M-ARY ORTHOGONAL MODULATION FOR MC-CDMA SYSTEMS IN INDOOR WIRELESS RADIO NETWORKS

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ABSTRACT

In this paper, we introduce the orthogonal M-ary Walsh modulation for *multicarrier code-division-multiple-access* (MC-CDMA) transmission. Analytical statements will be given for an AWGN channel and simulation results will be illustrated for a Rayleigh fading indoor channel assuming uplink transmission and coherent reception. Comparisons with antipodal modulation show that Walsh modulation performs better in terms of bit error rate and spectral efficiency.

1. INTRODUCTION

In mobile radio communication systems, much attention has been paid to CDMA. One well-known scheme is the so-called QUALCOMM system (IS-95) combining *direct sequence* CDMA (DS-CDMA) with M-ary orthogonal Walsh modulation. Results illustrated in [1] show the performance improvement of

Walsh modulation over classical modulation schemes such as BPSK.
Recently, MC-CDMA has been proposed combined with classical modulation [2, 3, 4, 5] and performances of different detection strategies have been analysed. It has been shown that MC-CDMA has a better spectral efficiency compared to DS-CDMA [6].
The aim of this paper is to introduce the M-ary Walsh modulation technique for MC-CDMA transmission. In particular, the performance of an AWGN channel will be evaluated analytically. Simulation results will be shown for the uplink bit error rate (BER) for coherent reception assuming a Rayleigh fading indoor radio channel. The results are also contrasted with BPSK performance.

2. TRANSMISSION SYSTEM

With CDMA systems in general, the *multiple access interference* (MAI) is mainly determined by the codes implemented. For MC-CDMA transmission over a downlink channel, where we have a synchronous situation, optimized codes like Walsh codes can be used. Since every user-specific codeword is affected by the same channel transfer function, the deterioration of the correlation properties can be restored by using suitable equalization schemes. For an uplink transmission scenario, which is considered in this paper, every user-specific codeword is affected by different channel transfer functions. This fact leads to an asynchronous situation involving the use of PN-sequences, which results in higher MAI . Furthermore, *maximum ratio combining* (MRC) detection strategy is applied, being proper to reduce the interferences caused by the frequency selective fading of the channel [7]. Ideal channel estimation is assumed and no channel coding is involved.
In contrast with single-carrier transmission, a MC-CDMA scheme yields a frequency resolution by dividing the available bandwidth into a finite number of subbands. The idea behind the application of M-ary Walsh modulation is to further increase this resolution in order to distinguish transmitted symbols without raising the required bandwidth. Therefore, instead of spreading one data symbol over a number of subcarriers, spreading can be achieved in two successive steps. By applying Walsh modulation, we further use orthogonality, which renders good performance in general. Such a MC-CDMA transmitter (mobile station) involving Walsh modulation is illustrated in fig. 1. For simplicity, one of J active users is taken into account (subscripts are omitted). The data bits, $b \in \{0, 1\}$ each of duration T_b, are serial/parallel converted to groups of $\log_2(M)$ data bits each. The Walsh modulation maps the $\log_2(M)$ data bits to one corresponding Walsh symbol (vector) $\boldsymbol{w}^m = [w_0^m, w_1^m, \ldots, w_{M-1}^m]^T$, $m \in \{0, M-1\}$ including M Walsh chips $w_\mu^m \in \{-1, 1\}$, $\mu = 0 \ldots M-1$. Each of the M parallel Walsh chips has a duration of $T = \log_2(M)\, T_b$. This modulation can also be interpreted as frequency spreading of value $M/\log_2(M)$. The set of M orthogonal Walsh symbols represents an orthogonal basis which can

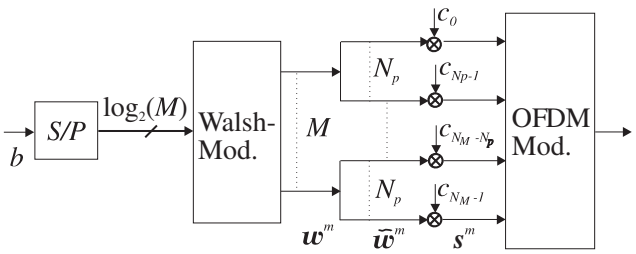

Figure 1: MC-CDMA transmitter with M-ary Walsh modulation

be evaluated recursively by applying

$$\boldsymbol{W}_{2M} = \begin{pmatrix} \boldsymbol{W}_M & \boldsymbol{W}_M \\ \boldsymbol{W}_M & -\boldsymbol{W}_M \end{pmatrix}, \quad \boldsymbol{W}_1 = (1)\,, \tag{1}$$

where $\boldsymbol{W}_M$ is the $M \times M$ *Hadamard-Matrix*. The Euclidian distance is identical for all possible pairs of symbols and equals

$$\varepsilon = \sum_{\mu=0}^{M-1} |w_\mu^m - w_\mu^n|^2 = 2M \quad \forall \quad m \neq n. \tag{2}$$

To finally get the transmitted symbols, the Walsh chips are replicated into N_p parallel copies where each branch of the parallel stream is multiplied with one chip of the user specific code $c_i \in \{\pm 1/\sqrt{N_M}\}$, $i = 0 \ldots N_M - 1$. Since each bandwidth of the M parallel subchannels decreases for larger values of M, the number of subcarriers N_M increases for the same available bandwidth B. The number of subcarriers is determined by $N_M = N_2 \cdot \log_2(M) = M \cdot N_p$, where N_2 is the number of subcarriers used for 2-ary Walsh modulation or BPSK, respectively. For the j^{th} user, this yields the transmission vector $\boldsymbol{s}^{m,j}$ before the OFDM modulation

$$\boldsymbol{s}^{m,j} = [s_0^{m,j} \ldots s_{N-1}^{m,j}]^T, \quad s_i^{m,j} = \tilde{w}_i^{m,j} \cdot c_i^j \tag{3}$$

with $\tilde{w}_i^{m,j} = w_\mu^{m,j}$, $\forall\ \mu = \lfloor i/N_p \rfloor$, m, j. OFDM modulation includes the IFFT (IDFT) and inserts the guard interval between adjacent OFDM symbols. To prevent *intersymbol interference* (ISI) and *adjacent channel interference* (ACI), the guard time T_g is chosen such that $T_g \geq \tau_{max}$, where τ_{max} is the maximum delay spread of the channel. Since the channel is regarded slowly time selective, $T \ll 1/f_{d,max}$ holds and $f_{d,max}$ indicates the maximum Doppler frequency. Due to the insertion of the guard interval, every subcarrier is affected by the corresponding channel transfer coefficient. For the uplink transmission scenario assumed here, the i^{th} coefficient for every user j is given by $h_i^j = \rho_i^j \cdot \exp(\phi_i^j)$, where ρ_i^j and ϕ_i^j are the random amplitude and phase. Hence, the channel can be described for every user by an $N_M \times N_M$ diagonal matrix $\boldsymbol{H}^j$.

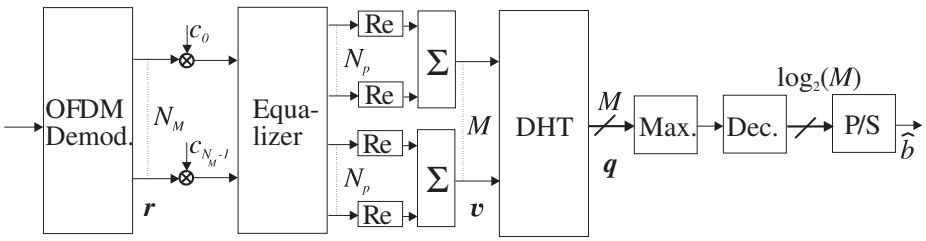

Figure 2: Coherent MC-CDMA receiver for M-ary Walsh modulation

The coherent MC-CDMA receiver for M-ary Walsh modulation is presented in fig. 2. Paying attention to J active users, the received signal after OFDM demodulation can be written as a sum of vectors $\boldsymbol{r}^{m,j}$

$$\boldsymbol{r} = \sum_{j=0}^{J-1} \boldsymbol{r}^{m,j} + \boldsymbol{n} = \sum_{j=0}^{J-1} \boldsymbol{H}^j \boldsymbol{s}^{m,j} + \boldsymbol{n} \tag{4}$$

with elements $r_i^{m,j} = h_i^j \cdot s_i^{m,j}$, $i = 0 \ldots N_M - 1, m \in \{0, M-1\}$. The vector $\boldsymbol{n}$ represents AWGN. After multiplication with the user specific code and equalization, the first part of despreading is obtained by subcorrelating N_p subcarriers. Reception for the user $j = 0$ is assumed (subscripts are omitted). The components of $\boldsymbol{v}$ are given by

$$v_\mu = \sum_{i=\mu N_p}^{(\mu+1)N_p-1} \mathrm{Re}\left\{ c_i e_i r_i^{m,0} + \sum_{j=1}^{J-1} c_i e_i r_i^{m,j} + c_i e_i n_i \right\}, \quad \mu, m \in \{0, M-1\} \tag{5}$$

where e_i indicates the equalization coefficient of the i^{th} subcarrier. Since MRC is considered $e_i = h_i^*$. To obtain *maximum likelihood detection* (MLD), the signal is correlated with all possible Walsh symbols $\boldsymbol{w}^m, m \in \{0, M-1\}$. The MLD can be realized by the *Discrete Hadamard Transform* (DHT) [1], using the Hadamard matrix eq.(1) according to

$$\boldsymbol{q} = \boldsymbol{W}_M \cdot \boldsymbol{v}. \tag{6}$$

Vector $\boldsymbol{q}$ includes M decision variables where the choice of the maximum value results in a symbol decision. Decoding of the decided symbol to $\log_2(M)$ data bits and parallel/serial conversion leads finally to the estimated data stream with bits $\hat{b}$.

3. AWGN CHANNEL

For a large number of users, the users can be considered as real Gaussian noise. In the case of random codes, the interference power equals $\beta_{int} E_b \approx (J-1)/N_M \, E_b$, where E_b is the data bit energy[1]. Assuming coherent reception,

[1] $E_b = 0.5A^2 T_b = 0.5T_b$ where A indicates the amplitude of the symbol.

the bit error probability P_b of M-ary Walsh modulation is given by [1]

$$P_b = A_M \int_{-\infty}^{\infty} [1 - [1 - \frac{1}{2}\mathrm{erfc}(x)]^{M-1}] \exp\left[-\left(x - \sqrt{\log_2(M)\,\gamma}\right)^2\right] dx \tag{7}$$

with

$$A_M = \frac{M/2}{\sqrt{\pi}(M-1)}, \quad \gamma = S/N \cdot \frac{1}{1 + 2\beta_{int} S/N \log_2(M)}. \tag{8}$$

S/N is the signal-to-noise ratio used for MLD. The guard interval involves mismatching $S/N = E_b/N_0(1 - T_g/T)$, where $N_0/2$ is the Gaussian noise spectral density [1]. Here, for BPSK the guard time is set to be $T_g/T = 0.2$ leading to

$$T_g/T = 1/(4\log_2(M) + 1) \tag{9}$$

in general. It can be seen, that the loss of signal-to-noise ratio will be reduced for higher values M, e.g. $T_g/T = 1/21$ for $M = 32$.

For BPSK modulation, P_b is given by the well-known formula [6]

$$P_b = 0.5 \cdot \mathrm{erfc}\left(\sqrt{\gamma}\right). \tag{10}$$

Fig. 3 presents the analytical results of the error probabilities as a function of E_b/N_0. Different values M are considered for the Walsh modulation. The number of active users equals $J = 8$. In the case of BPSK and 2-ary Walsh modulation $N_2 = 64$ subcarriers are assumed. For the Walsh modulation it can

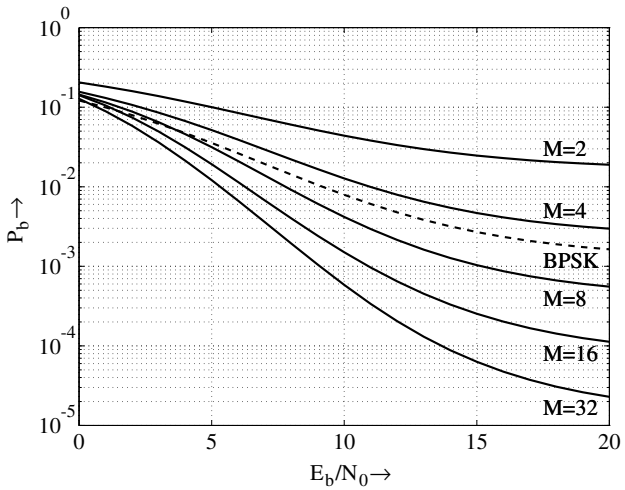

Figure 3: P_b versus E_b/N_0 for $J = 8$ active users and $N_2 = 64$ subcarriers

be seen that P_b decreases for larger values of M, which can be explained by the increasing Euclidian distance, see eq.(2). Since more subcarriers are used ($N_M = 64 \cdot \log_2(M)$), the MAI is also reduced. Walsh modulation outperforms BPSK for values $M \geq 8$ and $E_b/N_0 > 4$ dB. Modulation by $M = 32$ yields an error floor of $P_{b\infty} \approx 1.3 \cdot 10^{-5}$ instead of $P_{b\infty} \approx 1.2 \cdot 10^{-3}$ for BPSK.

4. INDOOR RAYLEIGH FADING CHANNEL

4.1. SYSTEM DESCRIPTION

The following results are given for an indoor Rayleigh fading channel. Assuming an exponential delay profile with a RMS delay of $\tau_{RMS} = 150\,\text{ns}$ and neglecting echos less than 10% of the maximum power yields a maximum delay spread of $\tau_{max} \approx 350\,\text{ns}$. The bandwidth is chosen to be $B = 25\,\text{MHz}$ in the 5.2 GHz range. A velocity of $v_0 = 0.5\,\text{m/s}$ results in a very low maximum Doppler frequency $f_{d,max}$ of about 9 Hz. Hence, long symbol durations T are possible. Assuming a constant guard time T_g, higher values of M therefore lead to less mismatching and better spectral efficiency. For example, if for BPSK $N_2 = 64$ subcarriers and $T_g/T = 0.2$ are considered ($T_g = 640\,\text{ns} > \tau_{max}$), mismatching will be reduced from 1 dB to 0.2 dB and the bit rate will be increased from 312 kbit/s to 372 kbit/s by raising M from 2 to 32.

4.2. SIMULATION RESULTS

Fig. 4 presents a performance comparison of BPSK and Walsh modulation. Assuming $J = 8$ active users and $N_2 = 64$ subcarriers, the bit error probability of Walsh modulation is shown for different values M. It can be seen that

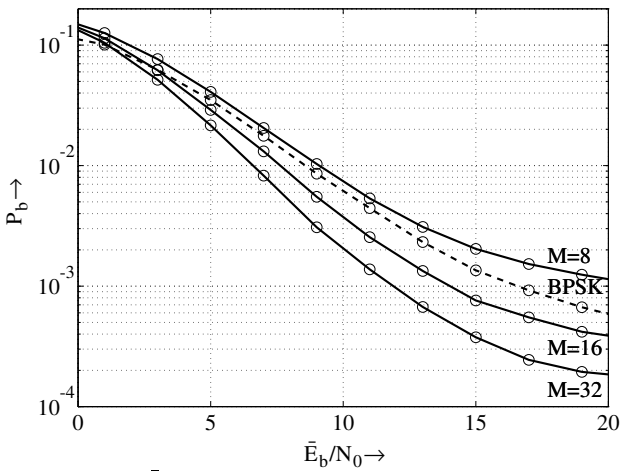

Figure 4: P_b versus $\bar{E}_b/N_0$ for $J = 8$ active users and $N_2 = 64$ subcarriers

Walsh modulation performs better than BPSK for $M \geq 16$ and an average $\bar{E}_b/N_0 > 4\,\text{dB}$. For the same number of active users, a bit error probability of $P_b = 10^{-3}$ is given for an 32-ary Walsh modulation $\bar{E}_b/N_0 = 12\,\text{dB}$ in contrast to a ratio of $\bar{E}_b/N_0 = 16.4\,\text{dB}$ for BPSK. Simulation of the error floors results in an approximately three times lower one for 32-ary Walsh modulation ($P_{b\infty} \approx 1.3 \cdot 10^{-4}$ for Walsh and $P_{b\infty} \approx 3.8 \cdot 10^{-4}$ for BPSK).

A comparison with the AWGN channel in fig. 3 illustrates a loss of the Walsh modulation performance. In the case of AWGN conditions, the Walsh modulation already performs better for $M \geq 8$. This effect can be explained by the deterioration of the orthogonality of the Walsh symbols. Since MRC is used for equalization, the orthogonality is not exactly restored which causes (self-)interference by all possible symbols applying the MLD.
To analyse the influence of the number of subcarriers, Tab. 1 presents the error probability for $N_2 = 64, 128$ subcarriers assuming $\bar{E}_b/N_0 = 12\,\text{dB}$. For

N_2	Walsh $M = 32$	BPSK
64	$P_b = 1.0 \cdot 10^{-3}$	$P_b = 3.1 \cdot 10^{-3}$
128	$P_b = 6.8 \cdot 10^{-5}$	$P_b = 8.0 \cdot 10^{-4}$

Table 1: P_b for $N_2 = 64, 128$ subcarriers with $\bar{E}_b/N_0 = 12$ dB and $J = 8$ active users

$N_2 = 64$, the 32-ary Walsh modulation performance is approximately three times and for $N_2 = 128$ it is even twelve times better. Hence, due to the fact of less MAI and less mismatching the improvement of M-ary Walsh modulation grows significantly. If we focus on the user interference of both schemes,

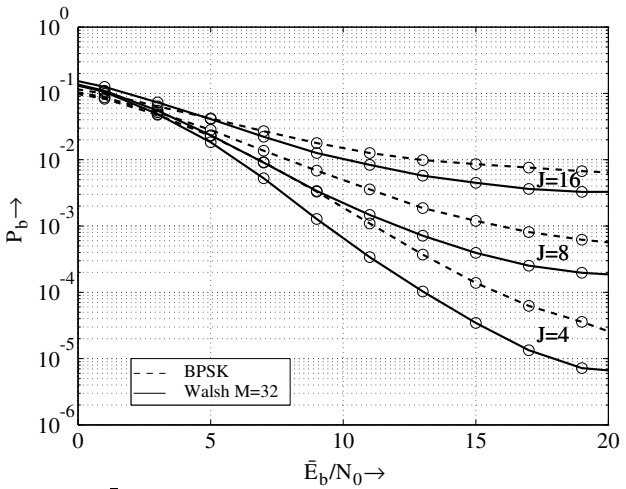

Figure 5: P_b versus $\bar{E}_b/N_0$ for $N_2 = 64$ subcarriers and different numbers of users

the results presented in fig. 5 show the tremendous MAI, which was expected for uplink conditions. Independent of the number of active users, the Walsh modulation performs better than BPSK.

5. CONCLUSION

In this paper, we introduced an M-ary orthogonal Walsh modulation concept for coherent reception under uplink conditions. In this case, we have an asynchronous reception and PN-sequences were applied. Performance evaluation has been presented for an AWGN channel. The results indicate that M-ary Walsh modulation significantly outperforms BPSK. Applying this modulation technique to an indoor Rayleigh fading channel further enhances the better performance. The concept of better using the available bandwidth by increasing the frequency resolution, combined with the advantages of raising Euclidian distance for larger values M, appears to be an interesting modulation scheme for mobile communication systems. Since the overall symbol duration grows for larger values M, which can be accepted for channels with low maximum Doppler frequency, mismatching is reduced and the spectral efficiency is increased. The results also indicate the MAI for traditional equalization such as MRC, which has been expected for uplink conditions. Therefore, uplink transmission with coherent detection requires new equalization schemes, e.g. multi-user detection. In addition, analyses have to be done for noncoherent transmission over uplink channels especially for indoor communication.

6. REFERENCES

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