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Digital Transmission Combining BLAST and OFDM Concepts: Experimentation on the UHF COST 207 Channel

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Abstract—Recent papers ([1], [2]) have shown that multipath wireless channels are capable of enormous capacities, provided that the multipath scattering is sufficiently rich and is properly exploited. A layered space-time architecture, known as BLAST, has been proposed. A basic hypothesis made by the BLAST algorithm is that the symbol period is large compared to the maximum echo delay (hence, the data rate cannot be too high). In this paper, we use an approach that combines BLAST and OFDM. Its interest is to suppress the data rate constraint. First, the symbols are packed into matrices; then matrix manipulations prior to BLAST transmission provide a transmission system which is theoretically equivalent to many independent BLAST channels. Results obtained with the UHF COST 207 channel corresponding to GSM transmission in urban area are provided and discussed.

Keywords—Digital transmissions, Spectral efficiency, Multielement antennas

I. BACKGROUND

Recent research [1] has shown that very high spectral efficiency can be obtained over rich scattering wireless channels by using multielement antenna arrays at both transmitter and receiver. An algorithm, now known as BLAST (Bell Laboratories Layered Space-Time) has been proposed and initial laboratory results [2] showed that spectral efficiencies as high as 20 bits/s/Hz can be obtained. This spectral efficiency is far above the efficiency provided by single antenna transmission systems. The principle of BLAST is as follows: M digital transmitters (for instance, QAM transmitters) operate co-channel at symbol rate $1/T$ with synchronized symbol timing. N digital receivers also operate co-channel ($N \geq M$), with synchronized timing. An algorithm described in [2] is used to estimate the transmitted symbols from the components of the received mixture.

Let us note a the vector containing the M transmitted symbols at a given time, and r the vector containing the N received samples. A basic assumption made by BLAST is that there exists a channel matrix H (with N rows and M columns) such that:

$$r = Ha + n \quad (1)$$

where n is the noise vector. The transmitted symbols are estimated: for instance, a Zero Forcing (ZF) method would estimate the transmitted symbols using the pseudo-inverse H^+ of the channel matrix: $\hat{a} = q(H^+r)$, where q is a quantification function which replaces each vector entry by the nearest symbol. The method proposed in [2] is more elaborate: the most reliable entry of H^+r is determined and used to estimate the symbol. Then, the contribution of this symbol is cancelled, and

the process is repeated among the $M - 1$ remaining symbols, and so on until all symbols are estimated.

The BLAST algorithm is very efficient but its basic hypothesis leads to restrictions on the bandwidth. As explained in the next Section, combination of BLAST with OFDM provides a solution to suppress this constraint. The remainder of the paper is organized as follows: Section 3 explains the combination of BLAST and OFDM and the equivalent theoretical model is presented in Section 4. Simulation results on a GSM channel are provided and discussed in Section 5, then a conclusion is drawn.

II. SUPPRESSING CONSTRAINTS ON ACHIEVABLE DATA RATES

Equation 1 is the basic hypothesis made by the BLAST algorithm. It is valid only if the inter-symbol interference in time is negligible. This means that the delays of the echoes must be negligible with respect to the symbol period T . For instance, in an outdoor environment, with a maximum echo delay equal to $5 \mu\text{s}$ (which corresponds, approximately, to a distance $d = 1500 \text{ m}$), the symbol period should be, at least, $T = 10 \times 5 \mu\text{s} = 50 \mu\text{s}$. Hence, the maximum symbol frequency is $1/T = 20 \text{ kHz}$, and the maximum data rate is 200 kbits/s (assuming a spectral efficiency of 10 bits/s/Hz).

A solution to remove this constraint would be to divide a large bandwidth into smaller bandwidths, each one being used by a BLAST transmission system transmitting at a relatively low data rate. However, this solution is not optimal because a large frequency band is lost between each couple of adjacent channels (for instance, with filters roll-off equal to 0.3, 60% of the frequency band is lost). There exists a solution to perform frequency multiplexing without inter-channel loss: it is OFDM (Orthogonal Frequency Division Multiplexing) [3]. However, OFDM cannot be inserted directly into a BLAST system, because a BLAST system is multidimensional. OFDM is based on Discrete Fourier Transform (DFT), and on the properties of this transform. Below, we explain how to combine DFT with matrix manipulations in order to take profit of the properties of this transform in the multidimensional context. Then, it is shown that this method divides a given bandwidth into orthogonal multidimensional BLAST subchannels.

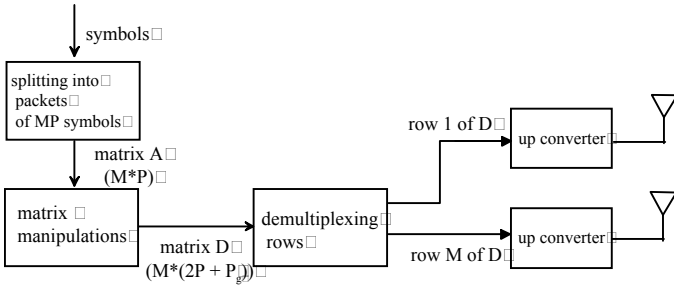


Fig. 1. Overview of the transmitter

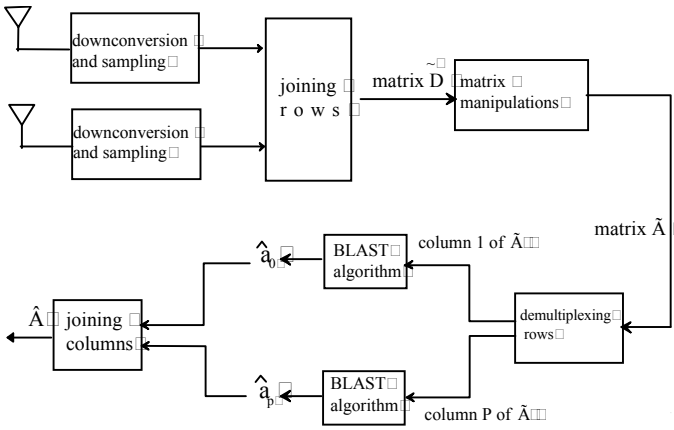


Fig. 2. Overview of the receiver

III. COMBINATION OF BLAST AND OFDM, USING MATRIX MANIPULATIONS

Figures 1 and 2 show the principle of the transmission system. On the transmitter side, the data is divided into packets of MP symbols, where P is a power of 2 (it corresponds to the number of subcarriers in an OFDM system) and M is the number of transmitters. Let us consider a packet of MP symbols and let us note s_k ($k = 0, \dots, MP - 1$) the symbols, T_s the symbol period in the initial symbol stream, and F_s the corresponding symbol frequency. These symbols are placed into an $M \times P$ matrix A as shown below:

$$A = \begin{pmatrix} s_0 & s_M & \cdots & s_{M(P-1)} \\ s_1 & s_{M+1} & \cdots & s_{M(P-1)+1} \\ \vdots & \vdots & \vdots & \vdots \\ s_{M-1} & s_{2M-1} & \cdots & s_{MP-1} \end{pmatrix} \quad (2)$$

Then, P columns containing zeroes are inserted in the middle of the matrix, between column $P/2$ and column $P/2 + 1$. Let us note B the resulting matrix (M rows, $2P$ columns) and compute:

$$C = B.W \quad (3)$$

where:

$$W = \frac{1}{\sqrt{2P}} \begin{pmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & w & w^2 & \cdots & w^{2P-1} \\ 1 & w^2 & w^4 & \cdots & w^{2(2P-1)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & w^{2P-1} & w^{2(2P-1)} & \cdots & w^{2(2P-1)^2} \end{pmatrix} \quad (4)$$

and $w = e^{j2\pi/2P}$. Equation 3 corresponds to an inverse DFT of the rows of B and can be realized with a fast algorithm. Finally, a copy of the P_g last columns of C is inserted at the beginning of the matrix. The resulting matrix is called D (M rows, $2P + P_g$ columns). Each i^{th} row of matrix D is a digital baseband band-limited signal which is then upconverted and fed to the i^{th} transmitting antenna.

Since a row of matrix D contains $2P + P_g$ samples and must have the same duration than the initial packet of MP symbols, the row sampling period is $T_{sd} = MPT_s/(2P + P_g)$. The signal is band limited because the null columns in the middle of matrix B cancel the high frequencies. Indeed, the spectrum of a row of D is close to the spectrum of a row of C . And since each row of B is the Fourier transform of a row of C , we deduce that the signal bandwidth is $1/(2T_{sd}) = (2P + P_g)F_s/(2MP)$. Note that, if oversampling is desired, more zeroes can be inserted during the construction of matrix B . The P_g first samples of any row of D correspond to a guard interval. They are similar to the P_g last samples, and their objective is to avoid interpackets interferences due to echoes. Thanks to this guard interval, the effect of echoes is similar to a circular convolution applied to the sequel of the row. The value of P_g is chosen such that the duration of the guard interval (namely $P_g T_{sd}$) is larger than the highest echo delay.

On the receiver side, after downconversion and sampling, a matrix \tilde{D} (N rows, $2P + P_g$ columns) is obtained. The first P_g columns are suppressed, which results in matrix \tilde{C} . Then, we compute:

$$\tilde{B} = \tilde{C}.W^{-1} \quad (5)$$

Finally, matrix \tilde{A} (N rows, P columns) is obtained by suppressing the P columns in the middle of \tilde{B} . The interest of the approach is that, as shown in the next section, the transmission system is equivalent to P parallel BLAST systems, each one transmitting a column of matrix A . Hence, applying the BLAST algorithm to each column of matrix \tilde{A} provides estimates of the transmitted symbols.

IV. EQUIVALENT THEORETICAL MODEL

For clarity of presentation, the noise is not mentioned in the equations below. Using the Z transform, the channel between

D and \tilde{D} can be modelled by a matrix $F(z)$:

$$F(z) = F_0 + F_1 z^{-1} + \dots + F_{P_g-1} z^{-(P_g-1)} \quad (6)$$

where each F_i is a matrix with N rows and M columns. Let us represent matrix C by the vector $c(z)$:

$$c(z) = c_0 + c_1 z^{-1} + c_2 z^{-2} \dots + c_{2P-1} z^{-(2P-1)} \quad (7)$$

where c_i stands for column $i + 1$ of matrix C . Using a similar representation for matrix \tilde{C} , we can write:

$$\tilde{c}(z) = F(z).c(z) \text{ mod } (z^{-2P} - 1) \quad (8)$$

because, due to the structure of matrix D , the channel effect can be seen as a multidimensional circular convolution on the columns of C . Furthermore, since $(w^k)^{-2P} = 1$ for any integer k , equation 8 yields to:

$$\tilde{c}(w^k) = F(w^k).c(w^k) \quad (9)$$

But, from equations 5 and 4 we see that:

$$\tilde{B} = [\tilde{c}(1), \tilde{c}(w), \tilde{c}(w^2), \dots, \tilde{c}(w^{2P-1})] \quad (10)$$

And the same relation occurs between matrices B and C . It follows that:

$$\tilde{b}_k = F(w^k).b_k \quad (11)$$

where $k = 0, 1, 2, \dots, 2P - 1$, and b_k and \tilde{b}_k stand for the columns of B and \tilde{B} . Finally, if we note a_k and \tilde{a}_k the columns of A and \tilde{A} , we have:

$$\tilde{a}_k = H_k a_k \quad (12)$$

where $H_k = F(w^k)$ for $k = 0, \dots, P/2 - 1$, and $H_k = F(-w^k)$ for $k = P/2, \dots, P - 1$ (because $w^P = -1$). Hence, the transmission system is equivalent to P parallel and independent BLAST channels, each one being characterized by an $N \times M$ matrix H_k . Therefore, we only have to input each vector \tilde{a}_k to a BLAST algorithm in order to estimate the vectors a_k .

V. SIMULATION RESULTS

Combination of BLAST and OFDM removes the narrow bandwidth constraint. However, as the basic algorithm, it works only over rich scattering channels, such as indoor, underwater acoustic or urban GSM channels. We experimented the method on a simulated GSM channel, the UHF COST 207 channel ([4], [5]), in the typical case for urban (non-hilly) area. We used 2^m -QAM modulations, $M = 4$ transmitters, $N = 8$ receivers, and $P = 128$ subcarriers. The COST 207 parameters are represented on the Table I. The behavior of the channel weights at specific time delays are described by three general classes of Doppler, the classical Doppler spectrum (CLASS) and two spectra based on Gaussian distributions (GAUS1 and

TABLE I
 TYPICAL CASE FOR URBAN (NON-HILLY) AREA

| Tap | Delay (μs) | Power (lin) | Power (dB) | Doppler category |
|-----|-------------------|-------------|------------|------------------|
| 1 | 0 | 0.4 | -4 | CLASS |
| 2 | 0.2 | 0.5 | -3 | CLASS |
| 3 | 0.4 | 1 | 0 | CLASS |
| 4 | 0.6 | 0.63 | -2 | GAUS1 |
| 5 | 0.8 | 0.5 | -3 | GAUS1 |
| 6 | 1.2 | 0.32 | -5 | GAUS1 |
| 7 | 1.4 | 0.2 | -7 | GAUS1 |
| 8 | 1.8 | 0.32 | -5 | GAUS1 |
| 9 | 2.4 | 0.25 | -6 | GAUS2 |
| 10 | 3.0 | 0.13 | -9 | GAUS2 |
| 11 | 3.2 | 0.08 | -11 | GAUS2 |
| 12 | 5.0 | 0.1 | -10 | GAUS2 |

GAUS2). In order to agree with these parameters, we chose a sampling period $T_e = 0.2 \mu s$, that implies for each subcarrier a bandwidth $\Delta f = 1/(2P \times T_e) = 19.5 \text{ KHz}$, and the largest echo delay of the model is $T_g = 5 \mu s$, i.e. $P_g = 26$ samples. The total bandwidth used is 2.5 MHz .

The experimental capacity is computed via the following equation:

$$C_{\text{exp}} = \eta \times M \times m \times c \quad (13)$$

with

$$\eta = \frac{2P}{2P + P_g} \quad (14)$$

and

$$c = 1 + \text{ber} \times \log_2(\text{ber}) + (1 - \text{ber}) \times \log_2(1 - \text{ber}) \quad (15)$$

where ber is the estimated Bit-Error-Rate.

Since each subchannel uses the same bandwidth, the theoretical global spectral efficiency is the average spectral efficiency (if the bandwidth were different, we would compute a weighted sum instead):

$$C = \frac{1}{P} \sum_{k=0}^{P-1} C_k \quad (16)$$

The spectral efficiency within a subchannel can be obtained from a result proved in [1], which is corrected here to take into account the efficiency lost due to the guard interval:

$$C_k = \eta \times \log_2 \{ \det [I_N + \rho_k G_k G_k^*] \} \quad (17)$$

where:

- G_k is the normalized version of the subchannel matrix H_k given by :

$$G_k = \frac{\sqrt{N}}{\|H_k\|} H_k \quad (18)$$

and $\|H_k\|^2$ is the sum of the square modulus of the entries of H_k .

- ρ_k is the average signal-to-noise ratio on a receiver, in sub-channel k .

The value of ρ_k is given by:

$$\rho_k = \frac{\|H_k\|^2 Q}{NMQ_N} \quad (19)$$

where:

- Q is the total transmission power.
- Q_N is the noise power in a subchannel, seen from a receiver (it is assumed to be independent of the receiver and of the sub-channel).

The global signal-to-noise ratio (SNR) used in the simulations is equal to:

$$SNR = \langle \rho_k \rangle = \frac{Q \sum_{k=1}^P \|H_k\|^2}{PMNQ_N} \quad (20)$$

The signal-to-noise ratio per bit is given by:

$$\frac{E_b}{N_0} = \frac{1}{\eta M m} \times SNR \quad (21)$$

Fig. 3 studies the impact of the SNR on the capacity of the BLAST-OFDM system. A Quadrature Amplitude Modulation (QAM) is used with a constellation of 2^m points with $m = 4, 8$ and 12 . This last case corresponds to a 4096-QAM modulation; this kind of constellation is of course practically unrealistic, but it's just used to show that the system follows the theory. Fig. 3 clearly illustrates that highest experimental capacities depend on the choice of the constellation with respect to the SNR. Best capacities are obtained for a 16-QAM modulation until 17 dB, for a 256-QAM between 17 and 30 dB, and for a 4096-QAM apart from 30 dB. There is no doubt that this kind of system reaches enormous capacities, but the gap between theoretical and experimental capacities means that there is still room for improvement of the demodulation algorithm.

Fig. 4 shows the BER with respect to E_b/N_0 , for 3 constellations (4, 16, and 256-QAM) and for the same channel as in Fig. 3. This figure illustrates the robustness of the BLAST-OFDM system in a difficult context: while the urban GSM channel offers relatively rich multipath, it may be more difficult than indoor channels, due to the fading and the urban noise.

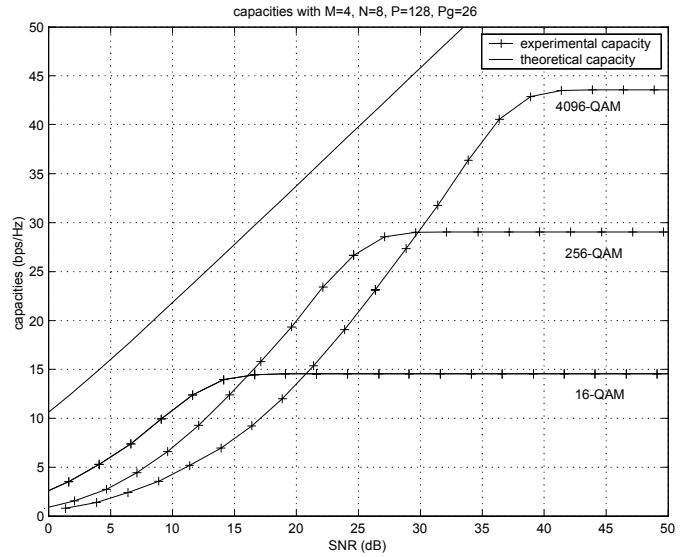


Fig. 3. Capacities (bps/Hz) for 4096, 256, and 16-QAM modulations

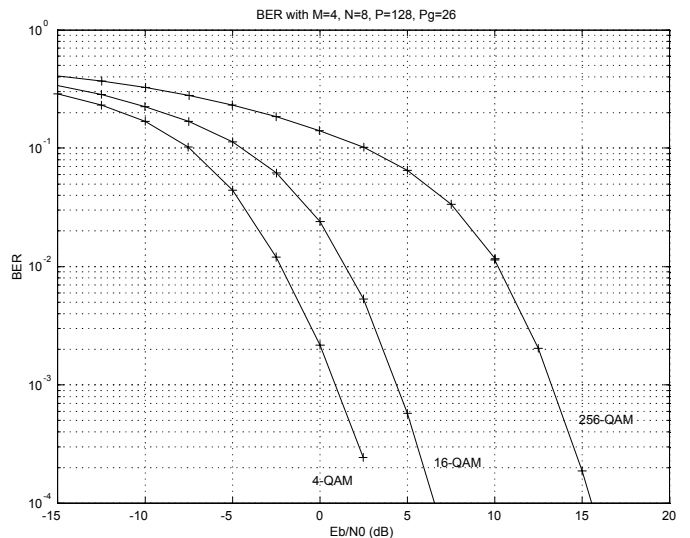


Fig. 4. BER for 256, 16 and 4-QAM modulations

VI. CONCLUSION

Taking profit simultaneously of spatial diversity (multiple transmitting antenna) and frequency diversity is a way to achieve very high spectral efficiencies and data rates over wireless transmission channels. This method is an improvement of the very efficient BLAST algorithm (which is based on spatial diversity only): it removes a basic constraint of BLAST which forbids to obtain high data rates when echo delays are long. It seems to work in every rich scattering multipath area, even in a difficult context as the urban GSM, as shown by the simulations on the UHF COST 207 channel.

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