Space-Frequency Turbo Coded OFDM for Future High Data Rate Wideband Radio Systems

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ABSTRACT

We propose a new bandwidth and power efficient signaling scheme for achieving high data rates over wide-band radio channels exploiting bandwidth efficient OFDM modulation, multiple transmit and receive antennas and large frequency selectivity offered in typical low mobility indoor environments. Due to its maximum achievable transmit diversity gain and large coding gain, space-frequency turbo coded modulation strongly outperforms other space-frequency coding schemes recently proposed in literature. We also propose a simple way of combining space-frequency coding with OFDM delay diversity as a cost-effective method for further bandwidth efficiency increase by exploiting more than two antennas at the transmitter.

1. INTRODUCTION

Due to its high bandwidth efficiency and suitability for high data rate applications, OFDM was chosen as a modulation scheme for a physical layer in the several new wireless standards, i.e. digital audio and video broadcasting (DAB, DVB) [1,2] in Europe and the three broadband wireless local area networks (WLAN) [3], European HIPERLAN/2, American IEEE 802.11a and Japanese MMAC.

Recent results in literature [4-7] demonstrate that multiple-input multiple-output (MIMO) wireless channels, apart from spatial diversity against detrimental effects of fading, enable increased information theoretic capacity as compared to single-input single-output (SISO) channels. A number of transmit diversity schemes for multi-antenna OFDM systems has been proposed recently that exploit a form of simple spatial processing at transmitter to overcome link budget limitations, moving a complexity burden from mobile terminals to access points. As seen by single antenna error control codes employed therein, the given diversity scheme over MIMO channel creates an equivalent SISO channel with characteristics, either desirably close to Gaussian [8] or with artificially increased frequency selectivity [9,10]. Therefore, potentially increased capacity of MIMO channels is not exploited in a proper way.

For the perfectly known channel state information (CSI) at both ends of a wireless link, optimal and capacity approaching signaling strategy impose the initial singular value decomposition (SVD) of MIMO channel into a number of parallel, SISO sub-channels. Single antenna error control codes, with optimal power and bit allocation, are employed then on each of parallel SISO sub-channels [7]. Sub-carrier based spatial sub-channel adaptive coding/modulation suggested in [11] results in large complexity even for a limited number of transmit antennas. Also it is not directly applicable for broadcast channels, i.e. in DAB and DVB.

When the channel state information (CSI) is not available at the transmitter, space-time coding (STC) is an optimal signaling strategy, designed to achieve potentially high capacity of MIMO Rayleigh fading channels by jointly exploiting the benefits of spatial and temporal diversity. Application of STC to space-frequency domain is however not always straightforward. For layered STC architectures [12], complexity reduction due to the applied single antenna channel codes is difficult to justify in a situation where large frequency selectivity may result in complex sub-carrier based spatial filtering at a receiver. Also the required number of receive antennas should be greater than or equal to the number of transmit antennas. Therefore, maximum likelihood detection (MLD) based STC [13,14] becomes again a cost-effective way of exploiting the frequency selectivity in the channel.

In [15], STC's from [13] were applied as space-frequency codes. Large bandwidth and power efficiency gains were reported as compared to single antenna channel codes employed with OFDM transmit diversity [10]. The concept of recursive space-time trellis codes (Rec-STTrC) for parallel-concatenated space-time turbo coded modulation (STTuCM) was introduced in [16] and further generalized in [17]. The proposed parallel concatenated scheme was designed to preserve the maximum transmit diversity gain but simultaneously enhance the coding gain as compared to STC's in [13]. In this paper, we advocate application of STTuCM on space-frequency domain and demonstrate significant performance improvements when compared to some other space-time (turbo) coding schemes applied to multi-antenna OFDM systems under somewhat realistic ITU and ETSI BRAN channel models and physical layer parameters. We also propose a simple way of combining space-frequency coding with OFDM delay diversity for cost effective exploitation of more than two transmit antennas.

2. SYSTEM MODEL

We consider system employing a R=(L_a+1)N transmit and M receive antennas depicted in Fig. 1. Applied STC is

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designed for N transmit antennas and L_a is the order of artificial multi-path introduced by additional OFDM delay diversity. Delays T_{la}, l_a=1..L_a are chosen in an ascending order $T_1 < T_{la} < .. < T_{La}$ as multiples of the OFDM sampling period T_s. Therefore the equivalent sampling rate discrete-time channel from any of the first N transmit to any of M receive antennas can be represented with an equivalent $L=\lceil (T_{La}+T_{DS})f_s \rceil+1$ order FIR filter with filter taps $\boldsymbol{h}_{n,m}^k=[h_{n,m,0}^k ..\ h_{n,m,L}^k]$ where T_{DS} denotes the maximum delay spread in the channel.

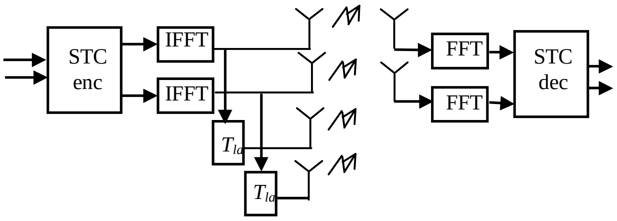

Fig. 1. Block diagram of space-frequency coded OFDM system

At each discrete time instant k, k=1..B, the input sequence of CZ bits $\boldsymbol{b}^k=[b_1^k\ b_2^k ..\ b_{CZ}^k]$ enters STC encoder where C is a number of sub-carriers in the OFDM symbol. Corresponding output of the STC encoder is a tall $C\times N$ matrix $\boldsymbol{S}^k=[\boldsymbol{S}_1^k\ \boldsymbol{S}_2^k\ ..\ \boldsymbol{S}_N^k]$ of coded complex symbols such that $\boldsymbol{S}_n^k=[S_{1,n}^k ..\ S_{C,n}^k]^T$ with $S_{c,n}^k$ denoting a point in complex constellation of 2^Z symbols. As in [8] let $\boldsymbol{F}=[\boldsymbol{F}_1\ \boldsymbol{F}_2 ..\ \boldsymbol{F}_C]$, $\boldsymbol{T}_{cp}=[\mathbf{I}_{LxC}^T\ \mathbf{I}_{CxC}^T]^T$ and $\boldsymbol{R}_{cp}=[\mathbf{0}_{CxL}\ \mathbf{I}_{CxC}]$ denote the $C\times C$ fast Fourier transform (FFT) matrix, $(L+C)\times C$ cyclic prefix insertion matrix and $C\times(L+C)$ cyclic prefix removal matrix respectively. After OFDM demodulation at the receiver, complex base-band $C\times 1$ signal vector at receive antenna m can be expressed

$$\boldsymbol{r}_m^k = \sum_{n=1}^{N} \boldsymbol{D}_{n,m}^k \boldsymbol{S}_n^k + \boldsymbol{F}\boldsymbol{R}_{cp}\boldsymbol{\eta}_m^k, \quad m=1..\ M \qquad (1)$$

where $\boldsymbol{\eta}_m^k$ denotes $(C+L)\times 1$ vector of noise samples, mutually independent zero mean complex Gaussian random variables with variance σ^2 per complex dimension. Diagonal matrix $\boldsymbol{D}_{n,m}^k$ is given as $\boldsymbol{D}_{n,m}^k = \boldsymbol{F}\boldsymbol{R}_{cp}\boldsymbol{H}_{n,m}^k\boldsymbol{T}_{cp}\boldsymbol{F}^H = diag[\alpha_{n,m,1}^k,\ ..\ \alpha_{n,m,C}^k]$ with $\alpha_{n,m,c}^k=[\boldsymbol{h}_{n,m}^k\ \mathbf{0}_{1x(C-L)}]\boldsymbol{F}_c$ and where $\boldsymbol{H}_{n,m}^k$ denotes $(C+L)\times\ (C+L)$ Toeplitz matrix with its (x,y) entry $h_{n,m,(x-y)}^k$. We assume in general that input information frame $\boldsymbol{b}=[\boldsymbol{b}^1 ..\ \boldsymbol{b}^k ..\ \boldsymbol{b}^B]$ consists of $V=BCZ$ bits, so that one coded information frame covers multiple of B successive OFDM symbols. For the perfect knowledge of channel state information (CSI) at the receiver, maximum likelihood detection (MLD) metric for Viterbi and maximum *a posteriori* (MAP) probability decoder is given by

$$\hat{\boldsymbol{S}} = [\ \hat{\boldsymbol{S}}_1^1 .. \hat{\boldsymbol{S}}_N^1 .. \hat{\boldsymbol{S}}_1^k .. \hat{\boldsymbol{S}}_N^k .. \hat{\boldsymbol{S}}_1^B .. \hat{\boldsymbol{S}}_N^B\ ] \qquad (2)$$
$$= \underset{Q_1^1..Q_N^1..Q_1^k..Q_N^k..Q_1^B..Q_N^B}{\arg\min} \sum_{k=1}^{B}\sum_{m=1}^{M} \left\| \boldsymbol{r}_m^k - \sum_{n=1}^{N} \boldsymbol{D}_{n,m}^k \boldsymbol{Q}_n^k \right\|$$

where the minimization is done over all possible code-words of the space-time code used for transmission.

3. SPACE-FREQUENCY CODING

3.1 Space-Frequency Trellis Coded OFDM

Based on the large effective code length, *Lu et al.* proposed a new family of space-time trellis codes for multi-antenna OFDM systems in [18]. Codes were designed upon already existed trellis coded modulation schemes optimized for frequency flat fading channels. A class of rate 2/3 8PSK TCM for single antenna transmission was transformed into rate 2/4 QPSK code for two transmit antennas by splitting the original 8PSK mapper into two QPSK mappers, one for each transmit antenna. We refer to this space-frequency trellis code approach as SFTrC-L to distinguish between *Tarokh et al.* codes in [15] which we denote as SFTrC-T. In both cases, Viterbi decoder is used for STC decoding.

3.2 Space-Frequency Turbo Coded OFDM

In case system applies STTuCM, STC encoder and decoder in Fig. 1 are depicted in Figs. 2 and 3 respectively. We refer to [17] for detailed description of encoding and decoding operations. We only outline that component STC in Fig. 2 are recursive non-systematic space-time trellis codes (Rec-STTrC) introduced in [16]. Also interleaving actually consists of two half-length bit-wise pseudorandom interleavers. One interleaving is scrambling the input bits on the odd input symbol positions, another is independently from the first one, scrambling the input bits on the even input symbol positions. This will assure that due to puncturing each input information bit contributes once and only once to the output STTuCM code-word.

In order to enable pseudo-random bit-wise interleaving at encoder, additional symbol-to-bit reliability transformation is performed at the output of component symbol-by-symbol MAP decoders. This result in log-likelihood ratio for each information bit b_i

$$L(b_i) = Log \frac{\sum_{d_t|b_i=1} \Pr\{d_t = [b_{(t-1)Z+1}..b_{tZ}]\ |\boldsymbol{r}\}}{\sum_{d_t|b_i=0} \Pr\{d_t = [b_{(t-1)Z+1}..b_{tZ}]\ |\boldsymbol{r}\}} \qquad (3)$$

for $\forall i\in\{(t-1)Z+1..tZ\}$, t=1..CB, $\boldsymbol{r}=[\boldsymbol{r}_1^1 ..\ \boldsymbol{r}_1^B ..\ \boldsymbol{r}_M^1 ..\ \boldsymbol{r}_M^B]$ being the total observation of the channel output and d_t taking values in $\{(0)_2, (1)_2,..(2^Z-1)_2\}$, where subscript 2 functions the Z-bits long binary representation of the value in brackets. Bit-level *extrinsic* information is now extracted

$$L_{ext}(b_i) = L(b_i) - L_{apri}(b_i) \qquad (4)$$

with $L_{apri}(b_i)$ being *a priori probability* of the information bit b_i . After being bit-wise interleaved it becomes $\tilde{L}_{ext}$ and is passed through bit-to-symbol reliability transformation to compute *a priori probability* for another symbol-by-symbol MAP decoder

$$\Pr\{d_t = [b_{(t-1)Z+1}..b_{tZ}]\} = \prod_{j=1}^{Z} \frac{\exp(b_{(t-1)Z+j} \cdot \tilde{L}_{ext}(b_{(t-1)Z+j}))}{1+\exp(\tilde{L}_{ext}(b_{(t-1)Z+j}))}. \quad (5)$$

Consequently, the resultant encoder and iterative (turbo) decoder operate on bit level. We refer to above bit-wise interleaved Space-Frequency Turbo Coded Modulation scheme as SFTuCM-Dbit.

Independently, *Cui et al.* proposed somewhat similar space-time turbo coded modulation scheme in [19]. Implemented codes were recursive systematic space-time trellis codes (RecSys-STTrC), somewhat different from Rec-STTrC. It is worth nothing that the component codes are systematic so the scheme in [19] can be depicted with the same block diagrams of encoder and decoder as those in Figs. 2 and 3. The major difference between two schemes lays in the structure of interleaving. In [19] *Z*-wise or symbol level pseudo-random interleaving between two constituent codes is applied. As a consequence resultant encoder and iterative (turbo) decoder operate on symbol level. Symbol-to-bit and bit-to-symbol reliability transformations in Fig. 3 are avoided and the exchange of log-likelihood information between the two component symbol-by-symbol MAP decoders is done directly on the symbol level. Therefore the extraction of *extrinsic* information is done in the following manner

$$L_{ext}(d_t) = L(d_t) - L_{apri}(d_t) \quad (6)$$

with $L_{apri}(d_t)$ being the *a priori probability* of the information symbol d_t. We refer to the above symbol-wise interleaved Space-Frequency Turbo Coded Modulation scheme as SFTuCM-Csymb. We also consider the parallel concatenation of two 8-state RecSys-STTrC's with bit-wise interleaving and symbol-to-bit and bit-to-symbol reliability transformations in decoder. We refer to this scheme as SFTuCM-Cbit.

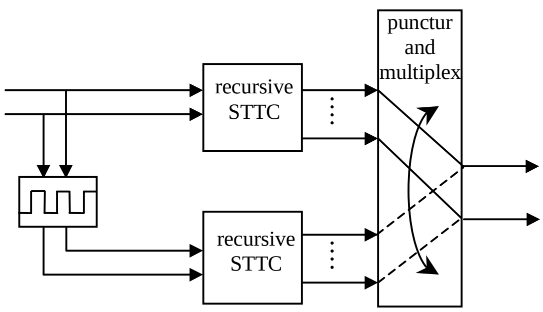

Fig. 2. Block diagram of STTuCM encoder

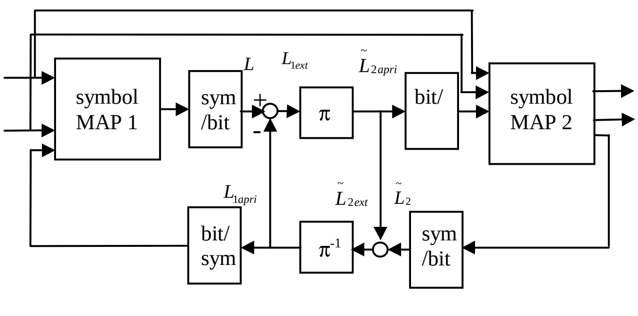

Fig. 3. Block diagram of STTuCM decoder

Finally, we applied two 8-state maximum effective code length *Lu et al.* space-time trellis codes from [18] with generator polynomials [11; 02; 04] in octal form as constituent codes in bit-wise interleaved space-time turbo coded modulation. We refer to this scheme as SFTuCM-Lbit.

4. SIMULATION RESULTS

All implemented STC's were designed to achieve spectral efficiency of 2 bits/sec/Hz using QPSK modulation and two transmit antennas (N=2). Penalty in band-with efficiency due to trellis termination is however lower with SFTuCM than with SFTrC's, because the number of tail bits is proportional to number of trellis states. We assume perfect frame and sample clock synchronization between the transmitter and the receiver. Prior to OFDM modulation at transmitter, complex code-word symbols were interleaved with length *BC* channel interleaving.

We adopted HIPERLAN/2 physical layer parameters [21] (the same as those for IEEE 802.11a) and evaluated performance under some specific ITU and ETSI BRAN, mainly indoor, low mobility channel models. Available bandwidth was 20 MHz with 64 sub-carriers in OFDM symbol corresponding to sub-channel separation of 3.125 kHz and OFDM frame duration of 3.2 μs. To each frame a guard period of 0.8 μs was added and a total of 48 sub-carriers were used for data transmission. Additional 4 sub-carriers were assigned for pilots though CSI was assumed to be perfectly estimated at receiver. A R=2 transmit and M=1 receive antennas were employed without optional delay diversity. Coded frame was spread across five consecutive OFDM symbols (B=5) during which fading is assumed to be quasi-static. The performance comparison between the considered schemes is depicted in Figs. 4 and 5.

In Fig. 4 the performance was evaluated on ITU-B [22], six path indoor, non-line of sight (NLOS) office channel model. The best performance is achieved with SFTuCM-Dbit which outperforms SFTuCM-Csymb and 256-state SFTrC-L by more than 2 dB and 32-state SFTrC-T by more than 4 dB at frame error rate (FER) of 10^{-2}. The performance of rather complex 256-state SFTrC-L can be achieved with lower complexity and more bandwidth efficient SFTuCM-Lbit, bit-wise interleaved parallel concatenation of two 8-state encoders of the same family. More than 2.5 dB performance loss as compared to SFTuCM-Dbit results from the fact that the large effective code length design criteria developed in [18] represent rather brutal force method not taking into account transmit diversity properties. Employing RecSys-STTrC from [19] in bit-wise interleaved manner, i.e. SFTuCM-Cbit, improves performance over symbol-wise interleaved version SFTuCM-Csymb by almost 1 dB but still suffers from more than 1 dB performance loss as compared to SFTuCM-Dbit as constituent Rec-STTrC's are better optimized for parallel concatenation than RecSys-STTrC's.

In Fig. 5 the NLOS large open space office environment ETSI BRAN-B [23] channel model with the total of 18 paths and 100*nS rms* delay spread was considered. SFTuCM-Dbit outperforms SFTuCM-Csymb and 256-state SFTrC-L by more than 2.5 dB and 32-state SFTrC-T by more than 5 dB, at frame error rate (FER) of 10^{-2}. The performance gain of SFTuCM-Dbit over SFTuCM-Cbit is further increased to 1.5 dB.

5. CONCLUSIONS

In this paper, we proposed a bandwidth and power efficient signaling scheme for achieving high data rates over wide-band radio channels exploiting bandwidth efficient OFDM modulation, multiple transmit and receive antennas and large frequency selectivity offered in typical low mobility indoor office environments, e.g. ITU and ETSI BRAN channel models. Due to its maximum achievable transmit diversity gain and large coding gain, space-frequency turbo coded modulation strongly outperforms other space-frequency coding schemes recently proposed in literature. We have demonstrated that space-frequency turbo coded modulation owes its good performance to mainly two important features. Relatively simple 8-state recursive space-time trellis codes are optimized for both, multi-antenna transmission and parallel concatenation. Another distinctive feature is the bit-wise interleaving between two constituent codes. We also proposed a simple way of combining space-frequency coding with OFDM delay diversity for cost effective exploitation of more than two transmit antennas.

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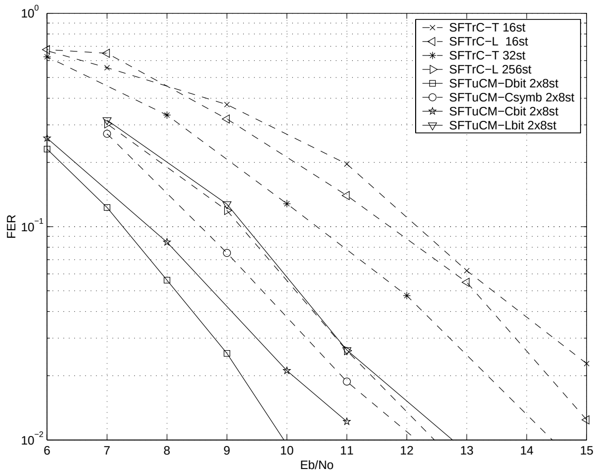

Fig. 4. ITU-B, six path indoor office, NLOS

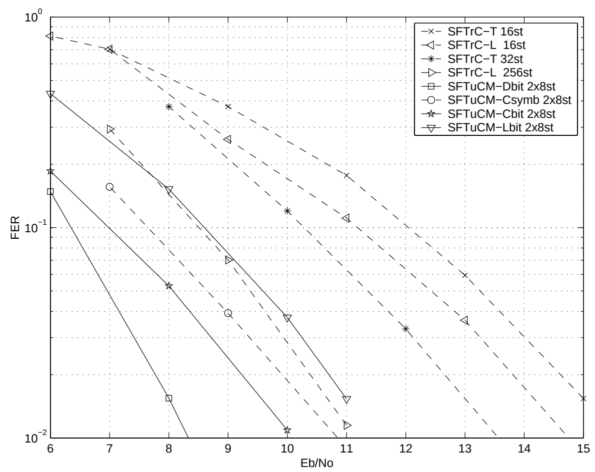

Fig. 5. ETSI BRAN-B, 18 path typical large open space office environment, NLOS