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A MEASUREMENT BASED FEASIBILITY STUDY OF SPACE-FREQUENCY MIMO DETECTION AND DECODING TECHNIQUES FOR NEXT GENERATION WIRELESS LANS

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Abstract— This article presents a performance evaluation of various multi-antenna concepts based on OFDM for Wireless LANs. The studies are based on state-of-the-art measured channel data in the 5GHz band. The investigated techniques include: spatial multiplexing (BLAST), space frequency trellis coded modulation, their concatenation, turbo bit interleaved coded modulation and turbo space frequency trellis coded modulation. The studies aim to assess the MIMO concepts for future high speed WLANs.

Index Terms—MIMO, WLAN, Space-time, OFDM.

I. INTRODUCTION

THE current generation of high data rate wireless local area network (WLAN) standards, such as IEEE802.11a, provide data rates of up to 54 Mbit/s. However, the ever-increasing demand for even higher data rate services, such as internet, video and multi-media, have created a need for improved bandwidth efficiency from next generation wireless LAN consumer products. The current IEEE802.11a standard employs the bandwidth efficient scheme of Orthogonal Frequency Division Multiplex (OFDM) and adaptive modulation and demodulation. The systems were designed as single-input single-output (SISO) systems, essentially employing a single transmit and receive antenna at each end of the link. Within ETSI BRAN some provision for multiple antennas or sectorised antennas has been investigated for improved diversity gain and thus link robustness.

Until recently considerable effort was put into designing systems so as to mitigate for the perceived detrimental effects of multipath propagation, especially prevalent in indoor wireless LAN environments. However, recent

work [1] has shown that by utilising multiple antenna architectures at both the transmitter and receiver, so-called multiple-input multiple-output (MIMO) architectures, vastly increased channel capacities are possible, limited only by the amount of multipath activity in the propagation environment and the number of transmit/receive antennas employed.

The ideas behind space-time trellis coded modulation (STTCM) were first presented in [2]. By adopting relatively simple coding and decoding strategies, across both the spatial and temporal domains, capacities within 2.5dB of the theoretical outage capacity were obtained. Recent attention has turned to the adoption of space-time coding techniques to wideband channels, and in particular their usage in OFDM-based systems where coding is performed in the space-frequency domain.

The technique of space-frequency coding for OFDM-based systems is of interest for future enhancements to consumer electronic WLAN products. Performance gains, in terms of capacity and/or link robustness, can be achieved at relatively small cost. The major cost component is borne by the need for multiple transmit and receive antennas, whilst signal processing relies upon well established methods (Viterbi maximum likelihood sequence estimation, interference suppression etc.).

II. SPACE-FREQUENCY TECHNIQUES IN MIMO-OFDM

In principle all techniques that have been developed for single carrier MIMO systems can be utilised in MIMO-OFDM. The only difference is that the MIMO channel, typically described by a mixing matrix $\mathbf{H}$, is not constant. The channel is described by a set of K matrices: $\mathbf{H}_{1:K}$. Entries of the matrix $\mathbf{H}_k$ describe the frequency response of

the channel between all N_T transmit antennas and all N_R receive antennas on the k^{th} subcarrier. In the presence of delay spread, the channel exhibits frequency selective fading and as a result the channel evolves from $\mathbf{H}_k$ to $\mathbf{H}_{k+1}$.

A. Space-frequency trellis coded OFDM

Space-time codes were originally proposed in 1998 by researchers from Bell Labs [2]. Space-time coding jointly optimised the design of channel coding, modulation mapping, transmit and receive diversity. Space-time coding has been designed as a transmit diversity technique that can also provide some coding gain for the case where the channel state information (CSI) is available only at the receiver.

When STTCM is applied to OFDM systems the coding takes place across frequency and space rather than time and space. In the time domain the amount of available diversity is related to the Doppler phenomenon. Conversely, the delay spread in the radio channel gives rise to diversity in the frequency domain. It is expected that WLAN systems will operate in environments ranging from frequency flat to frequency selective. Hence, the diversity may be available in both the space and frequency domain.

STTCM in general provides very good performance - it has the potential to approach the MIMO outage capacity within a few dBs. However, detection can prove to be a computational burden. STTCM is typically restricted to 2 Tx antennas and modulations that do not exceed 16 constellation points.

B. Spatially multiplexed OFDM

As primarily a diversity technique, the architectures of STTCM-OFDM typically do not exceed configurations of 2Tx by 3Rx antennas. Spatial multiplexing (known also as BLAST [3]) represents a direct exploitation of the available space-time resources. In spatial multiplexing for OFDM, independent codewords are sent on each sub-carrier. The decoding as a mirror operation is performed independently on all sub-carriers, which simplifies the detection. However, this also impairs the system performance since no frequency diversity is utilised. This situation can be ameliorated if the system uses outer channel coding with interleaving to recover some frequency diversity.

C. Turbo bit interleaved coded modulation (T-BICM)

Since their spectacular debut in Turbo codes [4], iterative decoding techniques have taken a prominent place in the quest for the promised capacities. Iterative (Turbo) detection splits the global estimation process into smaller more tractable sections that supply each other with appropriate *a priori* probability density functions. Although rigorous convergence analysis is yet to be established, overwhelming empirical evidence justifies huge interest and stimulates further

research. The T-BICM concept with transmit and receive diversity [5] is equivalent to turbo spatial multiplexing (Turbo-BLAST).

Fig. 1. Encoder of Bit Interleaved Coded Modulation for Space-frequency transmission.

The transmitter is depicted in figure 1. The binary stream of data is first transformed by a channel encoder to obtain an encoded (redundant) sequence. Typically, convolutional [6] or low density parity check (LDPC) [7] coding schemes are used for that purpose. The encoded sequence is multiplexed, interleaved and then mapped to the modulation symbols (e.g. QPSK, 16-QAM etc.). The modulation symbols are then mapped to the antennas, transformed by the IFFT pre-coders and sent by multiple antennas.

Fig. 2. Encoder of Bit Interleaved Coded Modulation for Space-frequency transmission.

The receiver (see figure 2) consists of two major soft-input-soft-output (SISO) blocks. First one accepts observations from all the antennas and calculates a set of marginal posterior distributions. This block also accepts prior distributions provided by the second block - SISO channel decoder. The channel decoder relies only on the posterior distributions produced by the first block (there is no additional prior). For the turbo system to work properly, the prior information that is supplied to the first SISO module has to be removed from the posterior distributions. This is illustrated in figure 2 by a branch traversing the turbo loop before the interleavers. The second branch ensures that only the so-called *extrinsic* part of the posterior distribution is handed over to the first SISO block for the next iteration. The extrinsic information is the "extra knowledge" about the data distribution gleaned through the decoding process.

A major advantage of T-BICM is its flexibility. Most of the detection chain remains unchanged and retains the same complexity regardless of the number of antennas used, the frame length or indeed the modulation format. The only affected part is the first SISO block. The complexity of the SISO front end can be very sensitive to the number of Tx antennas and modulation format. The optimal strategy (from

a performance viewpoint) evolves enumerating amongst all possibilities (MAP decoding). This can lead to gigantic complexity e.g. 4,294,967,296 states for 8 Tx antennas and 16-QAM modulation format. Currently, there is tremendous interest in the research community to bring this burden down.

D. Turbo - Space-frequency trellis coded modulation (T-SFTCM)

T-SFTCM attempts to cast the original turbo code (parallel concatenated convolutional codes [4]) framework on Space-frequency trellis coding. A T-SFTCM encoder is depicted in the block diagram of figure 3. It consists of parallel concatenated space-frequency encoders. The first encoder operates directly on a block of N bits and at each encoding step accepts L bits and produces 2 output symbols. The second encoder operates on the same incoming block of N bits but the bits are bit-wise interleaved using a pseudo-random interleaver. In addition to information bits each N bit block contains additional tail bits that are included in order to terminate the trellis of the upper encoder. Due to the presence of pseudo-random interleaver the trellis of the lower encoder is left untruncated.

Fig. 3. Encoder of turbo space-frequency trellis coded modulation.

A block diagram of the decoder is shown in figure 4. Demodulated received data symbols are fed to two symbol-by-symbol soft-input soft-output (SISO) decoders which provide a posteriori probability (APP) outputs.

As shown in section IV, the T-SFTCM provides better performance than SFTCM. The major drawbacks are the complexity and limited data rates. Both SFTCM and T-SFTCM coding are primarily diversity techniques, although in general they also offer coding gain. In fact, typically the constructions of SFTCM and T-SFTCM do not exceed a constellation of 2Tx and 3Rx antennas.

E. Combined spatial multiplexing and space-frequency coding

As aforementioned, the SFTCM is primarily a diversity technique. Hence, increasing the number of antennas on both the receive and transmit sides above a certain number does not give significant advantage. Spatial multiplexing on

Fig. 4. Decoder of turbo space-frequency trellis coded modulation.

the other hand can theoretically offer a nearly linear increase in capacity. However, since the spatial multiplexing is fundamentally an un-coded system, it suffers from poor link quality. One way forward could be to combine both approaches. This can be achieved using *Group Interference Suppression* (GIS) [8]. A modified version of the GIS receiver suitable for Space-Frequency coded OFDM is developed in [9]. A schematic of this idea is depicted in figure 5. Such an architecture can also be viewed as a spatial multiplexing system, where each stream of data is protected by G individual space-frequency codes (SFTCM). An optimal receiver would perform a systematic search over all possible code-words generated by the whole set of component codes. Such an approach however results in prohibitively high complexity. The component codes can be decoded separately, using the receive antenna array as a spatial processor to suppress other component codes - GIS.

Fig. 5. A combination of Spatial Multiplexing and Space-frequency Coding.

III. WIDEBAND MIMO CHANNEL MEASUREMENTS

The wideband MIMO measurements utilised in this work have been taken using a customised Medav RUSK BRI vector channel sounder operating in the 5.2 GHz band with 120 MHz of bandwidth. Each complete MIMO (8 Tx by 8 Rx) channel snapshot takes 102.4 ms, which is well within the coherence time of the channel.

The measurements were taken in an open plan office with approximate dimensions of 30L x 20W x 4H (m). The Mobile Terminal (MT) antenna array comprises of 4 dual polarised patch antennas as depicted in figure 6. The antennas

Fig. 6. "Laptop-sized" four double polarized element antenna array used for the mobile terminal.

were located in the corners of a dielectric plane with dimensions similar to that of a typical laptop computer cover. The Access Point (AP) utilises a circular array of printed dipoles - figure 7. The AP antenna was located approximately 0.5m below the ceiling in the middle of the office. The measurement procedure consisted of taking MIMO snapshots in 20 locations while the terminal was stationary. The locations were chosen to emulate a wireless LANs operational scenario, hence the mobile terminal antenna array was located vertically approximately 1m above the ground. The channel sounder uses a multitone signal comprising 97 frequency points. A subset of 17 consecutive points is used to interpolate the 64 point FFT grid over a 20 MHz bandwidth as required for IEEE802.11a. The channels have RMS delay spread in the order of 10ns.

IV. NUMERICAL STUDIES

The Packet Error Rate (PER) versus SNR has been adopted here as a suitable measure of performance. The packet contains 240 4-PSK symbols of data (5 OFDM symbols). The Channel State Information (CSI) is estimated by the modem via a sequential transmission of preambles from all Tx elements as depicted in figure 8.

Figure 9 depicts the results of SFTCM and T-BICM. The SFTCM uses 8 state 4-PSK code of Tarokh et al [2] and Viterbi detector. The T-BICM uses a 16 state rate $\frac{1}{2}$ binary recursive convolutional encoder and QPSK, hence the net data rate is identical in both cases. After 8 iterations the T-BICM outperforms the 8 state SFTCM code by around 2 dB. An additional 2dB (approx.) of SNR per receive antenna is needed to compensate for the lack of ideal CSI in both cases. Figure 10 shows the FER performance for the T-SFTCM (8 state recursive Tarokh) code with estimated CSI for ETSI channel models A to E and measured results after

Fig. 7. Circular array of printed dipoles used for the access point.

Fig. 8. Space-time transmission in MIMO-OFDM system with sequential MIMO training.

8 iterations. At high signal-to-noise ratios, the T-SFTCM coding performs best in ETSI channel E conditions. This channel has the longest excess delay (1760 ns) and hence the greatest frequency diversity, although performance in channel C is similar since this channel also has a large excess delay (1050 ns). Measured channels performance is approximately 3.7 dB worse than channel D. Comparing figures 9 and 10 it can be noticed that the performance of T-BICM and T-SFTCM is similar (1 dB in favour of T-BICM). Figure 11 depicts the frame error rate of the spatial multiplexing SFTCM concatenation. This is a case where a large number of transmit and receive antennas (8×8) was used. Each SFTCM encoder uses the same 32 state 4-PSK component code. It can be observed that the difference between measured and the ETSI channel A is $\approx 5 - 6$ dB. The difference is predominantly due to the larger amount of frequency diversity available in the simulated channels case. As before an additional 2dB (approx.) of SNR per receive antenna is needed to compensate for the lack of ideal CSI.

Fig. 9. Performance of T-BICM and SFTCM (8 state Tarokh Code) over measured channels: 2Tx by 2Rx antennas, ideal and estimated CSI.

Fig. 10. Performance of T-SFTCM: 2Tx by 2Rx antennas, 8 state recursive Tarokh code over simulated and measured channels - estimated CSI.

Fig. 11. Performance of Spatial multiplexing Space-frequency Coding concatenation over simulated and measured channels.

V. CONCLUSIONS

This paper investigates space-frequency concepts for MIMO-OFDM. In this context spatial multiplexing, space frequency trellis coded modulation, concatenation of the two, turbo bit interleaved coded modulation and turbo space frequency trellis coded modulation have been studied. The best performing techniques are T-BICM and T-SFTCM. However, T-SFTCM as iterative (turbo) version of SFTCM shares the same drawbacks. It can be regarded as a solid candidate but for small number of transmit antennas (≈ 2). Significant improvement in data rates over current WLANs can only be provided by the use of larger antenna constellations (more than 4×4). The inherent flexibility of T-BICM facilitates seamless increase in number of Tx antennas. Additionally, in T-BICM the complexity/performance trade-off can easily be scaled by adopting different approaches for the first SISO block. Another solution could be the hybrid techniques. The spatial multiplexing and space frequency trellis coded modulation hybrid mutually exploits the benefits of the both schemes. Performance results confirm the increased system robustness, indicating a vast potential for future OFDM based WLAN standards.

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