Improved Space-Time Coding Applications For Power Line Channels

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Abstract
In this paper we evaluate the performance of space-time block coding (STBC) with linear combining (LC) decoding in power line channels dominated by asynchronous impulsive noise. Based on the natural signal redundancy provided by the space-time structure, we present a new decoding scheme that shows a significant coding gain over the LC decoder for SNR levels below 18 dB. In addition, we propose a novel adaptive scheme, which combines both detection techniques at the receiver. The performance of the adaptive system is superior to conventional STBC with only LC detection over a wide range of SNR levels.

1. Introduction

Recently, the field of multi-antenna processing and space-time coding (STC) has attracted large interest in the scientific community due to the huge capacity of multiple-input multiple-output (MIMO) wireless channels [1], [2]. With a restricted number of receiving antennas, a part of this capacity increase can be realised using transmitting diversity. Space-time block coding (STBC) [3], [4] is an implementation of transmitting diversity whose essential feature is its inherent orthogonality. This guarantees that linear decoding provides maximum-likelihood (ML) detection. The use of STBC for data communication over MIMO power line channels affected by flat Rayleigh fading and corrupted by impulsive noise was recently proposed in [5], [6]. In this paper, we evaluate the performance of linear combining (LC) decoding in impulsive noise environments, and present a new decoding scheme whose performance is superior to the LC scheme for low to medium values of SNR. Furthermore, we propose a novel adaptive scheme, which combines very well the advantages of both decoding schemes. The emphasis of the paper will centre upon short distance data transmission over 3-phase 415V power lines in the presence of asynchronous impulsive noise. In the following section we introduce a non-orthogonal STBC scheme for transmission over three phase conductors using QPSK modulation and present simulations that compare the bit error rate (BER) performance of the STBC scheme using the conventional linear combiner at the receiver with the performance of a system transmitting over a single-input single-output (SISO) power line channel (single-phase transmission). In section three, we present a new decoding scheme based on the natural signal redundancy provided by the space-time diversity structure, and present results that show that the new scheme provides a significant coding gain over the linear combiner for SNR levels between 0 and 18 dB. In section four, we propose a novel adaptive decoder that combines the advantages of the two previous schemes over the SNR range 0-30 dB. Section five presents our conclusions and final comments.

2. Non-Orthogonal STBC/LC Scheme

In order to design an efficient STBC transmission scheme for power line communication (PLC) systems, we must take into account some important differences with respect to the wireless channel: 1) in an space-time wireless system with \( n \) transmitting and \( m \) receiving antennas, the signal received at antenna \( j \) (\( j = 1, \ldots, m \)), at any time \( t \), is the result of the combination of the signals emitted by the \( n \) transmitting antennas, which is not the case in the power line channel where each phase ideally provides an isolated path to the transmitted signal; 2) this isolation in turn provides a natural decoupling between any two signals corresponding to different symbols (spatial orthogonality); 3) power line channels are corrupted by narrow-band interference and asynchronous impulsive noise caused by switching transients in the network. With this in mind, and assuming we are using the three phases to obtain spatial diversity, the first difference means that the maximum spatial diversity order we can achieve is three. The second difference implies that we do not need to construct our transmission matrix using an orthogonal design [4]. Finally, the third difference obviously implies that we have to employ a different channel model to evaluate the performance of the STBC scheme. We next consider a communication system with 3 emitting points...
at the transmitter and 3 receiving points at the receiver (see Fig. 1). Here, we use the terms sending points and receiving points instead of the terms transmitting antennas and receiving antennas used in wireless communications.

Therefore, using the transmission matrix (1) and considering a constellation $S$ of size $2^b$ ($b = 2$ for QPSK), the encoding algorithm proceeds as follows: 1) at time slot 1, $kb$ bits select $k = M = 4$ constellation signals $s_1, s_2, s_3, s_4$ ($M = 4$ for QPSK); 2) the encoder populates the transmission matrix $G^{(3)}(x_1, x_2, x_3, x_4)$ by setting $x_i = s_i$ for $i = 1, 2, 3, 4$; and 3) at time slots $t = 1, 2, 3, 4$ the signals $G_{t1}, G_{t2}, G_{t3}$ are transmitted simultaneously from sending points 1, 2 and 3. The rate $R$ of this coding scheme is defined to be $kb / pb$, which is equal to $k / p$. In this case, $k = 4, p = 4$, and $R = 1$.

2.2. Channel model

The power line channel is assumed to be an equalised flat fading MIMO channel where the path gain from sending point $i$ to receiving point $j$ is defined to be $\alpha_{i,j}$. Here, $i = 1, 2, ..., n$ and $j = 1, 2, ..., m$, and $n = m = 3$. 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 $r_i^j$, received at the receiving terminal $j$ at time $t$, is given by

$$r_i^j = r_i^j = \alpha_{i,j} s_i^t + \eta_i^t = \alpha_{i,j} s_i^t + \eta_i^t$$  \hspace{1cm} (2)

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 [7]. Since the Class A noise is memoryless, it can be interpreted as a worst-case scenario to model impulsive noise on a power line [8].

2.3. Decoding algorithm

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 three phases using $G^{(3)}$, the linear combiner provides the following soft-decision variables
Then the maximum-likelihood detection rule using (3)-(6) is to choose $s_i$ among all the symbols $s$ of the composite signal constellation $S$ if

$$s_i = \arg\min_{s \in S} \left( r_i^1 - s \right)^2 + \left( -1 + |\alpha_{i,1}|^2 + |\alpha_{i,2}|^2 + |\alpha_{i,3}|^2 \right) |s|^2 \quad (7)$$

2.4. Implementation and simulation results

In our computer simulation, the average energy of the QPSK signal constellation was scaled so that the average energy of the constellation points is unity. Therefore, the variance $\sigma^2$ of the Class A noise at the input of each receiving point is $1/2\text{SNR}$. We used the class A noise parameters $A = 0.1$ and $T = 10^{-3} \quad [8]$. The performance results of the STBC $G^{(3)}$ were compared with those obtained using a system transmitting over a single-input single-output (SISO) power line channel (single-phase transmission). Fig. 2 shows the bit error rate performance for both systems. It is seen that at the bit error rate of $10^{-3}$ the STBC scheme with the space-time code $G^{(3)}$ gives a gain of about 12 dB over the use of a SISO system. Fig. 2 also shows that for SNR values below 10 dB the performance of the STBC system is not as good as might be expected, specially in the range 0-6 dB where the STBC scheme does not show a clear advantage over the SISO system. Since the latest ETSI standards regarding the propagation characteristics of power lines and EMC regulations stipulate that the injected transmitter power must be limited [9], it is highly desirable to enhance the system performance in this particular range of SNR levels. This motivated us to investigate how this issue could be overcome.

In fact, this loss in performance is closely related to the very nature of the impulsive noise and its effects on the ML decoding algorithm in (7).

$$R_1 = \left( r_i^1 \alpha_{1,1}^* + r_i^2 \alpha_{2,2}^* + r_i^3 \alpha_{3,3}^* \right) \quad (3)$$

$$R_2 = \left( r_i^1 \alpha_{1,1}^* + r_i^2 \alpha_{2,2}^* + r_i^3 \alpha_{3,3}^* \right) \quad (4)$$

$$R_3 = \left( r_i^1 \alpha_{1,1}^* + r_i^2 \alpha_{2,2}^* + r_i^3 \alpha_{3,3}^* \right) \quad (5)$$

$$R_4 = \left( r_i^1 \alpha_{1,1}^* + r_i^2 \alpha_{2,2}^* + r_i^3 \alpha_{3,3}^* \right) \quad (6)$$

Fig. 2 Bit error probability (BER) versus SNR in the presence of flat Rayleigh fading and additive white Class A noise (AWCN) for QPSK/SISO and QPSK/STBC 3 schemes (2 bits/sec/Hz).

3. Non-Orthogonal STBC/RC Scheme

The AWCN channel is characterised by an impulse free random time interval, with a very low noise power spectral density, followed by a strong noise spike with a sharp rising edge that exceeds the power spectral density of the background noise by at least 10-15 dB. As for the detection process, the ML decision rule used by the STBC scheme is based on the decision variables (3) to (6) obtained at the output of the linear combiner and formed by vector composition of the independent received vectors, three for each transmitted symbol $s_i$ ($i = 1, 2, 3, 4$). Therefore, the occurrence of a strong noise impulse in only one of the three phases may not only mutilate one of the independent received vectors, but also destroy the dependent augmented vector that results from the composition of the three independent vectors. Obviously, this effect is much more pronounced with lower levels of SNR. Since this situation may affect only one independent vector but not the other two, it is natural to think that if the ML estimation is taken individually over each independent vector instead of over their sum, we can still obtain a correct decision. In other words, we can use a repetition code of length three without sacrificing the symbol rate as can be seen from (1). Of course, like any repetition code of length three, this code will be able to correct only single errors. That is, if more than one independent received vector is corrupted by impulsive noise the decoder will decide on the wrong symbol, which will also be the case for the
linear combiner anyway. An implementation of a decoder based on this approach is depicted in Fig. 3.

Fig. 3 Alternative ST receiver with single detection of independent received vectors and majority vote decoders (repetition code of length 3).

3.1. Simulation results

Figure 4 shows the BER performance of the new system (STBC 3/RC-3) as compared with both the STBC scheme with linear combining (STBC 3/LC) and the SISO system. It is seen that at SNR = 1 dB, the new system gives about 9.5 dB gain over the use of an STBC/LC scheme. The BER performance of the STBC/LC system improves notably for SNR levels greater than 18 dB. This behaviour resembles the threshold effect in analogue frequency modulation systems, where the system performance deteriorates rapidly as the SNR falls below certain levels. Actually, the effect of impulsive noise on the linear combining operation of the STBC/LC scheme is very similar to the effect of noise spikes on the FM signal.

4. Adaptive STBC Scheme

The results obtained in the previous section strongly suggest the possibility of combining both the RC and LC detection schemes at the receiver to improve the system error performance over the SNR range 0-30 dB. A direct hardware implementation could be the inclusion of an impulse detector. If a strong noise impulse is detected, the symbol information that was just received has only little or no impact on the sequence estimation process. Thus the information of the impulse detector can be used to switch from the LC/ML output to the RC output until the impulse amplitude falls below certain threshold and the LC operation resumes. In power line environments, typical impulse widths range from 46 µs for the larger impulses to 90 µs for the smaller ones.

In this paper, we propose an alternative scheme where the occurrence of large noise spikes can be estimated during the normal course of data transmission. We first make some remarks:

a) For low levels of SNR the presence of a high impulse noise amplitude at any receiving point destroys the linear combination of the received vectors and the LC detector provides an erroneous output. Since the RC detector is less sensitive to impulse events, we shall choose this detection scheme for low to medium levels of SNR.

b) The impulse amplitude may indeed become much larger than the signal amplitude, which is already affected by multiplicative fading. Under such a condition, the received vector and the noise vector in (2) are of nearly equal amplitude. Thus we can assume that for 

\[ \alpha_{ij} \approx 1, \eta_i \ll \eta_i^{'} \],

the following condition holds

\[ r_i^{'} \cong \eta_i^{'} \]  \hspace{1cm} (8)
Therefore, we can directly use the received vector $r'$ to detect the occurrence of an impulse event by comparing the received power $|r'|^2$ with a predefined threshold.

c) Values of impulse noise power that do not exceed a certain level of impulse-to-threshold power ratio will not affect the LC decoder operation.

We next define the following parameters:

$p = \text{Block of channel uses (see subsection 2.1.)}$

$n = \text{Number of transmitting phases (see subsection 2.1.)}$

$L_e = \text{Number of blocks } p \text{ used for the noise estimation}$

$T^*_0 = \text{Power threshold}$

$I_T = \text{Impulse noise power}$

$ITR = \text{Impulse-to-threshold power ratio}$

Although a proper selection of $T^*_0$ and ITR can be made from channel measurements and modelling, we have found that choosing $T^*_0$ equal to the average power of all the signals received during the transmission of $L_e$ blocks of data, and ITR = 10, yields good results. We are now in position to summarise the adaptive decoder algorithm.

### 4.1. Adaptive decoding algorithm

1. During the transmission of $L_e$ blocks of data calculate $P_i$ and the total average received power ($P_{AVG}$) for $t = 1, 2, ..., p, ..., L_e,$ and $i = 1, 2, ..., n$:

   If $|r_{t+i}|^2 > |r_t|^2 \Rightarrow \text{set } |r_{t+i}|^2 = P_i$

   Else $\Rightarrow \text{set } |r_{t+i}|^2 = P_i$

   (store $P_i$ replacing the previous stored value)

   $P_{AVG} |_{t=1} = |r_1|^2 + |r_2|^2 + |r_3|^2$

   $P_{AVG} |_{t=2} = |r_2|^2 + |r_3|^2 + |r_4|^2 + P_{AVG} |_{t=1}$

   $\bullet$

   $P_{AVG} |_{t=L_e} = |r_{L_e}|^2 + |r_{L_e+1}|^2 + |r_{L_e+2}|^2 + P_{AVG} |_{t=L_e-1}$

2. At the end of the “training period” ($L_e$) compute:

   \[ T^*_0 = \frac{P_{AVG} |_{t=L_e}}{L_e} \]  

   and

   Noise Margin = $\frac{P_i}{T^*_0}$

   If (Noise Margin $> I_T$) $\Rightarrow$ take the detected symbols from the RC detector output.

   If (Noise Margin $< I_T$) $\Rightarrow$ take the detected symbols from the linear combiner/maximum likelihood detector output.

### 4.2. Simulation results

Figure 5 shows the BER performance of the adaptive scheme (STBC 3 ADAPTIVE) as compared with the SISO system. Comparing this plot with the one in Figure 4, it is quite obvious that the adaptive scheme combines very well the advantages of the two decoding schemes described in sections 2 and 3 of this paper.
5. Conclusions

The utilisation of space-time block coding techniques for high-speed data communications over 3-phase power line networks has been investigated in this paper. Assuming perfect isolation between the phases of the power line the space-time transmission matrix needs no orthogonal design. It was shown that the asynchronous impulsive noise caused by switching transients in the network could considerably affect the performance of the STBC receiver with linear combiner in the low to medium SNR range. Consequently, we proposed an alternative ST receiver scheme based on the inherent signal redundancy provided by the ST architecture, which realises independent ML detections of the received vectors and then performs a majority vote decision over three estimated symbols to produce the best symbol estimation. The results of simulations show that at SNR = 1 dB, the new system outperforms the STBC/LC scheme by 9.5 dB. Since the BER performance of the STBC/LC system improves notably for SNR levels greater than 18 dB, we propose an adaptive scheme that combines very well the advantages of the two decoding schemes described in this paper over the full range of SNR levels. Further work in this subject will be the investigation of other space-time coding/decoding schemes more specifically designed for the power line environment.

References


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