Turbo coding for an OFDM-based wireless LAN at 17 GHz

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***Abstract*— The considerable performance gain of turbo codes compared to other conventional coding schemes makes it to a primary candidate for OFDM-based wireless LANs. This paper shows the application of turbo coding in combination with bandwidth-efficient modulation for a flexible high bit rate modem architecture. The performance of the introduced coded modulation scheme is investigated by simulations for the indoor propagation channel at 17 GHz.**

***Index Terms*— Turbo coding, parallel concatenated coding scheme, OFDM, wireless LAN**

I. Introduction

THE constantly increasing demand for high speed and high quality mobile data transmission pushes research and development towards wireless local area network technologies incorporating adaptive and reconfigurable modem architectures. With those, the adaption of the system to varying radio channel conditions gets possible and the available channel capacity can be optimally exploited. Accordingly, the signal processing algorithms and techniques employed within the modem have to provide a certain flexibility of their parameters to support these different modes of operation.

The objective of the IST project WIND-FLEX is the development of such a flexible high bit rate modem architecture for a wireless indoor environment at 17 GHz allowing slow mobility [1]. To minimize the influence of time variant multipath propagation and to avoid the application of sophisticated equalizer techniques and expensive adaptive antennas, the multicarrier modulation technique OFDM has been adopted. However, the wideband nature of the OFDM spectrum makes it vulnerable to frequency selective fading, so that some subcarriers may be significantly attenuated due to deep fades. Even though most subcarriers may be received without errors, the overall error rate is mainly dominated by the few subcarriers with the smallest amplitudes. By using a powerful error correction coding across the subcarriers, errors of weak subcarriers can be corrected up to a certain limit that depends on code and channel. A powerful coding means that performance of an OFDM system is determined by the average received power rather than by the power of the weakest subcarrier [2]. Because of its ability to allow near Shannon limit error correction while keeping implementation complexity relatively low [3], turbo coding represents a considerable candidate for the introduced system.

The paper is roughly divided into two parts. As a first step, an overview about the demonstrator of the WIND-FLEX modem is given in section II. Therein, the general transmitter and receiver structure is presented. Section III, containing the second part, is devoted to the channel coding related issues. The system model, that forms the basis for all investigations, is briefly described. Following that, an approach is made towards the applied coded modulation scheme. Finally, the impact of the radio channel characteristics on the channel coding performance is considered.

II. System overview

The WIND-FLEX modem employs OFDM with 128 subcarriers in a 50 MHz channel based on TDMA/TDD as radio access scheme. Four channels, each 50 MHz wide, are then available between 17.1 and 17.3 GHz. The selection of this high frequency band is twofold. First of all, the demand for mobile high data rate transmission causes a need for higher bandwidth which is not available in the lower frequency band. On the other hand, the strong attenuation of the transmitted signal gives the possibility to reuse the same frequency band in adjacent areas of coverage with very low radio interferences. The coverage of the modem ranges from 10 m for non line of sight (NLOS) up to 100 m for line of sight (LOS) radio links. Considering a 25 % overhead for signalling and control information, a maximum payload of around 100 Mbps can be achieved for a point-to-point communication.

The general modem architecture has been designed to cope with environmental changes and different user requests at run-time while ensuring an overall operational efficiency. The latter can be interpreted as a compromise over several requirements like data rate, bit error rate, power consumption and others. For that purpose, the so-called supervisor was additionally introduced which takes the dynamic adaption of the transmit and receive parameters into account. Figure 1 shows the general modem architecture.

For the channel coding, a turbo code with variable code rate achievable by puncturing has been selected. After encoding, puncturing, and interleaving, the coded bits are mapped onto subcarriers which can be BPSK, QPSK, 16QAM, and 64QAM modulated. According to the employed weak subcarrier excision algorithm, the strongest

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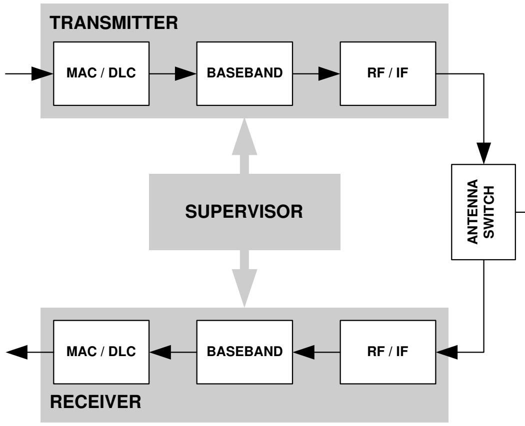

Fig. 1. General transceiver architecture

92 subcarriers are dynamically selected out of the 100 active ones. This algorithm has been included to minimize the influence of the strongest attenuated subcarriers. Following the 128 point complex IFFT, the guard interval is added to the useful part of the OFDM symbol resulting in a OFDM symbol length of 3.0 µs. Then, the preambles necessary for synchronization and channel estimation are inserted once per frame (178 OFDM symbols). Finally, the baseband signal is converted to analog IF. Table I summarizes the relevant baseband parameters.

TABLE I
MAIN BASEBAND PARAMETERS

system parameters	values
channel bandwidth	50 MHz
modulation scheme	OFDM
subcarrier modulation	BPSK, QPSK, 16QAM, 64QAM
number of subcarriers	128
active subcarriers	100
useful subcarriers	92
OFDM symbol length	2.56 µs
guard interval	440 ns
coding scheme	turbo code
code polynomial	$(13, 15)_{octal}$
code rate	1/2, 2/3, 3/4

At receiver side, the analog IF is down converted and filtered to digital baseband. Following that, synchronization is performed to synchronize the receiver in time and frequency. The guard interval is removed and the 128 point complex FFT is performed. Channel estimation and one-tap equalization is carried out to provide the equalized values and the corresponding fading coefficients for every subcarrier. The symbols loaded on subcarriers are handed over to the demodulator which calculates reliability (soft) values for every coded bit. The latter are processed in the soft input turbo decoder in an iterative way to obtain the information bits.

As mentioned above, the supervisor is the basic control unit at physical layer level. It controls all baseband relevant parameters and works closely together with the MAC. Incoming MAC requests are evaluated whether current channel and traffic conditions allow their processing. If the request can be permitted then the supervisor adapts the baseband parameters accordingly. If for example the current channel conditions do not permit the processing of the request, the supervisor and the MAC have to start negotiating again about what is practically possible. The main advantage of employing such a entity is, that the optimization task can be handed over from MAC to physical layer allowing now run-time parameters adaption. This can be seen as the basis for any so-called flexible modem where flexibility here mainly stands for a kind of umbrella concept representing adaptivity and reconfigurability. Concerning the WIND-FLEX modem, the supervisor tries to fit the QoS requirements from the MAC to the current channel conditions aiming at the minimization of transmission and processing power.

III. Channel coding aspects

According to Ungerboeck's fundamental paper about trellis-coded modulation (TCM) [4], coding and modulation should be combined in a single entity to achieve better performance. This has generally been accepted although it has led to partly complex and inflexible systems in terms of different coding and modulation parameters. Several powerful coded modulation schemes have been developed but most of them were merely designed for a specific combination of coding and modulation schemes. As an example, turbo trellis-coded modulation (TTCM) and parallel concatenated trellis-coded modulation (PCTCM) require different encoders and decoders for different modulation schemes.

Based on [5], [6], the idea of a joint encoder/modulator and demodulator/decoder was given up in favor of a new principle with two separate entities. The pragmatic coded modulation with the bit-wise interleaving at the encoder output and appropriate soft value calculation for every bit as input to a Viterbi or MAP decoder was later renamed by Caire to bit-interleaved coded modulation (BICM) [7]. This approach is well-suited for the presented modem architecture and provides the needed flexibility without sticking to one predefined parameters set.

A. System model

To investigate the error performance of the turbo-coded OFDM system and its channel coding related issues, the system model as described below has been considered. The following assumptions and simplifications have been made:

- ideal synchronization in time and frequency,
- flat fading on subcarriers,
- channel is static during the transmission of one OFDM symbol, i.e. OFDM symbol duration is shorter than coherence time of channel,

- without intersymbol interference, i.e. guard interval is long enough,
- linear channel.

If all these assumptions are taken into account then IFFT, guard interval insertion, channel, guard interval removal, and FFT can be represented by a multiplication of the modulator output with the fading coefficients provided by the channel model and the addition of Gaussian noise. A block diagram of the system model is presented in figure 2.

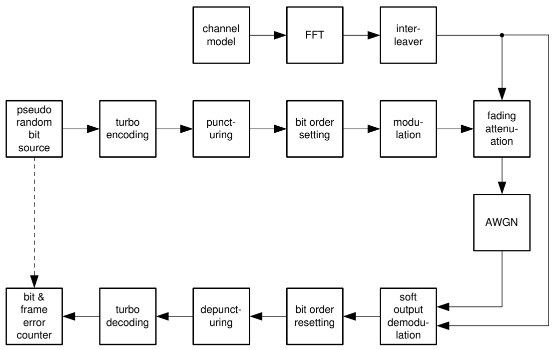

Fig. 2. Block diagram of the system model

Information bits are encoded with a turbo encoder containing two identical recursive systematic convolutional encoders. The parity bits can be punctured to achieve different code rates. The bit order setting allows an arbitrary assignment of systematic and parity bits to the bit positions within the modulation symbols for 16QAM and 64QAM. This offers the possibility to take advantage of the different protection levels inherently contained in higher-order modulation schemes. The modulator maps the coded bits onto Gray-encoded modulation symbols.

The channel itself is represented by a tapped delay line model in time domain. LOS and NLOS models for a SOHO (small office/home office) environment are provided in [8]. The fading coefficients for the OFDM subcarriers are obtained by performing a FFT at the channel model output. The total path loss that depends on the distance between transmitter and receiver is not considered. Furthermore, it is assumed that average transmitted energy is equal to average received energy referring to a relative long time. In the present case, long time stands for the frame duration of around 0.5 ms, because transmission parameters like information block length, code rate, modulation scheme, and others can be adapted frame by frame. During one frame, the channel is static. As it can be seen in figure 2, instead of interleaving the modulation symbols at transmitter side and deinterleaving them at receiver side, the fading coefficients themselves are interleaved (see also section III-B). Gaussian noise is added to every subcarrier.

In order to tickle the best performance out of the employed turbo coding scheme, the need for soft values at the turbo decoder input arises. Soft decision decoding clearly outperforms conventional hard decision decoding where the decoder can only use the hard values which are provided by the demodulator. In contrast to that, soft decision decoding takes additionally reliability information of the hard values into account. Therefore, the received symbols which have been distorted by the channel are demodulated and soft values for every coded bit are calculated [9]. The order of the soft values is restored according to the original bit sequence at transmitter side. The depuncturer inserts appropriate values at positions where bits have been punctured. The turbo decoder processes the incoming soft values over a variable number of iterations and provides the decided bits at the output.

B. A pragmatic approach to coded modulation

As indicated above, a pragmatic coded modulation scheme can be understood as a serial concatenation of a binary code for error correction, an interleaver and a memoryless modulator for bandwidth-efficient modulation schemes. At the transmitter side, the information sequence is encoded by the error correction scheme and interleaved. The purpose of the interleaver is to break the sequential fading correlation and increase diversity. The interleaved sequence is divided into subsequences of consecutive bits and the modulator maps the bits onto modulation symbols. On the receiver side, an optimal maximum likelihood decoding would require a combined demodulation/decoding which is far too complex for a practical implementation. Thus, the receiver also consists of two separate entities. The demodulator acts as a soft value calculator and provides these for every bit. After deinterleaving, the soft values are fed into the soft decision decoder.

Motivation for this principle is the wish to further increase performance of coded modulation in fading channels by gaining additional diversity. For OFDM systems, an increase of frequency diversity and when interleaving over several OFDM symbol even time diversity can be achieved. Moreover, it would be worth employing a standard off-the-shelf Viterbi or MAP decoder for all different coding and modulation schemes instead of designing a specific coder and decoder for every combination.

BICM for example offers a straightforward realization and high flexibility. Independent of the modulation scheme used, the same error correcting code can be applied. Furthermore, different code rates can easily be realized by puncturing the mothercode. In fact, the implementation of the main components in hardware can remain unchanged while switching parameters like code rate, information block length and modulation scheme. One drawback is the need for different bit interleaver sizes, because different information block lengths and code rates also result in different coded block lengths that have to be interleaved. Implementing optimized interleavers like the s-random type as look-up tables can get very memory consuming. A possible solution could be the application of algorithmic interleavers.

Based on the BICM principle, a modified approach is considered to reduce implementation complexity of the interleaver between encoder and modulator as well as demodulator and decoder without degrading performance. Interleaving modulation symbols rather than coded bits reduces the number of needed interleaver patterns to only one. If such a interleaver covers all subcarriers within one OFDM symbol then only the number of bits per modulation symbol changes. Additionally, symbol interleaving offers the possibility to take advantage of the different bit protection levels inherently contained in higher-order modulation schemes. Now, special bit mappings can be applied, because the positions of the turbo encoder output bits within modulation symbols are kept throughout the interleaving process. Figure 3 shows exemplarily the performance of 16QAM with different bit assignments in the AWGN channel. For all code rates, two different bit assignment strategies are depicted. Bit assignment A protects the systematic bits better and bit assignment B protects the parity bits better. Which strategy performs best depends on the target BER. Considering a BER of 10^{-5}, the mapping of systematic bits onto better protected bit positions achieves a better performance.

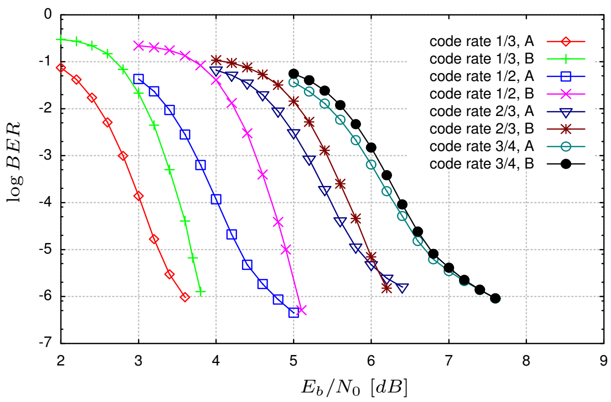

Fig. 3. Performance of 16QAM with different bit assignment strategies in the AWGN channel (code polynomial $(13, 15)_{octal}$, information block length 1024, Max-Log-MAP, 6 iterations)

The main difference of turbo-coded symbol-interleaved modulation (TCSIM) to conventional BICM is the replacement of the bit interleaver by a combination of bit mapping block and symbol interleaver. At the receiver side, the bit deinterleaver has to be replaced by a bit demapping block and a symbol deinterleaver. Figure 4 shows the performance of TCSIM compared to BICM.

It can be seen, that the principle of symbol-wise interleaving and mapping of the systematic bits onto better protected positions achieves for 16QAM and code rate 1/3 even a slightly better performance than bit-wise interleaving over the complete code block. Although the bit mapping is especially well-suited to gain additional performance in the AWGN channel, it is also recommended to employ it in fading channels like the WIND-FLEX NLOS channel type.

From an implementation point of view, the need of

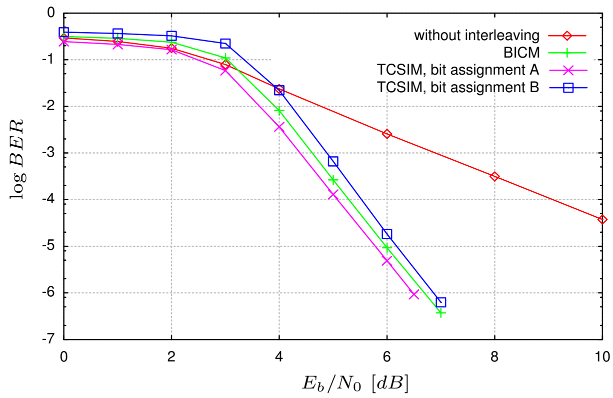

Fig. 4. Performance of TCSIM in the WIND-FLEX NLOS channel (16QAM, code polynomial $(13, 15)_{octal}$, code rate 1/3, information block length 1024, Max-Log-MAP, 4 iterations)

only one interleaver pattern is advantageous. Logic consumption of bit mapper and demapper can be neglected. Bit mapping patterns only have to be implemented for 16QAM and 64QAM, because different protection levels do not exist for BPSK and QPSK.

C. Channel impact on coding performance

Having in mind a real implementation, the question arises how to satisfy the optimization criterium that is predefined in the supervisor with the offered parameters flexibility. To take advantage of this ability to change parameters at run-time, the channel impact on the turbo coding performance has to be considered in more detail.

Starting point is the conventional approach based on average performance. Here, average performance stands for the performance over an infinite number of channel realizations with the same average signal to noise ratio (SNR) over all subcarriers within one OFDM symbol. This approach is sufficient if different channel coding schemes or parameters sets have to be compared with each other. Taking the general understanding of an optimized modem on the other hand, the average performance can not act as a criterium for parameters selection anymore, because turbo coding performance differs considerably for channel realizations with the same average SNR. Now, exact information about the current channel state is needed to select the most appropriate set of parameters.

An approach to cope with this problem is the classification of the different channel realizations into groups according to their variance of fading coefficients. The variance distribution of the fading coefficients for the NLOS channel is presented in figure 5. All variances have been obtained for channel realizations with the same average SNR.

As a first step, the distribution has been divided into four variance classes each covering a fixed range. These classes represent a kind of quality levels for the channel. That means, the channel realizations with smaller variance values denote channels with more or less equally attenuated subcarriers. In contrast to that, higher variance values are obtained for channel realizations, where

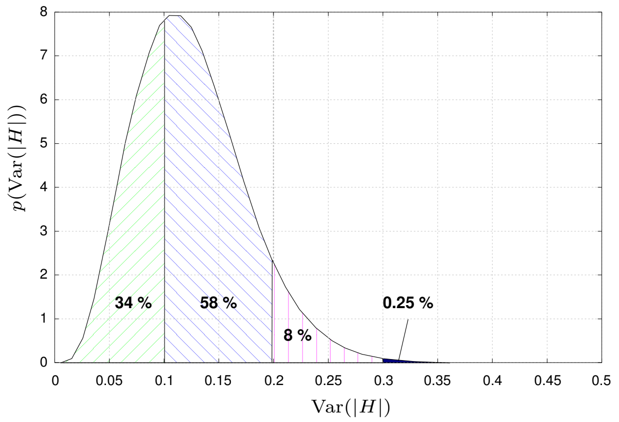

Fig. 5. Variance distribution of the fading coefficients for the NLOS channel

the greater part of the OFDM symbol is strongly attenuated and only some subcarriers are very good. It is still assumed, that the average energy of all subcarriers is always the same. If such bad channel realizations occur then the coded data that was transmitted is severely destroyed. The remaining data can be insufficient to provide the necessary information to decode the whole code block correctly. In the presented NLOS case, the group that occurs with a probability of 0.25 % stands for those kind of channels. Although only few channel realizations are characterized by higher variance values, the average performance is clearly determined by them. This can be seen in figure 6.

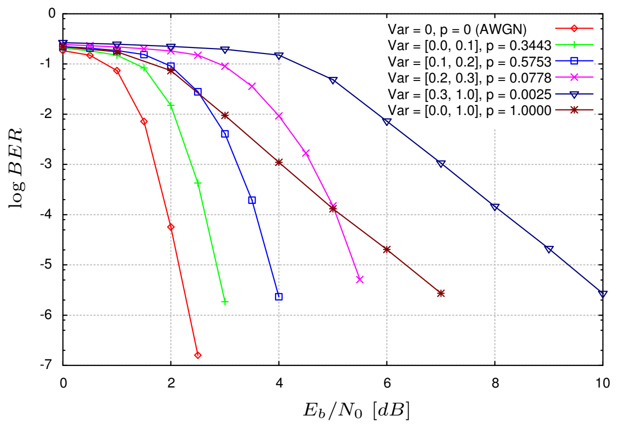

Fig. 6. Performance of TCSIM depending on fading coefficient variance in the WIND-FLEX NLOS channel (QPSK, code polynomial $(13, 15)_{octal}$, code rate 1/2, information block length 1024, Max-Log-MAP, 4 iterations)

The presented curves correspond to the channel classes introduced in figure 5. Additionally, the performance for the AWGN case and the average over all channel classes are depicted. As expected, the curve showing the average performance is for higher E_b/N_0 determined by the few bad channel realizations. All other curves follow the principle, the smaller the variance of the fading coefficients the closer they get to AWGN performance. It can be seen, that the performance of the turbo coding scheme is considerable better for small variance values.

A preliminary approach to cope with this problem can be the exclusion of some strongly attenuated subcarriers. Although such algorithms decrease the variance of the fading coefficients, the bad channel realizations where probably a lot of subcarriers had to be excluded still remain as the performance restricting factor. However, in order to optimally adapt all parameters of the modem, the channel realizations have to be classified into an appropriate number of groups. For each of the groups, separate simulations have to be performed to determine the exact BER performance. This ensures, that the supervisor knows all the necessary information about the current channel state and is able to choose the most suitable set of parameters.

IV. Conclusions

In this paper the employment of a turbo coding scheme within an OFDM-based modem architecture has been analyzed while ensuring flexibility of coding parameters and support of different modulation schemes was the primary objective. With the pragmatic approach of turbo-coded symbol-interleaved modulation an option was presented, how to realize this idea and ease implementation constraints at the same time.

Aiming at a real implementation, the need for a different approach of evaluating the radio channel was outlined. It has been shown that channel coding performance does not only depend on average SNR over all subcarriers but instead also on the fading characteristics of the radio channel, namely the variance of the fading coefficients. The supervisor has to take this variance into account to optimize all parameters and to be able to adapt the modem to the current channel conditions and user requests. On this area of research, further work will be carried out.

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