A HYBRID TDMA/CDMA MOBILE CELLULAR SYSTEM USING COMPLEMENTARY CODE SETS AS MULTIPLE ACCESS CODES

Pentti A. Leppänen and Pekka O. Pirinen
University of Oulu
Telecommunication Laboratory
P.O.Box 444, 90571 Oulu, Finland

Abstract - In this paper a method combining TDMA and CDMA in a digital cellular system is presented. This method makes use of complementary code sets. These codes have been selected due to their ideal autocorrelation and non-interacting characteristics. With these code sets orthogonality between users can be maintained even in the fading multipath channel which is valuable property that cannot be provided with conventional multiple access codes. Bit error rate simulations have been made to test the link level performance of the system. Both AWGN and Rayleigh fading channels have been employed. Simulation results confirmed that complementary code sets are well adapted for use as multiple access codes in a mobile radio environment. Link level simulations pointed out that by using complementary code sets the number of non-interacting users in Rayleigh fading channel on a single carrier can be increased. One clear advantage compared to the traditional CDMA systems is that power control is not necessary within a cell. Neither time synchronization requirements are so strict as usually. Erlang radio capacity was studied. The results indicated that approximately twofold improvement over TDMA is possible with hybrid techniques.

1. INTRODUCTION

Many different multiple access schemes can be used for transmitting information in radio channel. FDMA and TDMA are well known and widely employed schemes. The success and development of spread spectrum techniques have made CDMA increasingly attempting choice for several applications. One of the best features of CDMA in digital cellular mobile systems is its spectrum efficiency. Many studies (e.g. [1, 2]) and simulations have shown that the capacity of CDMA system can be much larger than in analog FDMA systems and significantly larger than in digital TDMA systems at least when low bit rate circuit-switched services are considered. The main advantages of CDMA are inherent frequency diversity and universal frequency reuse.

Spectrum scarcity is reality in cellular networks. The amount of users, however, expands constantly. Therefore it is important to use the available spectrum effectively. One choice in increasing the total capacity of the network is to add CDMA characteristics in the operational TDMA systems (e.g. GSM). Thus the capacity of a pure CDMA system (like Qualcomm’s IS-95) might be reached [3].

2. SYSTEM DESCRIPTION

2.1 Complementary code sets

Complementary code sets have some ideal properties for usage in CDMA multiple access codes. Firstly, the sum of the aperiodic autocorrelation functions of the code members in a code set is impulse-like (pulse compression property) [4]. Secondly, code sets for different CDMA users can be chosen so that the sum of the aperiodic cross-correlation functions between any CDMA user’s codes in the same time slot is zero at all delay values (non-interacting property). The latter property means that orthogonality between CDMA users can be maintained also in the asynchronous uplink. With conventional multiple access codes all code families introduce cross-correlation products in the case of many active users. Complementary code sets can be generated recursively from the Hadamard-matrices by the Kronecker product [5, 6]

$$H_m = H_2 \otimes H_{m/2},$$  \hspace{1cm} (1)

where $H_m$ is the generated matrix, $H_2$ is the $(2 \times 2)$ core Hadamard-matrix and $H_{m/2}$ is the matrix to be extended.

Hadamard-matrix $H_M$ $(M \times M)$ can be calculated recursively from equation

$$H_m = \begin{bmatrix} H_{m/2} & H_{m/2} \\ H_{m/2} & H_{m/2} \end{bmatrix},$$  \hspace{1cm} (2)

where $H_1$ is $+\$ waveform, $H_{m/2}$ is the complement of $H_{m/2}$ and $m = 2^k$, $k = 1, 2, ..., \log_2 M$.

In this paper $H_4$-matrices are used for code generation. They can be generated from two $2 \times 2$-matrices as

$$\begin{bmatrix} ++ \\ +- \end{bmatrix} \otimes \begin{bmatrix} ++ \\ +- \end{bmatrix} = \begin{bmatrix} +++++ \\ +---+ \\ -++-+ \\ +--+- \end{bmatrix} \Rightarrow H_2 \otimes H_2 = H_4.$$  \hspace{1cm} (3)

The columns (or equivalently the rows) of the $H_4$-matrix are the used spreading code members.
2.2 The principle of combining TDMA and CDMA

By using complementary code sets mutually non-interacting CDMA users can be added to a TDMA system. Fig. 1 shows the principle of the method [3].

![Diagram showing the combination of TDMA and CDMA](image)

**Fig. 1.** Combination of TDMA and CDMA.

All users in the communication system \((LK)\) are multiplexed to \(L\) TDMA users and \(K\) CDMA users. During the period \(T_K\) (to be formed from the information of \(L\) users) \(n\) data bits or symbols of each user are transmitted in their time slots \((T_{TDM})\). During each time slot \((T_{TDM})\) data from \(K\) other users are transmitted by the CDMA method using complementary code sets for spreading the spectrum.

**Fig. 2** shows the signal structure of one CDMA user’s time slot [3].

![Diagram showing a single CDMA time slot](image)

**Fig. 2.** One time slot with single CDMA user.

Complementary code set includes \(K\) member codes \(S_1, S_2, ..., S_K\) and the length of each of them is \(N\) chips. The spreading code of CDMA user \(\# 1\) comprises the members \(S_1, S_2, S_3, ..., S_K\), where \(S_k (k = 1, 2, ..., K)\) is one of the members \(S_1, S_2, ..., S_K\) determined by the complementary characteristics. In Fig. 3 one transmission burst contains \(n\) data symbols. In the beginning of the burst data symbols \(b_0, b_1, ..., b_n\) are spread by the code member \(S_1\). The length of this spreading modulated burst is \(nNT_C\) seconds. The burst is followed by a transmission pause. The pause lasts \(T_M + T_R + T_p\) seconds. It is used to prevent the blending of signals spread by the successive code members, due to the multipath propagation and timing inaccuracies. After the transmission pause the same data symbols are retransmitted but now spread by the code member \(S_2\). A guard period in transmission follows again. This sequence is repeated until each data symbol has been spreading modulated by all of the code members \(S_k\) in a user specific code set. The sum of the times \(nNT_C\) and \(T_M + T_R + T_p\) is indicated by \(T_{max}\) and it can be utilized in the receiver to change the matched filter when the spreading code member is changed in transmission.

The idea shown in Fig. 2 can be extended to a complete four CDMA users structure [3]. There CDMA users \(\# 1, \# 2, \# 3, \# 4\) can transmit in the same TDMA slot / to the base station (uplink). It is possible to use the same complementary code set for different CDMA users. Only the order of code members in the spreading code set is changed for each user enabling mutual non-interacting between users. In this case full orthogonality of the users is achieved by using the following complete complementary code set:

- \(# 1\): \(S_1 = ++++, S_2 = +++++, S_3 = +++, S_4 = +++++\)
- \(# 2\): \(S_1 = +++, S_2 = +++++, S_3 = +++, S_4 = +++++\)
- \(# 3\): \(S_1 = +++, S_2 = +++, S_3 = +++++, S_4 = +++++\)
- \(# 4\): \(S_1 = +++, S_2 = +++++, S_3 = +++, S_4 = ++++\)

The communication link is time synchronized, i.e. all users shall know the real time with a certain uncertainty as presupposed by the TDMA method. Because of ideal cross-correlation properties there is no need for exact time synchronization within a time slot.

- The processing gain \(KN\) created in the receiver when \(K\) matched filtering results are combined is used to combat co-channel and adjacent channel interferences from neighboring cells and other disturbances, especially narrow-band interferences or jamming. Notation TDMA/CDMA is used to identify this hybrid concept.

2.3 Convolutional spreading principle

Main drawback of using complementary code sets is that spectrum spreading is larger than the increase in the number of users. One solution to alleviate this problem and thus enhance spectral efficiency is to use convolution operation instead of multiplication in spreading. It is possible due to the ideal auto-correlation properties of the complementary code sets. This means that received signals can be separated chip by chip. In the case of four codes in the set this means the reduction in chip rate and bandwidth by four. Convolution results amplitude variation in the time domain which means tighter requirements for amplifier linearity. From now on this concept with convolutional spreading coding will be denoted as TDMA/CS-CDMA.

3. LINK LEVEL SIMULATION

3.1 Simulation parameters

The operation of the basic concept was tested with simple link level simulations. Data was generated as a very long pseudo-noise sequence. Antipodal binary phase-shift keying was used both for data and spreading modulation. Ideal chip synchronization was assumed. Some other system and simulation parameters are gathered in Table 1.
Table 1. System/simulation parameters ($K = 4$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{slot}}$ (possible length of time slot)</td>
<td>577 $\mu$s</td>
</tr>
<tr>
<td>$n$ (bits/burst)</td>
<td>148 (GSM normal burst without guard time)</td>
</tr>
<tr>
<td>$N$ (length of each code member)</td>
<td>4</td>
</tr>
<tr>
<td>$f_C$ (chip rate/sampling rate)</td>
<td>4.33 Msamples/s (= 16-270.83 kbps)</td>
</tr>
<tr>
<td>$T_C$ (chip period)</td>
<td>231 ns</td>
</tr>
<tr>
<td>$T_M + T_R + T_P$ (transmission pause)</td>
<td>33 chips (= 4.3 $\mu$s)</td>
</tr>
<tr>
<td>$f_0$ (carrier frequency)</td>
<td>900 MHz</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Ideal</td>
</tr>
<tr>
<td>$KN$ (processing gain)</td>
<td>$16 \approx 12$ dB</td>
</tr>
</tbody>
</table>

3.2 Simulation results

Fig. 3. Simulated uncoded BER in AWGN channel.

Fig. 4. Simulated uncoded BER in Rayleigh one-ray channel.

Fig. 5. Simulated uncoded BER in Rayleigh fading two-ray channels.

4. CAPACITY EVALUATION

4.1 Radio capacity

In this paper spectrum efficiency measurements are based on the radio capacity $m$ introduced by W.C.Y. Lee [7]. The radio capacity of the omni-cell system is defined as

$$m = \frac{B_c}{2^{C/I}} = \frac{M}{2}\sqrt{\frac{C}{I}} = \frac{M}{K_{C,S}}$$  \hspace{1cm} (4)

where $B_c$ is the total allocated spectrum for the system, $B_c$ is the carrier bandwidth, $(C/I)$ is the minimum required carrier-to-interference ratio, $M$ is the total number of carrier frequencies and $K_{C,S}$ is the number of cells in the reuse cluster (cluster size).
4.2 Assumptions

- Co-channel interference limited radio capacity (adjacent channel interference and thermal noise neglected)
- Rayleigh-distributed uncorrelated interferers
- GMSK as spreading modulation \( B_f R_c \approx 0.7385 \)
- path loss attenuation according to 4th exponent law
- no power control
- omnichannel hexagonal layout used
- geometrically worst case (interferers at closest cell borders) and average case (interferers at the cell centers) + desired user at the cell border in both cases in the uplink (reverse link)
- geometrically worst case (desired user at the cell border) and average case (desired user midway to the cell border) in the downlink (forward link)
- binomially weighted number of closest ring co-channel interferers active
- co-channel interference outage probability of 1-10% used
- Erlang B-formula used with 2% blocking probability

Table 2. Parameters for capacity evaluation.

<table>
<thead>
<tr>
<th>Concept</th>
<th>( B_c [MHz] )</th>
<th>( R_c [kHz] )</th>
<th>( B_t [kHz] )</th>
<th>( \alpha = (C/I)_r )</th>
<th>( M = B/B_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDMA</td>
<td>10</td>
<td>270.8</td>
<td>200</td>
<td>9 dB</td>
<td>50</td>
</tr>
<tr>
<td>TDMA/CDMA</td>
<td>10</td>
<td>4333</td>
<td>3200</td>
<td>-3 dB</td>
<td>3</td>
</tr>
<tr>
<td>TDMA/CS-CDMA</td>
<td>10</td>
<td>1083</td>
<td>800</td>
<td>-3 dB</td>
<td>12</td>
</tr>
</tbody>
</table>

where \( R_c \) is the channel bit or chip rate and carriers \( B_t \) are further divided for TDMA and CDMA users resulting 25 kHz user bandwidth.

4.3 Probability of co-channel interference

In reference [8] co-channel interference probabilities for Rayleigh and/or lognormally distributed signals have been derived. Co-channel interference probability can be defined as

\[
F(I_c) = \sum_{n} F(I_c | n) F_n (n),
\]

where \( F_n(n) \) is the probability of \( n \) co-channel interferers being active and \( F(I_c | n) \) is the corresponding conditional co-channel interference probability

\[
F(I_c | n) = P(p_d | p_n < \alpha),
\]

where \( p_d \) is the instantaneous power of the desired signal, \( p_n \) is the joint interference power from \( n \) active channels and \( \alpha \) is the specified co-channel protection ratio. When only Rayleigh fading is considered equation (6) can be rewritten into form [8]

\[
F(I_c | n) = 1 - \left( \frac{1}{\alpha \cdot p_0 / p_{0d} + 1} \right)^n,
\]

where \( p_0 \) is the local mean power of the interferers and \( p_{0d} \) is the mean power of desired signal. If the quality of service measure is set according to the outage \( P_{out} \) at co-channel interference probability, the following inequality can be derived [8]

\[
F(I_c) = \sum_{n} F(I_c | n) F_n (n)
\]

\[
= \sum_{n} \left[ 1 - \left( \frac{1}{\alpha \cdot p_0 / p_{0d} + 1} \right)^n \right] a_c \left( 1 - a_c \right)^{-n} \leq P_{out}
\]

where \( x \) is the number of co-channel interferers taken into account \((x = 6 \text{ for TDMA and } x = 24 \text{ for hybrids}) \) and \( a_c = m_I / m \) is the carried traffic per channel. Now, the Erlang radio capacity can be solved for each concept. Some results have been gathered in Fig.6 and Fig.7.

Fig.6. Uplink Erlang capacities in omni-cells (worst case).

Fig.7. Uplink Erlang capacities in omni-cells (average case).

Numbers in parenthesis after each concept are cluster sizes. These results show that TDMA/CS-CDMA(4) hybrid gives the best performance almost in the whole range of the studied cases, TDMA seems to be optimized for cluster sizes 9 or 7. In the
average case cluster size 9 gives slightly higher Erlang capacity when $P_{out} < 6.2\%$ (hard capacity limit reached with $K_c = 9$) but for higher outages the smaller cluster size is better. Hybrid schemes provide 1.1 - 2.0 times the Erlang capacity of the pure TDMA system.

Corresponding downlink results are presented in Fig.8 and Fig.9.

*Fig.8. Downlink Erlang capacities in omicells (worst case).*

*Fig.9. Downlink Erlang capacities in omicells (average case).*

In the average case maximum capacity is achieved with most of the concepts resulting straight horizontal lines in Fig.9. If large outages are allowed small cluster sizes give best capacity (soft capacity limit).

Similar studies were made for sectorized cell geometries with corner illuminated base stations. The trend in Erlang radio capacity comparison was similar to the omnicell case in favour of the TDMA/CS-CDMA hybrids.

### 5. CONCLUSIONS

In this paper the performance of a hybrid TDMA/CDMA system employing complementary code sets was studied. Link level simulations pointed out that by using complementary code sets the number of non-interacting users in Rayleigh fading channel on a single carrier can be increased. One clear advantage compared to the traditional CDMA systems is that power control is not necessary within a cell. Neither time synchronization requirement is so strict as usually. Problems arise in the multipath channel in worst-case intersymbol interference case. This general problem could be对付olved with equalizers at least in the channels with small delay spread. Same type of intercell interference cancellation schemes as for pure TDMA can be used because number of interferers is low [9]. Twofold Erlang capacity compared to TDMA is possible with the convolutional spreading technique. TDMA/CDMA with conventional spreading is not spectrum efficient scheme. However, it includes attempting characteristics that could be used for applications where system capacity is not of primary interest.

### 6. REFERENCES


