Implementation of end-to-end Wi-Fi Transceiver

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***Abstract*—In this project, we design a modular end-to-end wireless transceiver which can be used to study the impact of different elements of a digital communication system on the system performance. The parameters for implementation of different blocks have been borrowed from the IEEE 802.11 standard family (Wi-Fi). In particular, the source coding, interleaving, modulator, channel (AWGN and Rayleigh fading) channels along with OFDM based PHY blocks have been implemented and evaluated in the project.**

I. Introduction

In this project, our goal is to simulate the transmission of a bitstream reliably over an error-prone wireless channel. While achieving this goal, through this project, we implement different blocks of a wireless communication system and evaluate its performance. The project focuses on the implementation of channel encoder/decoder, modulator/demodulator and wireless channel blocks (Fig. 1, borrowed from [1]).

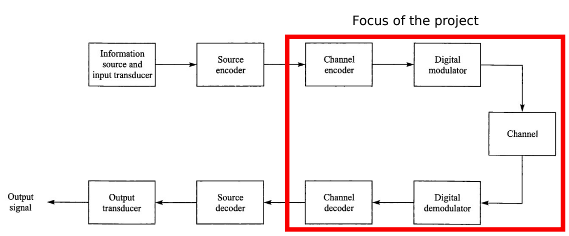


Fig. 1: Blocks implemented in the project, borrowed from [1]

The following learning objectives had been set at the beginning of the semester for this project.

- Understand the theory and implementation details of channel coding techniques in contemporary wireless standards such as LDPC.
- Understand the challenges encountered at a receiver in mitigating the effects introduced by a wireless channel (such as fading).
- Gain an understanding of an end-to-end wireless communication system (from channel encoder onwards).

The following sections and subsections aim to demonstrate the outcome of these learning objectives. Section II provides the relevant background used in the implementation of this project along with some fine details related to the implementation. Section III provides the results of the validation process as well as detailed analyes of the different blocks. Finally, Section IV identifies the areas where additions/improvements can be made to the current project.

II. Background and Implementation details

A. Components implemeted

The following components of a digital communication system have been implemented in this project.

- LDPC encoder and decoder as per Wi-Fi standard,
- Interleaver and de-interleaver,
- Bit-to-symbol mapper (modulator) and symbol-to-bit mapper (demodulator),
- OFDM Physical Layer (PHY) as per Wi-Fi standard,
- AWGN channel,
- Rayleigh fading channel (flat fading/single tap),
- Single tap equalizer (for non-OFDM as well as OFDM PHY).

The entire code has been written in a modular structure, where any component can be added or removed as per the requirement.

B. Implementation details

1) LDPC encoder and decoder: The parity-check matrix for the LDPC decoder were used from the Wi-Fi standard [2]. The parity-check matrix given in [2] is in the prototype form and needs to be converted to the binary form. Subsequently, the generator matrix can be created and used to encode blocks of data bits. A sample H matrix in the prototype form for rate = 1/2 is shown in Fig. 2.

0	-	-	-	0	0	-	-	0	-	-	0	1	0	-	-	-	-	-	-	-	-	-	-
22	0	-	-	17	-	0	0	12	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-
6	-	0	-	10	-	-	-	24	-	0	-	-	-	0	0	-	-	-	-	-	-	-	-
2	-	-	0	20	-	-	-	25	0	-	-	-	-	-	0	0	-	-	-	-	-	-	-
23	-	-	-	3	-	-	-	0	-	9	11	-	-	-	-	0	0	-	-	-	-	-	-
24	-	23	1	17	-	3	-	10	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-
25	-	-	-	8	-	-	-	7	18	-	-	0	-	-	-	-	-	0	0	-	-	-	-
13	24	-	-	0	-	8	-	6	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-
7	20	-	16	22	10	-	-	23	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-
11	-	-	-	19	-	-	-	13	-	3	17	-	-	-	-	-	-	-	-	-	0	0	-
25	-	8	-	23	18	-	14	9	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
3	-	-	-	16	-	-	2	25	5	-	-	1	-	-	-	-	-	-	-	-	-	-	0

Fig. 2: H matrix in prototype form for Wi-Fi, code rate = 1/2.

The code used to generate the binary parity check matrix and the generator matrix was borrowed from [4] and modified. The Wi-Fi standard allows for code rates of — 1/2, 2/3, 3/4 and 5/6. For each of these code rates, a different prototype matrix has been defined in [2]. All parity check matrices result in the same value of n, with corresponding number of k.

The Code for a Hard Decision Decoder for LDPC was implemented as per taught in the class.

C. Interleaver and de-interleaver

Without the use of error correction coding, an error in any location (random or bursty) cannot be corrected. Thus, the interleaver/de-interleaver is used only when LDPC coding is enabled. The width of the interleaver was set to the length of the codeword, i.e. n = 648 bits. The depth of the interleaver is a tunable parameter whose impact is studied later in the report.

D. Bit-to-symbol mapper (modulator) and symbol-to-bit mapper (demodulator)

The Wi-Fi standard defines the BPSK, QPSK, 8-PSK and 16-QAM coding schemes. A Bit-to-symbol mapper (modulator) block has been implemented that takes in the requisite number of input bits producing symbols. Similarly, the symbol-to-bit mapper (demodulator) takes the symbols as the input and generates the output bits. The receiver is implemented as a nearest-distance decoder, where the receiver simply computes the distance between the received symbol and all symbols in the constellation and declares the symbol with shortest distance to the received signal as the output symbol.

E. OFDM Physical Layer (PHY)

The OFDM PHY has been implemented as per the Wi-Fi standard [2]. The parameters used by the OFDM PHY are as shown in Table I.

Parameter	Value
Number of subcarriers	64
Subcarrier width	312.5 kHz
No. of pilot subcarriers	4
No. of data subcarriers	48
No. of null subcarriers	12
Basic symbol duration	3.2μsec
Cyclic Prefix length	0.8μsec

TABLE I: OFDM Wi-Fi parameters

As seen in Table I, there are 12 null subcarriers which are used as guardbands, and do not carry any data bits. The positioning of these subcarriers is shown in Fig. 3.

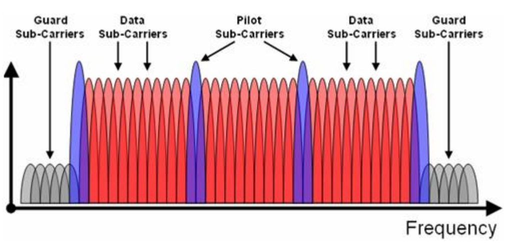


Fig. 3: Subcarrier arrangement in Wi-Fi [5]

Due to the addition of Cyclic Prefix in the time domain and the guardbands in the frequency domain, the OFDM symbol energy is not the same as the bit energy. The relation between OFDM symbol energy and bit energy is given by Eq. (1).

$$\left(\frac{E_s}{N_0}\right)_{dB} = \left(\frac{N}{N_{cp}+N}\right)_{dB} + \left(\frac{N_{st}}{N}\right)_{dB} + \left(\frac{E_b}{N_0}\right)_{dB}, \quad (1)$$

where N is the number of subcarriers, N_{cp} is the number of samples that carry cyclic prefix, N_{st} is the number of non-null subcarriers.

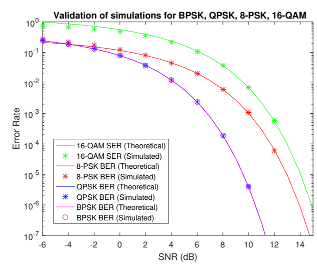
III. Results

A. Validation

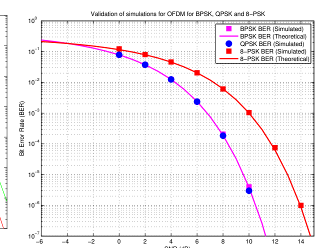
In order to ensure that the performance analysis can be done correctly, the simulations are first validated against known theoretical results. In particular, the following implementation steps have been validated.

- Performance of BPSK, QPSK, 8-PSK and 16-QAM in an AWGN channel.
- Performance of BPSK, QPSK, 8-PSK and 16-QAM in an AWGN channel with OFDM PHY.
- Performance of BPSK in a Rayleigh fading channel.
- Performance of BPSK in a Rayleigh fading channel with OFDM PHY.

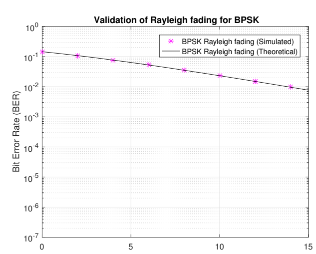
Fig. 4 shows the results of these validation experiments.



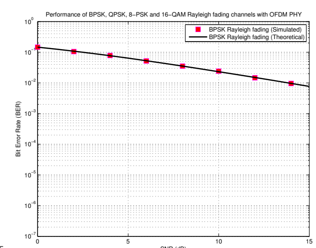
(a) AWGN channel



(b) AWGN channel, OFDM PHY



(c) Rayleigh fading channel



(d) Rayleigh fading channel, OFDM PHY

Fig. 4: Validation of modulation schemes in AWGN and Rayleigh fading channels

B. Performance Analysis

In this subsection, we analyze the impact of different components on the overall system performance.

1) Performance of different modulation schemes in an AWGN channel: As seen in Fig. 4c, as the modulation order increases, the energy efficiency of the modulation scheme reduces due to the tight packing of symbols. The error rate is the highest for 16-QAM, while it is the lowest for BPSK.

2) Performance of different modulation schemes in a Rayleigh fading channel: The performance of different modulation schemes in a Rayleigh fading channel is shown in Fig. 5. It can be seen that the same trends as observed in an AWGN channel can also observed in a Rayleigh fading channel, i.e. as the modulation order increases, the error rate rises. However, the notable difference in case of Rayleigh fading channels is that the error rate performance of all modulation schemes is significantly worse than that observed in an AWGN channel. Even for a BER of 10^{-2}, an additional 10 dB in SNR is required in a Rayleigh fading channel.

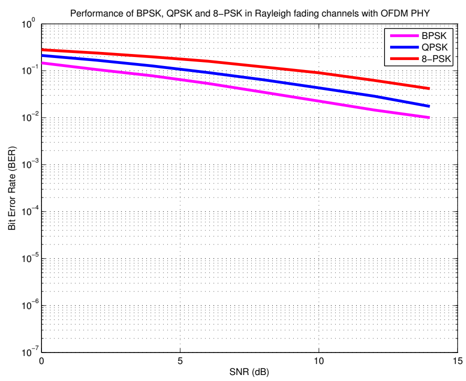


Fig. 5: Performance of different modulation schemes in a Rayleigh fading channel

3) Impact of coding and interleaving in an AWGN channel: Fig. 6 shows the impact of coding and interleaving in an AWGN channel when the modulation scheme used is BPSK. It can be clearly seen that channel coding improves the energy efficiency of the system. For a BER of 10^{-4}, a coding gain of approximately 2 dB is achieved. It must be noted that the LDPC decoding took a large amount of time and hence achieving lower BER (passing more bits through the channel) took too much time. Hence, results only upto BER of 10^{-4} have been presented.

At extremely low SNRs (up to 2 dB) LDPC coding performs worse than uncoded system. This is expected since for low SNR, when the error rate is extremely high, the bits decoded at the decoder are more or less random. The LDPC decoder will decode the codeword closest to received codeword. Since the received codeword is random, the decoded codeword is also random in nature, resulting in a high BER.

It can also be seen that the interleaving provides negligible gains in an AWGN channel. This is because AWGN channel does not cause bursty errors. As a result, shuffling the order in which data bits go in and out of the device is irrelevant.

4) Impact of coding and interleaving in a Rayleigh fading channel: The performance gains obtained using coding and interleaving in a Rayleigh fading channel is shown in Fig. 7.

Since the BER performance in a Rayleigh fading channel is poor, the error performance of the LDPC decoder is lower than that of uncoded BPSK up to SNR of 20 dB (as compared to 2 dB in AWGN channel). Beyond SNR of 20 dB LDPC shows coding gain. The coding gain for BER of 10^{-4} is

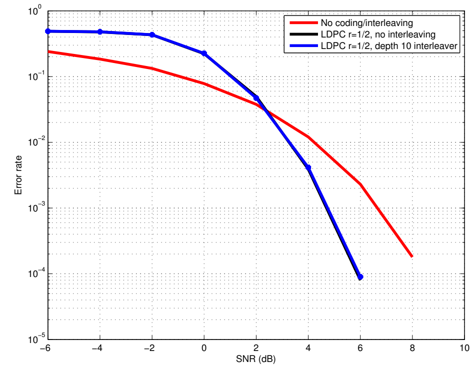


Fig. 6: Impact of coding and interleaving in AWGN channel for BPSK

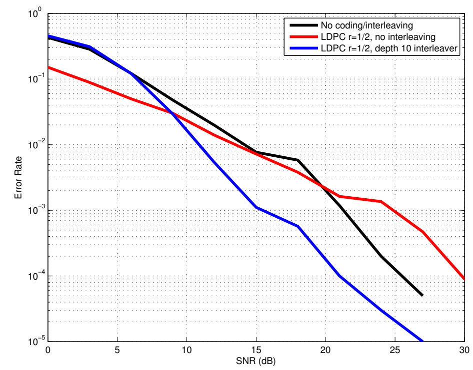


Fig. 7: Impact of coding and interleaving in Rayleigh fading channel for BPSK

approximately 5 dB, with a code rate of 1/2 and 50 iterations at the LDPC decoder.

As opposed to the AWGN channel, the use of an interleaver in a Rayleigh fading channel shows significant gains in the energy efficiency of the system. This is because a Rayleigh fading channel causes bursty errors. Thus, when the channel enters deep fade, several symbols are effected. It must be noted here that the Rayleigh fading channel is used along with the OFDM PHY. As a result, even though the channel can potentially come out of deep fade within one OFDM symbol interval, each OFDM symbol contains several BPSK symbols (52 in the case of Wi-Fi); thus causing bursty errors. For a BER of 10^{-4}, the use of an interleaver provides a gain of approximately 4 dB and 9 dB over coded and uncoded systems respectively.

5) Impact of LDPC decoder complexity: In this section, we see the impact of decoder complexity on the performance of BPSK modulation scheme over a Rayleigh fading complexity. Here, the complexity is in terms of the number of maximum iterations performed by the LDPC decoder (as opposed to Soft Decision Decoding). Fig. 8 shows the BER of BPSK for different number of maximum iterations performed at the LDPC decoder. All results have been obtained with the interleaver ON, and interleaver depth set to 10.

It can be seen that in general, the performance of the

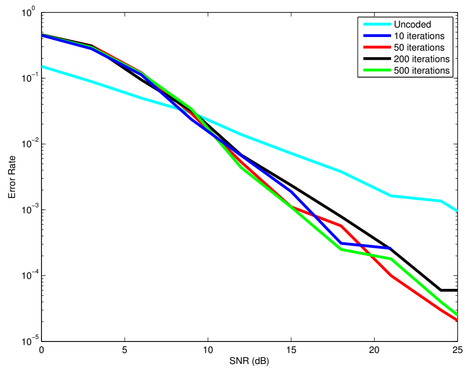


Fig. 8: Impact of LDPC decoder iterations in Rayleigh fading channel for BPSK

decoder improves as the number of iterations go up. However, this is not always true. For instance, the performance of LDPC decoder with a maximum iterations 50 is superior than the decoder with maximum iterations set to 200. Moreover, at higher SNRs, decoders with larger number of maximum iterations tend to overcorrect, leading to loss in performance. Thus, if the SNR at a receiver is known to be high enough, the number of maximum iterations at the LDPC decoder can be set to a moderately low value (around 50).

C. Impact of Interleaver depth

Fig. 9 shows the impact of interleaver depth on the error performance of BPSK in a Rayleigh fading channel. The interleaver is used along with LDPC with code rate 1/2. It can be clearly seen from the figure that although interleaving provides significant gain over the uncoded system, the depth of the interleaver plays very little role in the performance. Thus, a relatively small depth of the interleaver (such as 10 codewords) can be used without sacrificing the performance of the system. This helps in reducing the overall system delay.

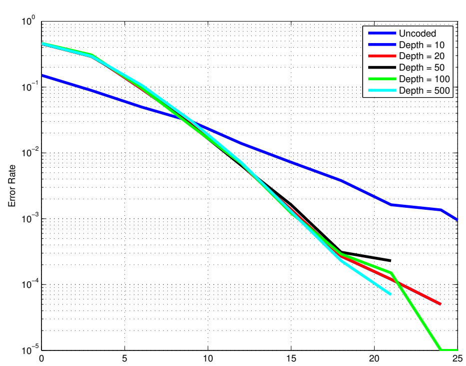


Fig. 9: Impact of interleaver depth in Rayleigh fading channel for BPSK

D. Impact of LDPC code rate

Fig. 10 shows the impact of LDPC code rate on the error performance of BPSK in a Rayleigh fading channel. It can be easily seen that the performance improves for decreasing code rate. The available code rate options for Wi-Fi are 1/2, 2/3, 3/4 and 5/6. The performance of the LDPC encoder/decoder is the best for code rate of 1/2 and successively deteriorates for increase in code rate.

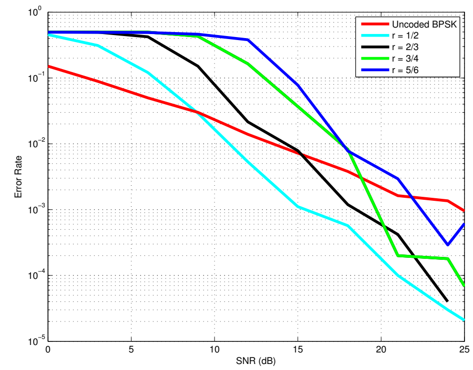


Fig. 10: Impact LDPC code rate in Rayleigh fading channel for BPSK

IV. Future Work

Due to the time constraints posed by the semester, there were several aspects of the project that I could not complete. I plan to add the following components to the project as a part of future work.

- LDPC soft decoding,
- Convolutional encoding and decoding,
- Frequency-selective fading and multi-tap equalization,
- More extensive simulations for low BER results.

References

[1] John G.. Proakis, and Masoud Salehi. “Digital communications”. McGraw-Hill, 2008.

[2] IEEE 802.11 Working Group. “IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.” IEEE Std 802, no. 11 (2010).

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