Collaborative Coding Multiple Access Communications

For Power Line Channels

Carlos L. Giovaneli†, Bahram Honary‡, Paddy Farrell† and Phillip Benachour‡

†Department of Communication Systems, Lancaster University, Bailrigg, Lancaster, Lancashire, LA1 4YR, UK
Tel: +44 1524 593055, Fax: +44 1524 592713
Email: c.lopezgiovaneli@lancaster.ac.uk b.honary@lancaster.ac.uk p.g.farrell@lancaster.ac.uk

‡Centre for Higher Education, School of Science and Technology, Blackburn College, Blackburn, BB2 1LH, UK
Email: p.benachour@blackburn.ac.uk

Abstract

Collaborative coding multiple access (CCMA) schemes permit simultaneous high-rate communications by two or more users in the same bandwidth with modest synchronisation requirements. However, the performance of CCMA systems degrades when the transmission of the composite signal takes place over fading channels. In this paper, we propose the utilisation of CCMA schemes combined with space-time block coding (STBC) for multi-user communications over power line channels. It is shown that for the same composite rate a CCMA/STBC scheme using three transmitting phases gives a gain of 10 dB over the use of a CCMA system without diversity when the channel is corrupted by impulsive noise, and a gain of 20 dB when the channel noise is additive white Gaussian (AWGN).

1. Introduction

Collaborative coding multiple access (CCMA) techniques [1], [2] permit the simultaneous transmission of information from several terminals over a common communication channel without the need of employing time, frequency or orthogonal coding subdivision. In addition, these schemes yield composite rates higher than unity [1]. For these reasons, CCMA provides a suitable access method for multi-user communications over power line networks, particularly for the up-link channel (users to the base station), where a coordination arrangement between the users for the channel access is not possible. However, the increase in the size of the composite symbol constellation, caused by the linear combination of independent codewords, induces a power penalty. As a consequence, the system performance degrades in fading environments. In [6], [7], space-time block coding (STBC) with channel state information (CSI) at the receiver was recently proposed to combat the effects of flat Rayleigh fading on single-user communications over power line channels. In this paper, we propose the utilisation of CCMA schemes combined with STBC for multi-user communications over multiple-input/multiple-output (MIMO) power line channels affected by flat fading and asynchronous impulsive noise. It is shown that at the expense of a moderate increase in complexity, a significant improvement in performance is achieved. The emphasis of the paper will centre upon short distance data transmission over 240/415V power lines. Since the effects of impulsive noise can be reduced through the use of appropriate mitigation techniques, we will also consider fading channels with additive white Gaussian noise (AWGN). In the following section we present a description of CCMA schemes for the multiple-access adder channel (MAAC) and provide an example for two active users. In section three, we introduce a new CCMA/STBC scheme for two active users that provides transmit diversity over two and three phase conductors, and compare its composite symbol error rate (SER) performance with that of a two-user CCMA scheme transmitting over a single-input/single-output (SISO) power line channel (single phase) without the benefit of diversity. In section four, we discuss a CCMA/STBC scheme for three active users with potential applications for multimedia communications, and present simulation results using a composite 8QAM signal constellation. Section five presents our conclusions and final comments.

2. Collaborative Coding Multiple Access Schemes

The multiple-access adder channel (MAAC) is a channel model where two or more users are allowed to transmit in the same bandwidth without the need of employing time, frequency or orthogonal coding subdivision. This can be achieved by the use of a multi-user coding scheme on the adder channel, which also leads to a significantly larger capacity. The coding schemes for the MAAC are known as collaborative coding multiple access (CCMA) schemes [1].
A T-user MAAC scheme is depicted in Fig. 1, where the inputs and their associated sources have independent encoders and a single decoder estimates their combined output.

![Diagram](image)

**Fig. 1 T-user multiple-access channel scheme**

Numerous codes have been constructed for the synchronous and asynchronous MAAC. These codes guarantee unique decodability and can also incorporate a certain degree of error protection. A code is said to be uniquely decodable if and only if all the received composite codewords resulting from the users' transmission are distinct. Code constructions for the synchronous MAAC have proved easier to achieve and were implemented under the assumption of bit and block synchronisation [3], [4]. Codes with short block length were found to be the simplest and gave better performance when uniquely decodability was required rather than the error correction function. The simplest [3] multi-user scheme that exploits the MAAC has \( T = 2 \) users and block length \( N = 2 \) bits. The component code rates are \( R_1 = 0.5 \) bits/channel use and \( R_2 = 0.792 \) bits/channel use. Thus the overall rate sum of the scheme is \( R = 1.292 \) bits/channel use. For this particular scheme, User 1 has two codewords \( C_1 = (00,11) \) and User 2 has three codewords \( C_2 = (00,01,10) \). This two-user code \( (C_1, C_2) \) is uniquely decodable because all the received composite codewords are distinct as shown in Table 1, where the output \( Y \) of the adder channel (see Fig.1) is the ordinary arithmetic sum of the transmitted sequences \( X_1 \) and \( X_2 \) each with block length \( N \). Therefore, the decoder can unscramble the two messages without ambiguity.

**Table 1: Two-user uniquely decodable code**

<table>
<thead>
<tr>
<th>( Y = X_1 + X_2 )</th>
<th>( C_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(00)</td>
<td>00</td>
</tr>
<tr>
<td>(01)</td>
<td>01</td>
</tr>
<tr>
<td>(10)</td>
<td>11</td>
</tr>
</tbody>
</table>

In [5], a class of T-user uniquely decodable codes for the MAAC with rates asymptotically equal to the maximal achievable value were constructed. In these coding schemes, each user has two component codewords of length \( N = 2 \) bits, and the overall rate sum is \( T/N \) (bits/channel use). We shall use a coding scheme of this type in section 4.

In order to transmit the users' coded information over a bandpass adder channel, we have to transfer the information to a carrier wave of appropriate frequency using some form of digital modulation. However, the linear combination of the users' modulated signals at the output of the adder channel increases the size of the composite symbol constellation, which results in a reduction of the immunity to noise and fading at the receiver. Since multi-path propagation, cable losses and various types of noise affect the transmission of digital data over power lines channels it is crucial to effectively reduce the error rate without the need of additional power or bandwidth. Although power line channels exhibit frequency-selective fading, the resultant signal distortion can be eliminated, or significantly reduced, by the introduction of efficient equalisation techniques. The next step is therefore to use some form of diversity to move the operating point from the flat-fading error-performance curve to a curve that approaches additive noise performance.

### 3. The 2-User CCMA/STBC Scheme

**Fig. 2 Two-User CCMA/STBC Scheme**

![Diagram](image)

Here, we consider a power line communication (PLC) system with \( n \) transmitting and \( m \) receiving phase conductors, where \( n = m = q \), with \( q = 2, 3 \). A CCMA/STBC scheme consists of a uniquely decodable “T-user collaborative code” \((C_1, C_2, \ldots, C_T)\), where each constituent code \( C_j \) is an independent binary block code of length \( N \). The messages from the \( T \) users are encoded independently, and the resulting codeword vectors modulate a carrier signal using some appropriate digital modulation scheme. At the output of each user's modulator, a space-time encoder takes blocks of \( k \) constellation symbols \( s_1, s_2, \ldots, s_k \), and at times \( t_1, t_2, \ldots, t_p \), a space-time block code \( G^{ij}(z_1, z_2, \ldots, z_p) \) populates the transmission matrix by setting \( s_i = z_i \). The rows of the transmission matrix represent space (transmitting phases) whereas the columns represent time (channel uses). At each time slot, the symbols on the
same row are transmitted simultaneously over the $q$ phases.

### 3.1. Space-time encoder for $q=2$ and $q=3$

Due to the natural isolation between different phase conductors, we are allowed to use non-orthogonal designs for the space-time block encoder. We note in passing that this arrangement is not effective in wireless STBC. Consequently, we now present two different space-time square matrices for transmission over two and three phases. Denoting the two space-time block codes by $G^2(z_1, z_2)$ and $G^3(z_1, z_2, z_3)$ respectively, the corresponding transmission matrices are expressed by

$$ G^2(z_1, z_2) = \begin{bmatrix} z_1 & z_2 \\ z_2 & z_1 \end{bmatrix} \quad \text{(1)} $$

and

$$ G^3(z_1, z_2, z_3) = \begin{bmatrix} z_1 & z_2 & z_3 \\ z_3 & z_1 & z_2 \\ z_2 & z_3 & z_1 \end{bmatrix} \quad \text{(2)} $$

Codes (1) and (2) have unity transmission rate and diversity order 2 and 3 respectively.

### 3.2. Channel model

The power line channel is assumed to be an equalised flat fading MIMO channel and the path gain from transmitting terminal $i$ to receiving terminal $j$ is defined to be $\alpha_{i,j}$. Here, $i=1,2,...,n$ and $j=1,2,...,m$, where $n=m=q$, with $q=2,3$. The path gains are modelled as samples of independent zero-mean complex Gaussian random variables with variance 0.5 per real dimension. The communication channel is assumed to be quasi-static so that the path gains are constant over a frame of length $p$ (number of rows of the space-time transmission matrix) and vary from one frame to another.

Assuming $n=m$ at any time, the signal $r_i^t$, received at the receiving terminal $j$ at time $t$, is given by

$$ r_i^t = \alpha_{i,j} s_i^t + \eta_i^t = \alpha_{i,j} s_i^t + \eta_i^t \quad \text{(3)} $$

The noise samples $\eta_i^t$ of additive white Class A noise (AWCN) are independently identically distributed (i.i.d.) complex random variables according to Middleton’s Class A noise model [8]. Since the Class A noise is memoryless, it can be interpreted as a worst-case scenario to model impulsive noise on a power line [9].

### 3.2. Decoding algorithm for $q=2$ and $q=3$

The STBC decoder may be defined by three functions: channel estimation, linear combining and maximum-likelihood detection. Through the use of channel estimation the receiver constructs an estimate of the path gains $\alpha_{i,j}$ for every data symbol transmitted.

For transmission over two phases using $G^2$, the linear combiner provides the following soft-decision variables

$$ R_1 = \left[ r_{1,1}^t \alpha_{1,1}^* + r_{2,2}^t \alpha_{2,2}^* \right] \quad \text{(4)} $$

and for transmission over three phases using $G^3$

$$ R_1 = \left[ r_{1,1}^t \alpha_{1,1}^* + r_{2,2}^t \alpha_{2,2}^* + r_{3,3}^t \alpha_{3,3}^* \right] \quad \text{(5)} $$

Using the superscript $c$ to denote composite constellation, the maximum-likelihood detection rule using (4) and (5) is to choose $s_i^t$ among all the symbols $s^t$ of the (composite) signal constellation $S^c$ at the output of the adder channel if

$$ s_i^t = \arg \min_{s^t \in S^c} \left| R - s^t + \left( -1 + |\alpha_{1,j}| + |\alpha_{2,j}| \right) s_i^t \right|^2 \quad \text{(9)} $$

or using (6), (7) and (8), choose $s_i^t$ if

$$ s_i^t = \arg \min_{s^t \in S^c} \left| R - s^t + \left( -1 + |\alpha_{2,j}| + |\alpha_{3,j}| + |\alpha_{1,j}| \right) s_i^t \right|^2 \quad \text{(10)} $$

### 3.3. Implementation and simulation results

The CCMA/STBC scheme for two active users was implemented using the uniquely decodable code of Table 1. Codewords for user 1 were generated by the direct mapping of the source bit 0 onto the codeword (00) and
of the source bit 1 onto the codeword (11). For user 2, the binary sequence coming from the source was first converted to a ternary sequence (-2,0,2) where the ternary symbol 0 corresponds to binary 1, and the ternary symbols -2 and 2 correspond to binary 0. The mapping for user 2 is then: 0 → (00), -2 → (01), 2 → (10). In order to minimise the size of the composite signal constellation at the output of the bandpass adder channel, we take advantage of the fact that, for user 2, the codewords (01) and (10) represent the same source bit 0. Therefore, these two codewords can be mapped onto the same constellation point and, as a result, we are allowed to use BPSK modulation for both user 1 and user 2. The rate sum in this case is only unity but the performance is enhanced. Making the individual BPSK constellations orthogonal to each other, we obtain a composite QPSK complex constellation at the output of the adder channel. In our computer simulation, the average energy of each BPSK signal constellation was scaled so that the average energy of the composite QPSK constellation points is unity. Therefore, the variance $\sigma^2$ of the Class A noise at the input of each receiving point is $1/2\text{SNR}$.

The composite symbol error rate (SER) performance using space-time codes $G^{(2)}$ and $G^{(3)}$ were compared with that of a two-user CCMA scheme transmitting over a SISO channel (single phase) without the benefit of diversity.

![Fig. 3 Composite symbol error rate performance of two-user CCMA/SISO, CCMA/STBC/2 and CCMA/STBC/3 schemes, transmitting over power line channels affected by flat Rayleigh fading and impulsive noise.](image)

In Fig. 3, it is seen that for SNR = 10 dB the CCMA/STBC/2 scheme gives 5 dB gain over the use of the CCMA/SISO system and that for SNR = 5 dB the CCMA/STBC/3 scheme outperforms the CCMA/SISO system by 10 dB. Above these thresholds, the gains of both diversity schemes with respect to the CCMA/SISO system increase continuously. The threshold effects that are observed in the performance of the STBC schemes are caused by the impact of impulsive noise on the linear combiner operation [10]. However, since the effects of impulsive noise can be significantly reduced through the use of interleaving/deinterleaving combined with channel coding/decoding and pulse-jamming detectors, we also evaluated the SER performances of the different schemes when the transmission takes place over power line channels affected by flat Rayleigh fading and additive white Gaussian noise (AWGN).

![Fig. 4 Composite symbol error rate performance of two-user CCMA/SISO, CCMA/STBC/2 and CCMA/STBC/3 schemes, transmitting over power line channels affected by flat Rayleigh fading and additive white Gaussian noise (AWGN).](image)

In Fig. 4, it is seen that at the composite symbol error rate of $10^{-3}$, the CCMA/STBC/2 and CCMA/STBC/3 schemes outperform the CCMA/SISO system by 15 dB and 20 dB, respectively.
4. The 3-User CCMA/STBC Scheme

In this section we present a CCMA/STBC system for three active users. This scheme could be useful for the simultaneous transmission of multimedia information such as text, images and sound over power line channels. We consider the uniquely decodable code: \( C_1 = (11,00) \); \( C_2 = (10,01) \); \( C_3 = (10,00) \), where the subscripts represent the user number [5]. Table 2 represents the encoding table for the three-user scheme where User 1 and User 2 codes have already been combined.

<table>
<thead>
<tr>
<th>User (_1) + User (_2) (\backslash) User (_3)</th>
<th>10</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td>01</td>
<td>11</td>
<td>01</td>
</tr>
</tbody>
</table>

Since there are only two codewords per user in this scheme, the individual rate is 0.5 bits/channel use, and the total rate sum in this case is \( R_{123} = 1.5 \) bits/channel use.

4.1. Implementation and simulation results

The three-user CCMA/STBC scheme was implemented using a composite 8QAM complex constellation for representing the eight different composite symbols at the output of the bandpass adder channel, where the average energy of the constellation points was scaled to unity. As before, we use the space-time block codes \( G^{(2)} \) and \( G^{(3)} \) for transmission over two or three phase conductors. We note that STBC schemes are independent of the type of modulation used. This feature makes STBC very attractive for applications where the same transmit diversity arrangements have to be used with different signal constellations.

Fig. 5 shows the composite SER performance of the three-user CCMA/SISO, CCMA/STBC/2 and CCMA/STBC/3 schemes when the transmission takes place over power line channels affected by flat Rayleigh fading and impulsive noise. The threshold positions are now shifted to the right with respect to the positions observed in Fig. 3 for a composite QPSK constellation. That is, both the 5 dB improvement obtained by the CCMA/STBC/2 scheme and the 10 dB improvement obtained by the CCMA/STBC/3 scheme occur at \( \text{SNR} = 15 \) dB.

The SER performances of the different schemes when the transmission takes place over power line channels affected by flat Rayleigh fading and additive white Gaussian noise are shown in Fig. 6.

![Composite SER performance of three-user CCMA/SISO, CCMA/STBC/2 and CCMA/STBC/3 schemes](image1)

In comparison with the results of Fig. 4, it is seen that irrespective of the use of diversity, the increase in the size of the composite constellation signal from QPSK...
(two users) to 8QAM (three users) degrades the overall performance of the three schemes by 5 dB. Despite this, the SNR improvements obtained through the use of spatial and temporal diversity remain unchanged.

5. Conclusions

The utilisation of collaborative coding multiple access (CCMA) schemes for multi-user communications over power line networks was proposed in this paper. It was shown that the increase in the size of the composite symbol constellation, caused by the linear combination of independent codewords at the output of the multiple-access adder channel, induces a power penalty that degrades the system performance. Consequently, we proposed the use of CCMA combined with space-time block coding schemes to provide spatial and temporal diversity over two or three phase conductors. We presented new CCMA/STBC schemes for two and three active users and showed that for the same composite rate a CCMA scheme using three transmitting phases gives a gain of 10 dB over the use of a CCMA/SISO system when the channel is corrupted by impulsive noise, and a gain of 20 dB when the channel noise is additive white Gaussian (AWGN). The CCMA schemes presented in this paper assume the use of symbol, block and carrier synchronisation between users. Since ideally a CCMA system should be completely asynchronous, it would be useful to investigate methods to reduce the degree of required synchronisation. It would be also useful to study methods to reduce the effects of impulsive noise on the PLC performance.

References