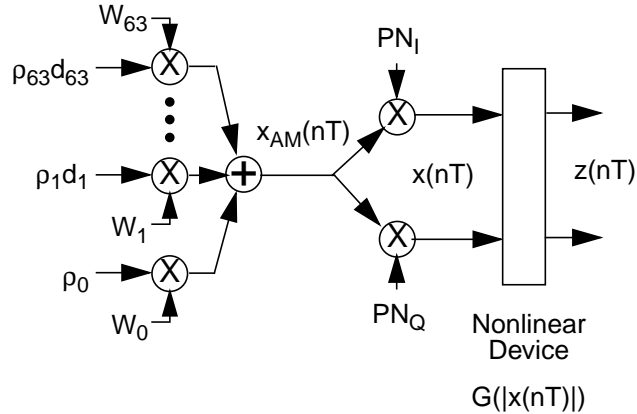

Fig. 1. Generation of a forward-link CDMA signal.

The equations for the baseband signals shown in Figure 1 are as follows. The Walsh-coded signal, $x_{AM}(nT)$, is

$$x_{AM}(nT) = \sum_{i=0}^{63} \rho_i d_i(nT) \cdot W_i(nT) \tag{1}$$

where T is the sample (chip) interval and $d_0 = 1$. Each data symbol, d_i, is held constant at +1 or -1 over an interval of 64T. Each Walsh code, W_i, comprises 64 chips that are repeated for each data symbol:

$$W_i = \left[W_i(0) \; W_i(T) \; ... \; W_i(63T) \right].$$ (2)

The scale term, ρ_i, is used to adjust the transmitted power of the individual channel associated with Walsh code W_i, and it is assumed to be constant over the data symbol interval [0,63T]. The relationship between the chip interval (T) and the symbol interval ([0,63T]) is shown in Figure 2.
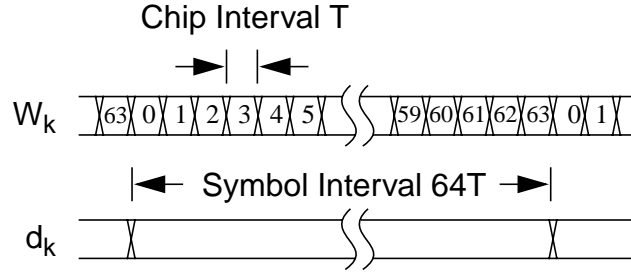

Fig. 2. Walsh code and data symbol timing and alignment.

The sampled CDMA signal is generated by QPSK modulation using two PN sequences [12], [13] (denoted by PN_I and PN_Q):

$$x(nT) = x_{AM}(nT) \cdot 2^{-0.5} \cdot [PN_I(nT) + j \cdot PN_Q(nT)]$$ (3)

The phase modulation has the effect of spreading the spectrum of the signal, as well as ensuring that each baseband sample is uncorrelated with it's neighbor (that is, E[x(nT) x(mT)] = 0 when n is not equal to m).

The output signal is described by

$$z(nT) = G(|x(nT)|) \cdot x(nT),$$ (4)

where G is the nonlinear gain of the device. It is assumed that G can be represented, adequately, by the following series:

$$G(|x(nT)|) = G_o \cdot \sum_i a_i \cdot |x(nT)|^i$$ (5)

where a_i are complex coefficients, $a_0 = 1$, and G_o is the nominal gain of the nonlinear device. Since the device model is defined in terms of the envelope of x(nT), any measure of the effect of

3

nonlinearities on the output signal must include statistics of the input signal. One such nonlinear measure, the power variance, is discussed below. An input signal with a reduced power variance has the desirable property of allowing the linearity requirements of output devices, such as amplifiers, to be relaxed.

A perfectly linear device has a constant gain, $G = G_o$. Thus, the variation in G is a good measure of the nonlinearity of the device for a given input signal format and power level. Using a model with a second-order gain variation (that is, $a_0 = 1$ and $|a_2| > 0$), we assign the following cost function:

$$J \; = \; E\left[\frac{\left|G\{|x(nT)|\} - G_o\right|^2}{\left|G_o\right|^2}\right] \; = \; 2 \cdot \left|a_2\right|^2 \cdot E[|x(nT)|^4] \tag{6}$$

where E[] denotes expected value. With respect to distortion in the output signal, this simple model captures third-order intermodulation products [15], and depends on the fourth-order moment of the input signal.

In this paper, we are interested in comparing the nonlinear sensitivity of various input signals created within the CDMA modulation format. Rather than use the fourth-order moment directly, it is useful to normalize the cost function to remove dependence on the average power:

$$\nu_e^{\;2} \; = \; \frac{E[|x(nT)|^4]}{\left\{E[|x(nT)|^2]\right\}^2} \cdot \tag{7}$$

The measure in (7), denoted by $\nu_e^{\;2}$, is the normalized power variance; however, for convenience, it will be referred to as the "power variance". The power variance can be viewed as a substitute for the peak-to-average power measure. The former measure has the advantage over the latter of being more repeatable.

An alternative measure of the sensitivity of modulation formats to nonlinearities can be found in [3], which is based on distortion power rather than gain error.

The remainder of the paper is as follows. In Section 2.0, the power variance of the sampled CDMA signal is defined in terms of data sequences and Walsh codes. Approaches for reducing the power variance of the sampled CDMA signal by using Walsh code selection and data encod-

ing are discussed in Section 3.0. Section 4.0 contains results of simulations verifying the statistical models derived in Section 2.0, as well as demonstrating the reduction in power variance provided by the approaches proposed in Section 3.0. Section 5.0 contains the concluding remarks.

2.0 Estimation of Power Variance for the Forward-Link CDMA Signal

This section defines two even-order moments, $E[|x(nT)|^2]$ and $E[|x(nT)|^4]$, of the forward-link CDMA signal in terms of Walsh codes and data sequences. These even-order moments, used to compute the power variance, contain intermodulation products of Walsh codes and data. Interesting characteristics of code domain intermodulation are discussed in Section 2.1. In particular, it is shown that the product of two or more Walsh codes is another Walsh code from the original 64 code set. In Section 2.2, the fourth-order moment is derived. It is shown that correlation between data sequences from specific Walsh code groups alters the fourth-order moment.

2.1 Walsh Code and Data Intermodulation

High-order Walsh code products arise when a CDMA signal passes through a nonlinearity. For example, the gain model in (5) comprises a weighted sum of nonlinear operators applied to the input signal, where the i-th order operator is $|x(nT)|^i$. Walsh code products also arise is the calculation of the second- and fourth-order moments used to compute the power variance (see Section 2.2).

Consider the response of a CDMA signal to a second-order operator. Noting that $|x(nT)|^2 = x_{AM}^2(nT)$, we have

$$x_{AM}^2(nT) = \sum_{i,j=0}^{63} \rho_i \rho_j \cdot d_i(nT) d_j(nT) \cdot W_i(nT) W_j(nT). \tag{8}$$

Equation (8) contains second-order intermodulation terms of the data sequences (d_i^2 and $d_i d_j$) and of the Walsh codes (W_i^2 and $W_i W_j$). These second-order intermodulation terms are discussed below.

Each of the 64 Walsh codes can be represented as the product of 6 (or less) Hadamard basis functions, which are shown in Figure 3 (see also Rademacher functions in [14]). A Walsh code W_i is defined as

$$W_i = B_1 \cdot B_2 \cdot B_4 \cdot B_8 \cdot B_{16} \cdot B_{32} \tag{9}$$

where

$$i = c_1 + 2c_2 + 4c_4 + 8c_8 + 16c_{16} + 32c_{32} \tag{10}$$

and

$$B_k = \begin{cases} W_k & \text{if the basis is active } (c_k = 1) \\ 1 & \text{if the basis is inactive } (c_k = 0) \end{cases}. \tag{11}$$

A Hadamard basis function B_k that is used in the definition of a Walsh code W_i is referred to as "active", and this active state is indicated by $c_k = 1$. An inactive state is indicated by $c_k = 0$. Two examples of Walsh codes decomposed into the product of Hadamard basis functions are $W_{14} = W_8 W_4 W_2$ and $W_{40} = W_{32} W_8$.
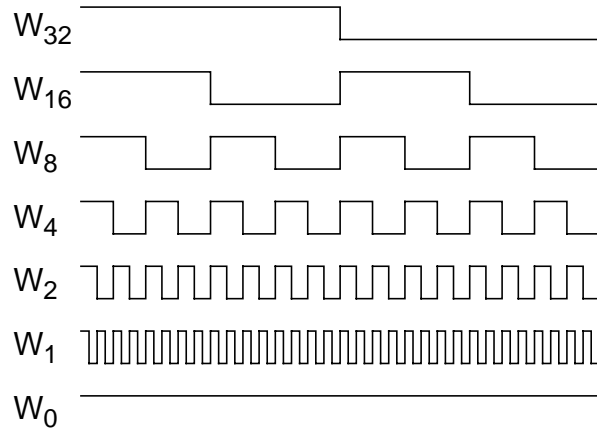

Fig. 3. Hadamard basis functions used to form Walsh codes.

The product of two Walsh codes, W_i and W_j, can be understood by noting an important property: $W_i W_i = W_0 = 1$. An application of this property is $W_{14} W_{40} = W_{32} W_4 W_2 = W_{38}$. If the indices 14 and 40 are rewritten in binary form (001110 and 101100), it can be seen that the result-

ant index 38 (100110) is obtained using an exclusive-or operation. In general, the product of two Walsh codes, W_i and W_j, produces a new Walsh code, which for convenience, is written as $W_i W_j = W_{i \oplus j}$. This Walsh code intermodulation can be extended to higher-order products using the exclusive-or of the corresponding set of Walsh codes: $W_i W_j ... W_z = W_{i \oplus j \oplus ... \oplus z}$. For example, the fourth-order product can be written as $W_i W_j W_k W_l = W_{i \oplus j \oplus k \oplus l}$.

The active basis functions for an intermodulation code $W_{i \oplus j}$ are determined by the basis functions active within W_i and W_j. Let the corresponding states of the basis function B_k for Walsh codes W_i and W_j be denoted by $c_k(i)$ and $c_k(j)$, respectively. If $c_k(i)$ and $c_k(j)$ are different (only one is active), the basis B_k of $W_{i \oplus j}$ will be active ($c_k(i \oplus j) = 1$); if both share the same state, the basis B_k of $W_{i \oplus j}$ will be inactive ($c_k(i \oplus j) = 0$). Thus, for the case of $W_{i \oplus j}$, (10) becomes

$$i \oplus j \ = \ [c_1(i) \oplus c_1(j)] + ... + 32 \cdot [c_{32}(i) \oplus c_{32}(j)] \tag{12}$$

where $\oplus$ is the exclusive-or operator.

Consider, now, the product of data sequences. Each data sequence is bipolar, containing values of 1 and -1. The square of a data sequence is unity: $d_i d_i = 1$. The product of two independent data sequences results in a third bipolar sequence: that is, $d_i d_j = d_m$ when i is not equal to j. As was the case with the Walsh codes, the intermodulation of data sequences can be extended to higher-order products, where the resultant data sequence, $d_i d_j ... d_z$, is denoted by $d_{ij...z}$.

The intermodulation properties of Walsh codes and data, mentioned above, are used in Section 2.2 to derive the second- and fourth-order moments of the sampled CDMA signal.

2.2 Second- and Fourth-order Moments

Consider a CDMA signal described by (3). The second-order moment, or the average power, of the sampled CDMA signal is

$$E[|x(nT)|^2] \ = \ \sum_{i, j = 0}^{63} \rho_i \rho_j \cdot E[d_{ij}(nT) \cdot W_{i \oplus j}(nT)] . \tag{13}$$

Since the data sequences are independent of the Walsh codes, we can simplify (13) by replacing $E[d_{ij} W_{i\oplus j}]$ with the product $E[d_{ij}] E[W_{i\oplus j}]$.

The expected value of Walsh code W_0 is unity; for all other Walsh codes W_i, it is zero. Thus, $E[W_{i\oplus j}]$ is unity when $i = j$, and zero otherwise. Similarly, $E[d_{ij}] = 1$, when $i = j$. However, $E[d_{ij}]$, when i is not equal to j, can have any value between -1 and 1, depending on the correlation between data sequences $d_i(nT)$ and $d_j(nT)$. Substituting the above-mentioned expectations in (13), the average power is

$$E[|x(nT)|^2] = \sigma^2 = \sum_{i=0}^{63} \rho_i^2 . \tag{14}$$

From (14), it is apparent that the average power is determined by the scale terms, ρ_i, and is not affected by data correlation.

The fourth-order moment of the sampled CDMA signal is

$$E[|x(nT)|^4] = \sum_{i,j,k,l=0}^{63} \rho_i \rho_j \rho_k \rho_l \cdot C_{ijkl}(n) \tag{15}$$

where

$$C_{ijkl}(n) = E[d_{ijkl}(nT)] \cdot E[W_{i \oplus j \oplus k \oplus l}(nT)] . \tag{16}$$

The values of $E[W_{i\oplus j\oplus k\oplus l}]$ and $E[d_{ijkl}]$ are unity when one of the following three conditions exist: $(i = j = k = l)$; $(i = j$ and $k = l)$; and $(i = l$ and $j = k)$. Thus, we can rewrite (15) as

$$E[|x(nT)|^4] = 3\sigma^4 - 2 \cdot \left[\sum_{i=0}^{63} \rho_i^4 \right] + Q_C(n) \tag{17}$$

where

$$Q_C(n) = \sum_{S(i,j,k,l)} \rho_i \rho_j \rho_k \rho_l \cdot C_{ijkl}(n) . \tag{18}$$

The notation $S(i, j, k, l)$ within (18) indicates that the summation includes all C_{ijkl} except for the following terms: $(i = j = k = l)$; $(i = j$ and $k = l)$; and $(i = l$ and $j = k)$.

For Q_c to be non-zero, the four selected Walsh codes within C_{ijkl} must combine such that $W_i W_j W_k W_l = W_0$. That is, $E[W_{i \oplus j \oplus k \oplus l}] = 1$ when $i \oplus j \oplus k \oplus l = 0$ and zero otherwise. Thus, (18) can be simplified:

$$Q_C(n) = \sum_{\substack{i \neq j \neq k \neq l \\ i \oplus j \oplus k \oplus l = 0}} \rho_i \rho_j \rho_k \rho_l \cdot E[d_{ijkl}(nT)]. \tag{19}$$

It is apparent that Q_c is affected by data correlation ($E[d_{ijkl}]$) and Walsh code selection ($\rho_i > 0$).

The four Walsh code groups where the product $W_i W_j W_k W_l = W_0$ are referred to as "quadruples". If, in addition, all four codes are active ($\rho_i \, \rho_j \, \rho_k \, \rho_l > 0$), then the four Walsh code group is referred to as an "active quadruple". It can be seen from (19) that the overall correlation (Q_c) is the weighted average of the all active quadruples, where the weighting factor is $\rho_i \, \rho_j \, \rho_k \, \rho_l$. Thus, when more than four Walsh codes are active, the effect of data correlation is determined by decomposing the signal into a set of active quadruples.

Since the goal is to reduce the power variance (and the fourth-order moment), Q_c should be made negative. This is achieved using data encoding and Walsh code selection, as described in Section 3.0.

In the following, references to "data correlation" should be interpreted as correlation between data symbols from different Walsh code channels, as opposed to a temporal correlation of a data sequence from a single Walsh code channel.

3.0 Reducing the Power Variance of a CDMA Signal

In this section, four approaches are proposed that exploit the data and Walsh code relationship to reduce the short-term power variance. Much of the initial discussion involves defining the transformation between the 64 data symbols in the code domain and the 64 samples in the time domain. Finally, "orthogonal variable short functions" (OVSF), proposed for use in "third generation" (3G) CDMA standards [5], [9], are discussed, and their effect on the power variance is investigated.

Let us look at the relationship between the sampled signal, $x_{AM}(nT)$, and the data ensembles. The sampled signal, $x_{AM}(nT)$, over the symbol interval [0,63T], is described by the following vector:

$$\bar{x}_{AM} = \left[x_{AM}(0) \ x_{AM}(T) \ ... \ x_{AM}(63T) \right]^T .$$ (20)

The vector describing the data ensemble within the corresponding interval is

$$\bar{d} = \left[(\rho_0) \ (\rho_1 d_1) \ ... \ (\rho_{63} d_{63}) \right]^T$$ (21)

where the channel scale terms ρ_i have been included. Note that the vectors $\bar{x}_{AM}$ and $\bar{d}$ are the time domain and code domain representations, respectively, of the information within the interval [0,63T]. The vectors $\bar{x}_{AM}$ and $\bar{d}$ are related through the Hadamard matrix, which is denoted by H_{64x64}:

$$\bar{x}_{AM} = H_{64x64} \cdot \bar{d} \quad \text{and} \quad \bar{d} = H_{64x64} \cdot \bar{x}_{AM}$$ (22)

where

$$H_{64x64} = \frac{1}{64} \cdot \left[W_0^T \ W_1^T \ ... \ W_{63}^T \right]^T .$$ (23)

The columns of H_{64x64} are the 64 chips of the individual Walsh codes; the rows are the indices of the 64 available Walsh codes (that is, column = time, row = code index). Note that H_{64x64} is symmetrical and orthonormal.

The "short-term power variance" is defined by (9), measured over the data symbol interval [0,63T]. The short-term power variance is highest (worst-case) when all of the signal energy is concentrated into a single peak. From (22), the amplitude at sample kT is

$$x_{AM}(kT) = \frac{W_k \cdot \bar{d}}{64} .$$ (24)

A peak occurs at kT when $\overline{d}$ is identical to (or the negative of) one of the Walsh code W_k; a null occurs at sample kT when $\overline{d}$ is orthogonal to the Walsh code W_k. Thus, when the data vector is the same as one of the Walsh code (for example, $\overline{d} = W_0{}^T$), one peak and 63 nulls appear over the symbol interval. This worst-case power variance is $v_e{}^2 = 64$, which is much larger than the base-line value defined by (17) when $Q_c = 0$ (that is, $v_e{}^2 < 3.0$). This worst case requires that all 64 Walsh code be active and have the same power (all ρ_i's are equal).

Let us consider a more practical case where only a subset of the channels are active. For an inactive channel, where $\rho_k = 0$, the sign of the data symbol d_k is not relevant, thereby making the symbol a "don't care" element within the data vector $\overline{d}$. A data vector $\overline{d}$ containing don't care elements has the potential of matching multiple Walsh codes, and from (24), producing multiple peak responses within the symbol interval [0,63T].

The short-term power variance can be expressed in terms of a weighted sum of active quadruples. If the quadruple is viewed in isolation (the other 60 channels are inactive), the sampled signal $|x_{AM}(nT)|$ has the following characteristics over the symbol interval [0, 63T]: 16 peak responses of equal magnitude and 48 null responses when the data correlation is positive ($d_i d_j d_k d_l > 0$); and 64 responses of equal magnitude when the correlation is negative ($d_i d_j d_k d_l < 0$). The former case is the largest short-term variance ($v_e{}^2 = 4$), whereas the latter case is the smallest ($v_e{}^2 = 1$). Having high weights ($\rho_i \rho_j \rho_k \rho_l$) associated with negative-correlated quadruples is desirable because it leads to a lower power variance.

In the following, four approaches for reducing the power variance are described; they are referred to as (1) "data bit reversal", (2) "reduced amplitude coding", (3) "channel hopping", and (4) "channel selection". The first three approaches can be viewed as types of data encoding where the short-term power variance is reduced altering the data vector such that positive-correlated quadruples are transformed into negative ones. The fourth approach is based on the selection of a Walsh code set that minimizes the number of active quadruples.

The first approach, "data bit reversal", involves identifying a symbol interval that has a large short-term power variance, then reversing the sign of one of the data symbols to reduce it. By changing the sign of d_i, for example, the correlation of each active quadruple containing d_i

changes sign. For a symbol interval with a large short-term variance, the majority of active qua-druples are positive. As a result, the sign reversal creates more negative quadruples, and hence, lowers the overall power variance. Introducing a sign error is less effective when the short-term power variance is modest. This is due to the fact that the sign reversal may actually increase the power variance by transforming more negative-correlated quadruples into positive ones than posi-tive into negative. Note that a data bit reversal creates a bit error, thereby increasing the bit error rate of the system. Although a CDMA system can tolerate modest amounts of data errors, the data bit reversals should be used sparingly. For an example of the potential improvement using the data bit reversal approach, see Table 5 in Section 4.0.

The second approach, "reduced amplitude coding", transmits encoding data on otherwise inac-tive channels to reduce the power variance. These new Walsh code channels, referred to as "encoding channels", form quadruples with the original active channels. In the limiting case, referred to as "constant amplitude coding [17]", the data on the encoding channels are selected such that all quadruples are negative, giving the sampled CDMA signal a constant amplitude. To achieve this, the numbers of encoding channels for various numbers of transmitted channels are as follows: one encoding channel is required for four transmitted channels (one encoding, three active); seven encoding channels are required for 16 transmitted channels; and 37 encoding chan-nels are required for 64 transmitted channels. There are also restrictions on the number of Walsh codes that are transmitted ($L = 4^n$ including both active and encoding channels), as well as which Walsh codes are grouped together.

In general, the drawback of the constant amplitude coding approach is that the use of encoding channels increases the average power transmitted. For the 16 transmitted channels example of [17], the average power increases by 16/9. It is noted in [17] that the additional power can be recovered if all channels are demodulated at the receiver and the encoding data is used for error detection and correction; however, the complexity of the system is increased.

"Reduced amplitude coding" is a generalization of [17] which is obtained by allowing the sam-pled CDMA signal to have modest amplitude variations. We use encoding channels to reduce the short-term power variance without embracing the limiting case of a constant amplitude. The data on the encoding channels are selected such that the newly formed quadruples are negative, on

average. Accepting a modest variation in amplitude in exchange for a reduced number of encoding channels is a good compromise for Walsh code sets with a large number of active channels.

In the previous two approaches, it is assumed that the scale term, ρ_i, is constant. However, it need only be constant over each symbol interval [0,63T]. By allowing inter-symbol power variations, many new possibilities exist. One such approach, believed to be novel, is "channel hopping", which is described in the following.

The third approach, "channel hopping", reduces the power variance by transmitting a data symbol over one of a group of assigned channels, typically two. It assumes that only a subset of the 64 Walsh code channels are in-use. Within the proposed approach, two Walsh codes, W_i and W_j, are assigned to a voice transmission. To perform channel hopping, the scale factors for the two Walsh codes are set as a pair: either $(\rho_i, \rho_j) = (0,1)$ or $(1,0)$ over the symbol interval [0,63T].

When multiple voice transmissions are setup for channel hopping, it is advantageous to consider all hopping alternatives together, selecting the set of Walsh codes that minimizes the short-term power variance for the current data vector. Since the best Walsh code set is dependent on the data vector, the channel assignment will, in general, change with each symbol interval [0,63T]. At the mobile receiver, both assigned channels for a given voice transmission are demodulated and the data symbol with the larger power is used. The increased complexity at the handset is modest because the two Walsh codes are synchronized to a common pilot, and the handset does not require knowledge of the hopping algorithm. For the basestation, the average transmitted power is not affected. Channel hopping is discussed further in Section 4.0 (see Table 4).

The fourth and final approach for reducing the power variance of the sampled CDMA signal is "channel selection". The Walsh code set is selected to minimize the number of active quadruples. One such set is presented in Section 4.0 (Set 3). In general, each of the six basis functions (B_i, see Section 2.1) must be active in at least one of the Walsh codes to minimize the number of active quadruples.

In summary, each of the four approaches for reducing the power variance of the sampled CDMA signal involve trade-offs. The "data bit reversal" approach has the advantage of being easily incorporated into the IS-95 system because there are no modifications to the mobile; however, improvements in the power variance introduce data bit errors. The "constant amplitude coding"

approach of [17] provides significant improvement in the power variance and can be implemented without modifying the mobile. However, there is an increase in the transmitted power due to the encoding channels, which results in reduced capacity of the CDMA network because of increased interference between cells [6]. The "channel hopping" approach improves the power variance without increasing the data error rate or transmitted power. It has the disadvantage that the mobile must demodulate two channels simultaneously. The "channel selection" approach is possible without modification of the IS-95 mobile or basestation; however, the improvement in the power variance is less pronounced than the other approaches.

Proposed third generation (3G) CDMA standards, such as cdma2000 [9] and WCDMA [5], include upgrades over the IS-95 version of CDMA. One change that affects the power variance of the signal is the use of "orthogonal variable short functions (OVSF) [5]". The OVSF approach uses Walsh codes of various lengths to transmit data. Short functions, whose lengths are $L = 2^n <$ 64 chips, are derived from code sets comprising fewer ($n < 6$) basis functions, and are suitable for data transmissions whose rate exceeds that of a single voice channel. In this paper, short functions, or "short Walsh codes", will be denoted by $W_{i(SF=L)}$, where i is the channel number and $L = 2^n$ is the length of the code (number of chips per data symbol), as well as the size of the code set.

The utility of short Walsh codes, such as $SF = 2^{6-n}$, is that higher data rates of 2^n are obtained. For example, $W_{1(SF=16)}$ is the short Walsh code 1 with a length of 16 chips. The time alignment of the short Walsh code (SF = 16) relative to the original Walsh codes (SF = 64) is shown in Figure 4. With respect to the original SF=64 code set, the SF=16 Walsh code channel transmits at four times data rate. Although short Walsh codes can accommodate a 2^n increase in the data rate, it is obtained by using 2^n channels from the original 64 Walsh code set. However, it is important to note that the use of a short Walsh code is not the same as the parallel transmission of multiple Walsh codes from the SF=64 set. The former has a lower power variance ($v_e^2 = 1$ compared to v_e^2 = 2.5 for the example shown in Figure 4). Thus, the OVSF approach allows the transmission of high data rates without incurring the high power variance associated with the parallel transmission of multiple IS-95 (SF=64) Walsh codes.
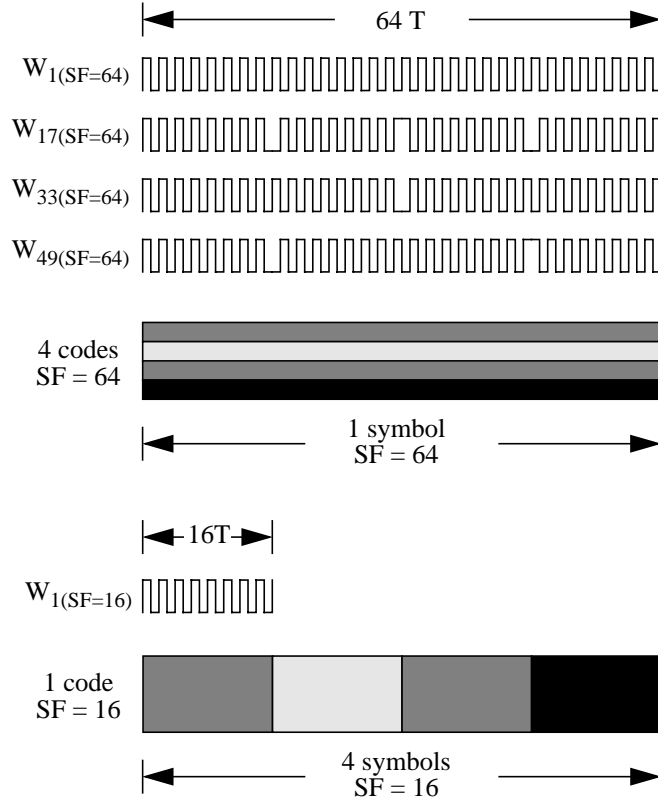
Fig. 4. Time alignment of short Walsh code $W_{1(SF=16)}$ and four data symbol intervals (SF = 16) relative to the four original Walsh codes, W_1, W_{17}, W_{33}, and W_{49}, and one data symbol interval (SF = 64).

Let us relate OVSF to the concept of active quadruples. Let the four data symbols associated with $W_{1(SF=16)}$ be denoted by $\bar{y} = [y(0)\ y(1)\ y(2)\ y(3)]^T$ where each SF=16 symbol spans 16 chips; let the four data symbols associated with $W_{i(SF=64)}$ be denoted by $\bar{d} = [d_1\ d_{17}\ d_{33}\ d_{49}]^T$. It can be shown that

$$\bar{d} = H_{4x4} \cdot \bar{y} \tag{25}$$

where

$$H_{4x4} = \frac{1}{4} \cdot \left[W_{0(SF=4)}^T \ \cdots \ W_{3(SF=4)}^T \right]^T . \tag{26}$$

For a negative-correlated quadruple, where $y(0)y(1)y(2)y(3) < 0$, all four SF=64 Walsh codes are transmitting at equal power ($\rho_1 = \rho_{17} = \rho_{33} = \rho_{49}$ and $d_1 d_{17} d_{33} d_{49} < 0$). However, when

$y(0)y(1)y(2)y(3) > 0$, the vector $\bar{y}$ matches one of the SF=4 Walsh codes in H_{4x4}, causing all of the power to be transmitted on one Walsh code channel. This latter form of transmission is the same as channel hopping. Thus, OVSF is a hybrid of parallel transmission and channel hopping where the choice of techniques is determined by the data correlation within the active quadruple (negative and positive correlation, respectively).

Shorter Walsh codes, used for higher data rates, provide further reductions in the power variance. However, the higher-rate OVSF approaches can still be decomposed, recursively, into a hybrid of parallel transmission and channel hopping.

4.0 Results

In this section, measurements from six Walsh code sets and four data vectors illustrate the variability of the short-term power variance in the presence of data correlation. It is shown that the spread in the power variance is proportional to the number of active quadruples within the Walsh code set. Examples are presented for the "channel hopping" and "data bit reversal" approaches, which show a desired reduction in the power variance.

For the examples shown in this section, the measured values of the power variance are obtained from computer simulations where the signals are over-sampled, by a factor of four compared to the chip rate, and lowpass filtered (bandlimited) using the IS-95 baseband filter [10]. The phase equalizing filter [10] specified in IS-95 is not included. The effects of bandlimiting on the power variance were not modeled in the previous sections, but are described in [2]. In general, when the basis function B_1 is present in at least one Walsh code, the variations in the power variance due to filtering will be much smaller than the variations due to data correlation.

The nine-channel forward-link CDMA signal is considered by many to be a "standard" test waveform [8]. It contains pilot, paging, sync, and six traffic channels. Within this paper, the pilot, paging, and sync channels are assigned relative scale factors (ρ_i/ρ_0) of 1.0, 0.9, and 0.45, respectively. The traffic channels each have a relative scale factor of 0.8.

Six Walsh code sets are presented in Table 1; each forming a nine-channel forward-link CDMA signal. Within each set, the pilot and sync channels are W_0 and W_{32}, respectively. The

paging channel is W_1 for all sets except for Set 1, where it is W_4. The remaining Walsh codes are traffic channels. Within Set 1 and Set 4, the paging and traffic channels are selected such that two Hadamard basis functions (see Section 2.1) are not used in any of the active Walsh codes (referred to as "missing" in [2]): B_1 and B_2 for Set 1; and B_8 and B_{16} for Set 4. These two sets have the maximum number of active quadruples. For Set 2 and Set 5, the traffic channels are selected as a block of six consecutive Walsh codes: W_{58} to W_{63} for Set 2; and W_8 to W_{13} for Set 5. Set 5 is the default nine-channel forward-link code assignment in [8]. For Set 3, the Walsh codes are selected to have zero active quadruples. Set 6 is a modification of Set 3, designed to introduce active quadruples into the code set. Sets 3 and 6 are used later in the "channel hopping" example where two of the traffic channels are allowed to hop in order to reduce the power variance (discussed later; see Table 3 and Table 4).

Table 1. Measured power variance and peak-to-average for various Walsh code sets and data vectors.

Active Walsh codes $\rho_i > 0$	Data vector $\overline{d} = [d_0 ... d_{63}]$	Peak to average	Measured Power Variance
Set 1:	all $d_i = 1$	14.3 dB	7.25
0, 4, 8,	$d_8 = -1$;	12.0 dB	3.11
16, 24, 32,	$d_8 = d_{16} = -1$;	10.5 dB	2.62
40, 48, 56	random	13.8 dB	3.21
Set 2:	all $d_i = 1$	10.5 dB	3.76
0, 1, 32,	$d_{59} = -1$;	9.1 dB	2.55
58, 59, 60,	$d_{59} = d_{60} = -1$;	8.5 dB	2.04
61, 62, 63	random	10.4 dB	2.46
Set 3:	all $d_i = 1$	10.7 dB	2.59
0, 1, 2,	$d_8 = -1$;	10.4 dB	2.72
4, 8, 15,	$d_8 = d_{15} = -1$;	11.0 dB	2.72
16, 32, 51	random	10.8 dB	2.56
Set 4:	all $d_i = 1$	9.8 dB	5.59
0, 1, 2,	$d_2 = -1$;	8.4 dB	2.51
3, 4, 5,	$d_2 = d_3 = -1$;	6.3 dB	1.81
6, 7, 32	random	9.8 dB	2.44

Table 1. Measured power variance and peak-to-average for various Walsh code sets and data vectors.

Active Walsh codes $\rho_i > 0$	Data vector $\overline{d} = [d_0 ... d_{63}]$	Peak to average	Measured Power Variance
Set 5:	all $d_i = 1$	10.5 dB	3.84
0, 1, 8,	$d_8 = -1$;	9.5 dB	2.62
9, 10, 11,	$d_8 = d_{13} = -1$;	8.7 dB	2.04
12, 13, 32	random	10.4 dB	2.49
Set 6:	all $d_i = 1$	11.6 dB	3.26
0, 1, 2,	$d_{13} = -1$;	10.7 dB	2.71
4, 8, 13,	$d_{13} = d_{18} = -1$;	9.1 dB	2.09
16, 18, 32	random	11.1 dB	2.60

Two measurements are made in Table 1: the peak-to-average and the power variance. Both measure the extent of the AM component of the CDMA signal; however, they are not equivalent. For a given code set, the peak-to-average increases with the power variance. However, between code sets, the two measures diverge. For example, the peak-to-average for Set 4 is much lower (for a given power variance) than measurements obtained from other sets. The main problem is that the peak is defined by a single measurement whereas the power variance is a statistical measure based on the entire waveform. As a result, the power variance is more repeatable measurement, and in the opinion of the author, easier to predict.

For each of the six Walsh code sets listed in Table 1, measurements are provided using four data vectors. Both constant and random data vectors are used to illustrate the effect of the data correlation, as well as the reduction in power variance provided by "data bit reversal" encoding (see Section 3.0). For the constant data vectors, $\overline{d}$ has a fixed value for the entire period of the PN sequence. Three constant data vectors are used: the worst-case data vector, $\overline{d} = W_0 = [1... 1]$; worst-case plus the reversal of one data bit; and the worst-case plus the reversal of two data bits. (Recall that the worst-case data vectors match the Walsh codes, such as $\overline{d} = W_0$). The random data vectors are formed as follows. For the case of nine active channels, the data vector has 256 distinct values (2^8 because only 8 of the data bits can change signs; the pilot data is constant, $d_0 = 1$). Since there are 512 symbol intervals within a PN sequence period, each value is used twice. The

time positions of the 512 data vectors over the PN sequence period are selected using a random permutation.

Let us compare the power variances for the constant data vectors listed in Table 1 to determine the effect of bit reversals. For Set 3, the power variance is not affected significantly by the choice of data vectors; however, this is an exceptional case. For the remaining sets, "reversals" of one or two bits within the worst-case data vector improves (reduces) the power variance. The reduction is most pronounced for Set 1 and Set 4, which have the most active quadruples. It is important to note that there is no advantage to reversing more than two bits for the case a nine-channel code set. For Set 1 and Set 4, reversing one, two, and three bits from the worst-case data vector causes seven, eight, and seven active quadruples, respectively, to become negative. Since negative quadruples reduce the power variance, reversing two of the nine bits within the worst-case data vector provides the best results. In general, there is no benefit to reversing more than 1/4 of the bits within the active code set.

The quadruples affected by a single bit reversal, for each set, are shown in Table 2. Set 1 and Set 4 each have 7 active quadruples that become negative due to the bit reversal. It is not surprising that the changes in the power variances are large: 4.14 and 3.08, respectively. Set 2 and Set 5 have 3 active quadruples that are affected by the bit reversal; the changes in the power variances are moderate, with values of 1.21 and 1.22, respectively. For Set 6, only one active quadruple is affected, and the resulting change in the power variance is only 0.65. No active quadruples are present within Set 3; as a result, the power variance is unaffected by data correlation across Walsh codes. However, there is still a minor variation in the power variance, -0.16, which is due to the effects of filtering (see [2]). Despite the minor variations, there is a good correspondence between the number of active quadruples affected by the data bit reversal and the spread of the measured power variance. Thus, the extent with which data correlation and Walsh code selection affect the power variance is predictable, and it is proportional to the number of active quadruples.

Table 2. Active quadruples affected by a one-bit reversal from worst-case data vector, $\overline{d} = [1...1]$.

Code Sets	Reversed data bit	Affected Active Quadruples	Change in Power Var. (1 bit rev.)
Set 1	d_8	$W_0 W_8 W_{16} W_{24}$	4.14
		$W_0 W_8 W_{32} W_{40}$	
		$W_0 W_8 W_{48} W_{56}$	
		$W_8 W_{16} W_{32} W_{56}$	
		$W_8 W_{16} W_{40} W_{48}$	
		$W_8 W_{24} W_{32} W_{48}$	
		$W_8 W_{24} W_{40} W_{56}$	
Set 2	d_{59}	$W_0 W_1 W_{58} W_{59}$	1.21
		$W_{58} W_{59} W_{60} W_{61}$	
		$W_{58} W_{59} W_{62} W_{63}$	
Set 3	d_8	none	-0.16
Set 4	d_2	$W_0 W_1 W_2 W_3$	3.08
		$W_0 W_2 W_4 W_6$	
		$W_0 W_2 W_5 W_7$	
		$W_1 W_2 W_4 W_7$	
		$W_1 W_2 W_5 W_6$	
		$W_2 W_3 W_4 W_5$	
		$W_2 W_3 W_6 W_7$	
Set 5	d_8	$W_0 W_1 W_8 W_9$	1.22
		$W_8 W_9 W_{10} W_{11}$	
		$W_8 W_9 W_{12} W_{13}$	
Set 6	d_{13}	$W_1 W_4 W_8 W_{13}$	0.65

In the remainder of this section, two approaches for reducing the power variance are demonstrated: "channel hopping" and "data bit reversal". Let us first look at the effect of channel hopping on the power variance. Channel hopping allows each data vector to be transmitted using a "favorable" code set. The first step is to choose a default Walsh code set, then assign a second channel (referred to as a hopping channel) to a subset of the traffic channels. When "n" of the traffic channels are allowed to hop, the potential channel assignments span 2^n code sets. The simplest

hopping criterion involves computing the active quadruples for each code set, then selecting the traffic/hop channels associated with the most negative quadruples (lowest short-term power variance).

An example of a channel assignment based on the channel hopping approach appears in Table 3. Set 3 is used as a default code set, ensuring that the "favorable" set is at least as good as the baseline power variance (where $Q_c = 0$). Traffic channels 5 and 6 are allowed to hop from their default Walsh codes of W_{15} and W_{51} to W_{13} and W_{18}, respectively. The criteria for traffic channels 5 and 6 to hop are $d_1 d_4 d_8 d_{15(13)} < 0$ and $d_0 d_2 d_{16} d_{51(18)} < 0$, respectively.

Table 3. Channel assignment for channel hopping example. Default assignment is the same as Set 3.

Channel Type	Default Channel	Hop Channel	Hop Criterion
Traffic 5	W_{15}	W_{13}	$d_1 d_4 d_8 d_{15(13)} < 0$
Traffic 6	W_{51}	W_{18}	$d_0 d_2 d_{16} d_{51(18)} < 0$
Fixed Channels: W_0, W_1, W_{32}, W_2, W_4, W_8, W_{16}			

The channel hopping algorithm selects one of four code sets depending on the signs of $d_1 d_4 d_8 d_{15(13)}$ and $d_0 d_2 d_{16} d_{51(18)}$. The default code set (Set 3) has no active quadruples. Forcing either traffic channel 5 or 6 to hop introduces one active quadruple; forcing both to hop introduces two. The hopping criteria are chosen so that each active quadruple is negative, which reduces the power variance. The results of applying the algorithm for the case of random data appear in Table 4. The hopping of two channels reduces the power variance by 10 percent from the baseline value of 2.56. Greater improvement can be expected by introducing more hopping channels to produce code sets with more active quadruples.

Table 4. Measured power variance and peak-to-average for the channel hopping example (see Table 3). A random data vector is used.

Walsh codes	Data	Peak to average	Power Variance
Fixed codes of Set 3	random	10.8 dB	2.56
Hopping codes of Table 3	random	10.5 dB	2.30

Table 5 shows the results of the data bit reversal approach, applied to the random data case, for Set 4. The one-bit reversal is applied to the 32 worst-case data vectors occurring within the 512 symbol intervals spanned by the PN sequence. The power variance is reduced by 12 percent.

Table 5. Data bit reversal encoding example using the Walsh codes in Set 4. A single bit reversal is applied to 32 of 512 data vectors spanned by the PN sequence.

Walsh codes	Data	Peak to average	Power Variance
Set 4 (no encoding)	random	9.8 dB	2.44
Set 4 with 32 single-bit reversals.	random + bit reversals	8.8 dB	2.25

Comparing the channel hopping and data bit reversal examples, we see that the reduction in power variance is similar. However, the peak-to-average is reduced for the latter case, and largely unaffected in the former. On the otherhand, the data bit reversal approach introduces 32 bit errors over the 512 symbol intervals. Assuming that these errors are distributed equally amongst the six traffic channels, the bit error rate for each channel would be 1.0 percent. The channel hopping is desirable in the sense that no data bit errors are introduced. However, to be effective, the channel hopping approach requires that a certain fraction of the mobile units in-use have the ability to detect and process two channels concurrently.

In both the channel hopping and data bit reversal examples, the resulting power variance is lower than any of the sets using random data within Table 1.

5.0 Conclusion

The power variance of a forward-link CDMA signal has been defined in terms of data sequences and Walsh codes. It is shown that Walsh code selection and data encoding can be used to produce active quadruples with negative correlations, which in turn results in lower power variances for sampled CDMA signal. The effectiveness of two data encoding methods, the data bit reversal encoding and channel hopping, have been demonstrated.

6.0 References

[1] R. A. Birgenheier, "Overview of code-domain power, timing, and phase measurements," *HP Journal*, pp. 73-93, Feb. 1996.

[2] R. N. Braithwaite, "Nonlinear amplification of CDMA waveforms: an analysis of power amplifier gain errors and spectral regrowth," in Proc. IEEE Veh. Tech. Conf., Ottawa, Canada, May 1998, pp. 2160-2166.

[3] J. K. Cavers, "The effect of data modulation format on intermodulation power in nonlinear amplifiers," in *Proc. IEEE Veh. Tech. Conf.*, Stockholm, Sweden, June 1994, pp. 489-492.

[4] S.-W. Chen. W. Panton, and R. Gilmore, "Effects of nonlinear distortion on CDMA communication systems," *IEEE Trans. Microwave Theory and Techniques,* vol. 44, no. 12, pt. 2, pp. 2743-2750, Dec. 1996.

[5] E. Dahlman, P. Beming, J. Knutsson, F. Ovesjo, M. Persson, and C. Roobol, "WCDMA---the radio interface for future mobile multimedia communications," IEEE Trans. Vehicular Technology, vol. 47, no. 4, pp. 1105-1118, Nov. 1998.

[6] A. O. Fapojuwo, "Radio capacity of direct sequence code division multiple access mobile radio systems," *IEE Proceedings-I*, vol. 140, no. 5, pp. 402-408, Oct. 1993.

[7] K. S. Gilhousen, I. Jacobs, R. Padovani, A. Viterbi, L. Weaver Jr., and C. Wheatley III, "On the capacity of a cellular CDMA system," *IEEE Trans. Vehicular Technology*, vol. 40, no. 2, 303-312, May 1991.

[8] "HP ESG-D series signal generators, dual arbitrary waveform generator and multi-channel CDMA personality," User's and Programming Guide, HP Part No. E4400-90148, March 1998.

[9] D. N. Knisely, S. Kumar, S. Laha, and S. Nanda, "Evolution of wireless data services: IS-95 to cdma2000," I*EEE Communications Magazine*, pp. 140-149, Oct. 1998.

[10] "Mobile station-base station compatibility standard for dual-mode wideband spread spectrum cellular system," TIA/EIA IS-95-A, Arlington VA, May 1995.

[11] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*. McGraw Hill, 1984.

[12] R. L. Pickholtz, L. B. Milstein, and D. L. Schilling, "Spread spectrum for mobile communications," *IEEE Trans. Vehicular Technology*, vol. 40, no. 2, pp. 313-321, May 1991.

[13] R. L. Pickholtz, D. L. Schilling, and L. B. Milstein, "Theory of spread-spectrum communications---A tutorial," *IEEE Trans. Communications*, vol. COM-30, no. 5, pp. 855-884, May 1982.

[14] M. Schetzen, *The Volterra and Wiener Theories of Nonlinear Systems.* Krieger Publishing, 1989.

[15] S. P. Stapleton, G. S. Kandola, and J. K. Cavers, "Simulation and analysis of an adaptive predistorter utilizing a complex spectral convolution," *IEEE Trans. Vehicular Technology*, vol. 41, no. 4, pp. 387-394, Nov. 1992.

[16] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communication*. Addison-Wesley, 1995.

[17] T. Wada, T. Yamazato, M. Katayama, and A. Ogawa, "A constant amplitude coding for orthogonal multi-code CDMA systems," *IEICE Trans. Fundamentals*, vol. E80-A, no. 12, pp. 2477-2484, Dec. 1997.

[18] D. P. Whipple, "North American cellular CDMA," *HP Journal*, vol. 44, no. 6, pp. 90-97, Dec. 1993.