Wireless Communication Project

1 Introduction

The objective of this project is to design and implement a wireless communication in Matlab considering a real-life propagation environment. The considered framework is close to the IEEE 802.11n standard. We will use the orthogonal frequency division multiplexing (OFDM) modulation which can efficiently deal with the memory of the propagation channel. To be able to make this communication, you need to be familiar with the digital signal processing part of the communication and the propagation channel. We will provide you channel measurements done in our lab to build a realistic channel model.

The project is divided in two parts. First a Single Input Single Output (SISO) communication will be addressed. The channel will be characterized for a single antenna. In the second step, we will consider multi-antenna devices. More precisely, we will study the Single Input Multiple Output (SIMO) configuration. It will help us to have a better understanding of the propagation channel. We will see how a multi-antenna receiver can be used to improve the communication performances.

At the end of the project you must be able to completely understand and implement the communication system including the wireless channel to show how to obtain the best performance and to transmit information.

This design contains several steps:

- Study the time characteristics and spatial distribution of the channel.
- Based on those properties, build a physical model of the SISO channel.
- Implement a SISO OFDM transceiver (IFFT/FFT, cyclic prefix addition and removal, channel equalization) and study its Bit Error Rate (BER) performance subject to an Additive White Gaussian Noise (AWGN) and a multi-path channel.
- Discuss the choice of modulation parameters (block size, cyclic prefix length, sampling rate).
- Implement the synchronization structure to support the OFDM communication.
- Extract the angular distribution of the Multi-Path Components (MPC's) and deduce the spatial correlation of the channel.
- Knowing the angular distribution, build a SIMO channel model.
- Extend the OFDM transceiver to a SIMO configuration and show the performance gain.

The project is organized over 9 sessions. At the end of the project, you will be evaluated based on an oral presentation of 15 minutes and a technical report (20 pages) sent to the assistant and professors (Deadline to be discussed, probably week 38). The digital communication system will be completely designed and studied by your group (2-3 persons).

Table 1: Agenda

	Dates	Theme
1	21/4	Transfer function, Impulse response, PDP, Coherence bandwidth
2	24/4	SISO Channel model with a 20 MHz bandwidth: Statistical model of the narrowband and wideband channel
3	28/4	OFDM and channel equalization
4	2/5	Channel estimation
5	5/5	Time of Arrival (ToA) estimation
6	8/5	Carrier Frequency Offset (CFO) acquisition, compensation and tracking
7	12/5	Beamforming, SIMO channel model and Spatial Correlation
8	15/5	SIMO communication
9	19/5	Question and answer
10	TBD	Evaluation

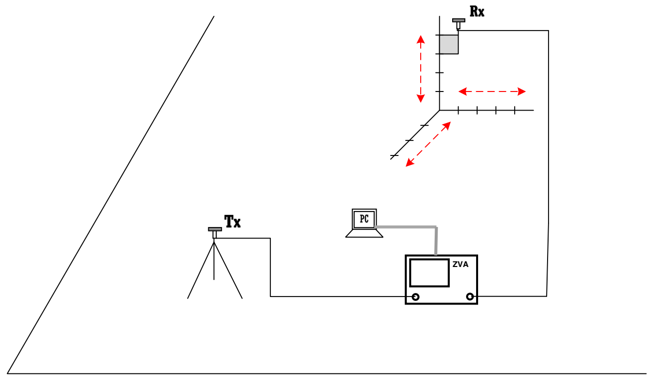

Figure 1: Experimental Plan

2 Channel measurement

For the channel measurement campaign, the TX is placed at some location in an indoor environment and the RX on the 3D automatic positioning device. For each position of RX, a channel acquisition is made. These positions are defined on a 3D grid thanks to the control software. This measurement lead to the construction of a virtual antenna array in a local area (Figure 1). The measurement campaign has been done in Line-Of Sight (LOS) and Non-Line-Of-Sight (NLOS) configurations.

The measures have been done between 2.25 GHz and 2.45 GHz (200 MHz bandwidth) at each position of a $10 \times 10 \times 10$ virtual antenna array. For each position i in the virtual array, the frequency response $H_i(f)$ is measured, with a frequency resolution of 400 kHz. Each position is separated by 2 cm. You will receive a file with the frequency response for each point of measurement. Each transfer function is stored in Data{x}{y}{z}.

3 SISO Communication

3.1 Channel model

Distribution of the tap

Narrowband and wideband

Let us consider a case where N waves are incident onto a receiver in a local area. In narrowband, the transfer function h is given by

$$h = \sum_{i=0}^{N-1} a_i e^{j\phi_i} e^{-j\vec{\beta}_i.\vec{r}} \tag{1}$$

where $\vec{\beta_0}$ is the wave vector of the direct wave. In this scenario, the receiver cannot discriminate all Multi-Path Components (MPC's).

On the other hand, wideband models take into account time dispersion. If B_m is the measurement bandwidth, all waves arriving during a delay tap of duration $\Delta\tau = 1/B_m$ sum up at the receiver. The channel impulse response, which is the inverse Fourier transform of the frequency response (see Eq. 4.13[1]), can be written as (also called tapped delay line model)

$$\tilde{h}(n) = \sum_{i=0}^{N-1} A_i e^{j\phi_i} e^{-j\vec{\beta}_i.\vec{r}} \delta(n\Delta\tau - \tau_i) \tag{2}$$

where τ_i is a multiple of $\Delta\tau$.

The time dispersion of the channel can be observed with the Power Delay Profile (PDP). It characterizes the mean power arriving in the local area as a function of propagation delay. We can quantify the time dispersion of the channel with the delay spread σ_τ which characterizes the PDP duration. It can be related to the channel selectivity. Channel coherence bandwidth Δf_c is defined as the bandwidth over which correlation is above a given threshold (typically 0.7). If the signal bandwidth B_s is smaller than Δf_c, all signal frequencies will experience about the same channel gain. We are in flat fading. Otherwise, channel must be modelled taking into account frequency selective fading.

For both scenarios, LOS and NLOS:

- Extract the channel frequency response, calculate the impulse response at each position;
- Observe the effect of the limited bandwidth, and fix this problem;
- Extract the Power Delay Profile (average over all positions), calculate its delay spread and confirm that it follows an exponential decay;
- Evaluate the coherence bandwidth;
- Reduce the bandwidth to 20 MHz using a rectangular and non-rectangular window. Interpret the impact on the impulse response (Power Delay Profile, Delay Spread, Coherence Bandwidth).

Narrowband and Wideband statistical model

For a given set of incident plane waves, the transfer function could be calculated by equations (1) and (2). This method is impossible in practice, however. The phases and amplitudes of the incident waves depend on the interactions of each wave with the Interacting Objects (IO). To be able to predict these values, it would be mandatory to have the full knowledge all the IO's characteristics. A small

[1] See Wireless Communication Channels, Chapter 4

error in these characteristics would lead to major differences in the calculated phases ϕ_i.

As a consequence, we will use another methodology: we will build a stochastic model of the interference patterns, by assuming that h is a random function in a given local area.

In narrowband, in a NLOS situation, the deterministic model for h is replaced by the stochastic model

$$h = Ae^{j\Phi} \tag{3}$$

where Φ is a random variable with uniform distribution between 0 and 2π and A, the amplitude of h, follows a Rayleigh distribution.

This is not the case when there is a LOS channel between transmitter and receiver : the direct wave is then much stronger than the multi-paths since it has a shorter propagation distance, and does not experience any reflection or diffraction off the IO's. In the receiver local area, h is then written as

$$h = \sqrt{\frac{K}{K+1}}e^{j\Phi_0} + \sqrt{\frac{1}{K+1}}Ae^{j\Phi} \tag{4}$$

where K is the channel Rice factor, A is Rayleigh faded and Φ is uniformly distributed. In this case, $|h|$ follows a Rice distribution.

In wideband, to each tap is associated a stochastic model :

$$\tilde{h}(\tau) = \sum_{i=0}^{M} A_i e^{j\phi_i}\delta(\tau - \tau_i) \tag{5}$$

in which A_i corresponds either to a Rayleigh or to a Rician distribution.

You can use the toolbox dfittool from Matlab to evaluate the parameters of the Rice and Rayleigh distribution.

For both scenarios, LOS and NLOS:

- Build a narrowband model. Verify the statistical distribution law and calculate the parameters. Explain the Rice factor K;
- In the wideband case, for each tap, verify the statistical distribution law and calculate the parameters. Explain the evolution of the Rice factor K as a function of the delay.

3.2 Channel equalization

Orthogonal frequency-division multiplexing

The orthogonal frequency-division multiplexing (OFDM) modulation is used in most wireless communication systems to efficiently deal with the multi-path channels. The principle of OFDM is to transmit independent data symbols on orthogonal narrowband sub-carriers. The wideband frequency selective channel is thus divided into a set of narrowband frequency flat sub-channels effecting each sub-carrier.
At the receiver, each frequency flat sub-channel can be easily equalized by simple scalar multiplication. OFDM can therefore equivalently be seen as a method to equalize a time domain convolutive channel by simple coefficient multiplications in the frequency domain.

In practice, sub-carriers are created as illustrated in Figure 2. At the transmitter, the QAM symbols are defined in frequency domain. The stream of QAM symbols is serial to parallel (S/P) converted

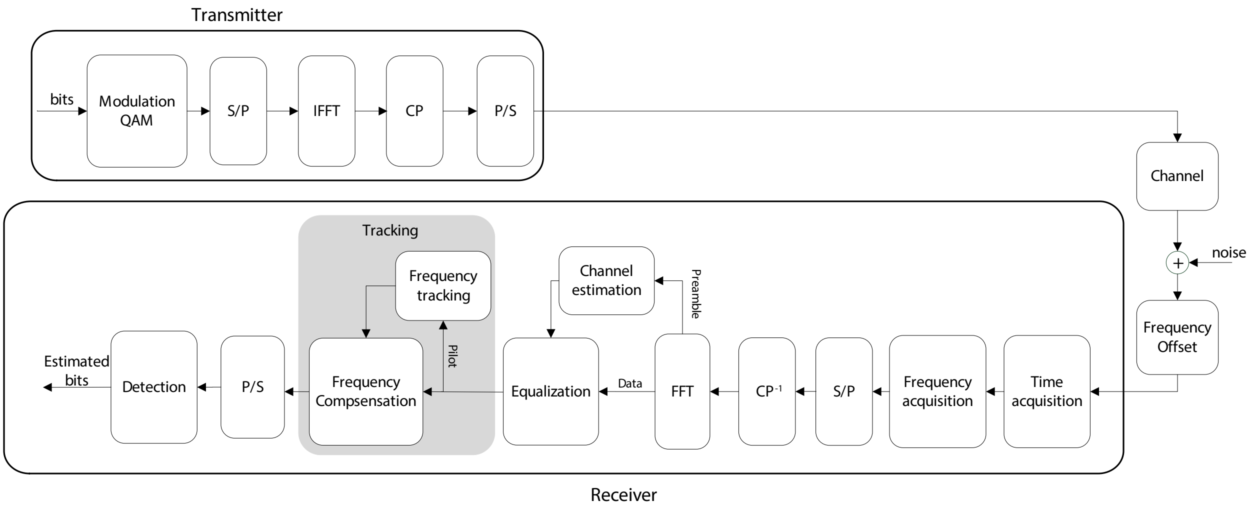

Figure 2: Bloc diagram of the OFDM communication system

in a sequence of N-point blocks. Those blocks are then brought to time domain by taking an N-point Inverse Fast Fourier Transform (IFFT). The signal is transmitted through the channel after parallel-to-serial conversion (P/S). A Cyclic Prefix (CP), which has to be larger than the channel impulse response, must be added to each block. It consists in repeating the last symbols of each data block in front of the block as shown in Figure 3 and makes therefore the data block sequences appear periodic to ensure the orthogonality among the sub-carriers. It also avoids Inter-Block Interference (IBI) as shown in Figure 4. At the receiving side, a Fast Fourier Transform (FFT) is applied after the CP removal. An estimate of the data symbols is found at the output of the frequency domain equalizer.

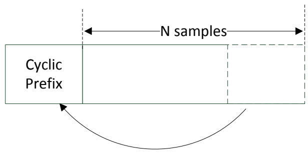

Figure 3: OFDM symbol with its cyclic prefix

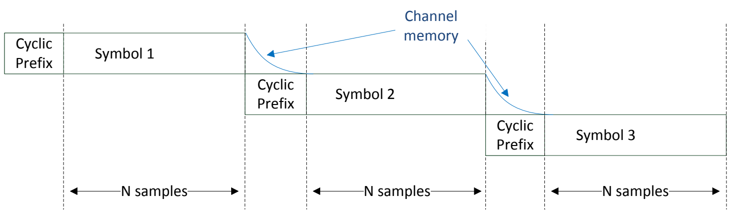

Figure 4: IBI mitigation effect of the cylic prefix

In the case of wireless local area networks, the blocks are generally composed of 64 data symbols. The length of the cyclic prefix is 16. The sampling frequency at the output of the transmitter is equal to 20 MHz.

Table 2: System Parameters

Number of sub-carriers	N	64
Cyclic prefix length	L_{CP}	16
Bandwidth	B	20 MHz
Carrier frequency	f_c	2.35 GHz

The main steps to follow for this session are:

- Implement the OFDM transceiver (IFFT/FFT, cyclic prefix addition and removal). Use the provided 'mapping' and 'demapping' Matlab functions;
- Explain why the CP addition allows to restore orthogonality among sub-carriers in a multi-path environment and verify using your Matlab model that there is neither Inter-Carrier Interference (ICI) nor IBI;
- Assess the BER performance of the OFDM system in the presence of additive noise;
- Add the channel model using your statistical model from last session, add the frequency domain equalizer at the receiver and compare the performances in a LOS and NLOS scenario. Suppose that the channel is known by the receiver;
- Discuss the impact of the channel parameters (coherence bandwidth, delay spread) on the choice of the modulation parameters (block size, cyclic prefix length, sampling rate);
- Confirm that each sub-carrier is affected by a narrowband channel in our case.

Channel estimation

The OFDM technique relies on the knowledge of the channel frequency response for the equalization task at the receiver. Therefore the channel needs to be estimated before the beginning of the data communication.

It is assumed in practice that the channel stays constant during a frame composed of multiple data blocks. A known symbol block, referred to as the preamble, is generally transmitted at the beginning of the frame to support the channel estimation. At the receiver, an estimate of the channel coefficient on each sub-carrier can easily be constructed based on the observation of the corresponding received signal. The frame structure is given in Figure 5. A preamble is typically composed by two repetitive symbols. You can make two independent estimations of the channel and average the estimates to reduce the impact of the noise. Build the preamble symbol in the frequency domain with a random sequence of $+1$ and -1.

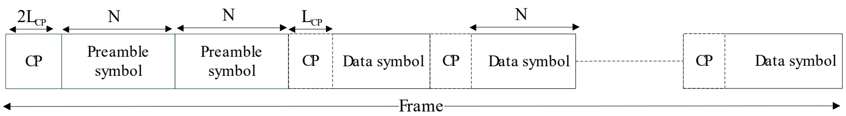

Figure 5: Frame structure

The main steps to follow in this session are:

- Form the preamble and implement the channel estimation. Keep in mind that the power of the preamble should be equal to the power of the rest of the signal. Then, form the overall frame, including the preamble and the data blocks;
- Assess the accuracy achieved on the channel estimate (normalized mean square error as a function of the signal to noise ratio) and assess the bit error rate performance degradation due to channel estimation errors;
- Bonus: Estimate the channel transfer function from an estimation of the channel impulse response. Compare the performance to the frequency domain estimation. Explain the difference.

3.3 Synchronisation

To finalise the communication system, we need to include the synchronisation strategy composed by a time and a frequency acquisition. You can find the final communication structure on Figure 2.

Time acquisition

The receiver has no a-priori information about the frame time-of-arrival. In order to successfully receive the information within the frame, the receiver must estimate the beginning of the frame.

We can use the two-times repetitive preamble symbols to support the time acquisition. The autocorrelation of the observed signal is continuously computed at the receiver. It peaks when the autocorrelation window, which has the size of a symbol, is precisely aligned on the preamble, delivering therefore an estimate of the frame time-of-arrival.

A time synchronization error can equivalently be seen as a delay introduced by the channel impulse response. The system is therefore robust to synchronization errors as long as the error falls within the cyclic prefix. Note that we neglect the clock skew in our system.

The main steps to follow in this project are:

- Add the uncertainty on the time-of-arrival to the simulation;
- Evaluate the impact of an error on the time of arrival estimation;
- Implement the time acquisition. The cyclic prefix introduces an unwanted effect. Explain this effect and carefully deal with it;
- Evaluate the accuracy achieved on the time-of-arrival estimate (Root Mean Square Error of the estimate as a function of the signal to noise ratio). Does the time-of-arrival estimation impact the BER performance?

Frequency acquisition

Unfortunately local oscillators on the receiver and transmitter sides are not perfect, incurring errors on the generated carrier frequency. The receiver must therefore estimate and compensate for the difference in carrier frequency with respect to the transmitted signal. This effect is referred to as the carrier frequency offset (CFO).

This is generally done in two steps:

- A rough estimate of the CFO is obtained during the acquisition phase. The resulting estimate is used to remove most of the CFO from the overall frame.
- At the output of the acquisition, there remains a small error on the carrier frequency (mostly due to the noise). It generates a phase shift growing with the time, that needs to be corrected using phase tracking.

The CFO is first roughly estimated during the acquisition phase based on the repetitive preamble also used for the acquisition of the frame time-of-arrival. It is performed by evaluating the constant phase shift due to the CFO between the corresponding samples of the two repetitive parts of the preamble. The output of the auto-correlator used for the time acquisition directly provides an average of the phase shift over the samples. The CFO is afterwards easily compensated by multiplying the received signal with a complex exponential in time domain.

When the time/frequency acquisition and the channel estimation are performed, the communication of OFDM data blocks is possible. The CFO remaining at the output of the acquisition causes inter-carrier interference and a common phase rotation within each received data block. If the frequency acquisition accuracy is sufficient, the inter-carrier interference can be neglected. The residual phase rotation can be compensated with the tracking operation. The common phase rotation within each data block is estimated by averaging the phase rotation observed on a few pilot symbols interleaved within the data (see Fig.6). The remaining CFO is easily compensated within each OFDM data block by inverting the estimated phase rotation on all data symbols. We will treat each data block independently from the others, even if improvements could be obtained by following the evolution of the phase rotation over the data blocks with a phase-locked loop.

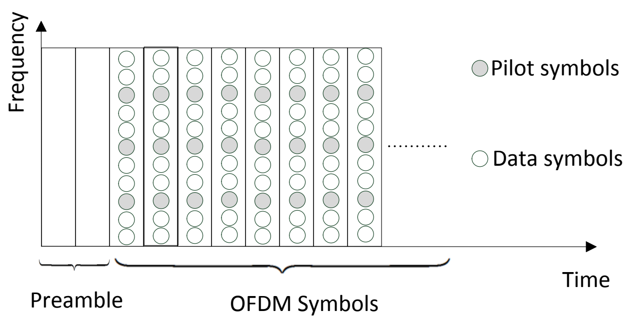

Figure 6: Position of the pilots sub-carriers in an OFDM symbol.

In the case of wireless local area networks, the number of pilots within each data block is generally equal to 4 and placed on sub-carriers -21, -7, 7 and 21.

The main steps to follow in this project are:

- Add the carrier frequency offset to the simulation and evaluate its impact;
- Implement the frequency acquisition;
- Assess its performance and show by simulation that the overall data frame can be decoded in the presence of CFO (which CFO range can be corrected?);
- Replace a few symbols with pilots within the data blocks and implement the frequency tracking.

4 SIMO Communication

4.1 SIMO channel

Formalism

Previously, we defined the SISO channel models. These models can be straight fully generalized to the SIMO case. In the narrowband case:

$$y = \mathbf{H}x + n \tag{6}$$

where x is the symbol sent through the transmit antenna, y is the vector of symbols received at the M antennas:

$$y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{pmatrix} \tag{7}$$

n is the noise vector, and H the SIMO channel vector:

$$\mathbf{H} = \begin{pmatrix} h_1 \\ h_2 \\ \vdots \\ h_M \end{pmatrix} \tag{8}$$

Beamforming

The idea of beamforming is to discover the direction of arrival of each wave. In that way, we use the 3D beamformer function $B_i(\theta, \varphi)$:

$$B_i(\theta, \varphi) = e^{-j\vec{\beta}\cdot\vec{r}_i} = e^{j\frac{2\pi}{\lambda}(X_i \sin\theta\cos\varphi + Y_i \sin\theta\sin\varphi + Z_i\cos\theta)} \tag{9}$$

with θ and φ the angular direction of arrival and i the subscript of the virtual antennas. Then, for each tap n, we obtain the amplitude of each incident wave in the direction (θ, φ) by using the following formula:

$$a_n(\theta, \varphi) = \frac{\sum_i \tilde{h}_i(n) \cdot B_i^*(\theta, \varphi)}{\sum_i |B_i(\theta, \varphi)|^2} \tag{10}$$

By identifying the different peaks in equation (9), a set of incident plane waves can be deduced for each tap. A new channel model can be build from these peaks with equation (1).

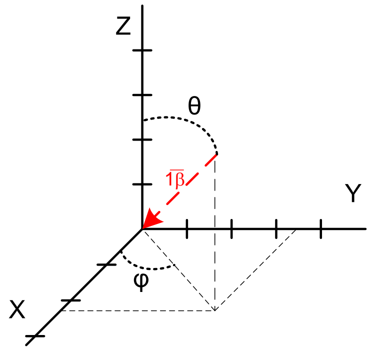

Figure 7: Geometry used for the beamforming

Spatial Correlation

An important SIMO parameter is the spatial correlation and its influence on the communication performance. It also depends on the scenario (LOS or NLOS). In this project we only have a SIMO model, so the correlation can be calculated only at the receiver. But, since the environment around the transmitter and the receiver is the same, we can assume that the channel is reciprocal and consider that the correlation is the same at TX and RX.

To calculate the spatial correlation along the z-axis from a channel model expressed similarly to equation (1), we start by defining the MPC angular distribution :

$$a(u) = 2\pi \sum_{i=1}^{N} a_i e^{j\Phi_i} \delta(u - u_i) \tag{11}$$

from which the angular spectrum can be obtained:

$$\mathrm{E}\left[a(u)a^*(u')\right] \equiv 2\pi S(u)\delta(u - u') \tag{12}$$

In these equations, $u = \beta \cos\theta$, and θ is the angle between the z-axis and the direction of incidence. The spatial correlation is then obtained as

$$R(\Delta z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S(u) e^{ju\Delta z} du \tag{13}$$

For both scenarios, LOS and NLOS:

- Explain the beamforming method (10);
- Deduce by using beamforming the angular spectrum of the MPCs for each tap;
- Build a physical model of the channel for each tap based on beamforming;
- Study the spatial correlation of the channel model you built as a function of distance between antennas, for the three directions - x, y, z - in narrowband and wideband. Compare to Clarke's model.

4.2 Communication with a multiple antenna receiver

The wireless propagation channel suffers from the fading phenomenon that causes local attenuations of the received signal and degrades therefore significantly the performance. When multiple antennas are deployed, multiple local versions of the received signal can be obtained. Even if the probability is high to obtain a single bad fading coefficient, the probability that multiple coefficients are bad simultaneously is much lower. Therefore multiple antenna systems are an attractive solution to cope with fading.

In this project, we will focus on the gain achieved when multiple antennas are deployed at the receiver. This system is generally referred to as a SIMO system. Each OFDM sub-carrier is considered as being affected by an independent frequency flat channel that suffers from the fading phenomenon. The conventional maximum ratio combining (MRC) technique is implemented on each sub-carrier independently. The estimated symbol on the q^{th} sub-carrier of a block is recovered as follows:

$$\hat{\mathbf{s}}(q) = \sum_{i=1}^{N_{\text{rx}}} \frac{\mathbf{h}_i^{F*}(q)\mathbf{r}_i^F(q)}{\sum_{j=1}^{N_{\text{rx}}} |\mathbf{h}_j^F(q)|^2} \qquad q = 1, 2, ..., N \tag{14}$$

where $\mathbf{h}_i^F$ and $\mathbf{r}_i^F$ are respectively the frequency domain channel estimation and the unequalized symbol block for the i^{th} reception antenna. Symbol * represents the conjugate operator.

Note that the CFO and time of arrival is the same for each received signal (why?). The channel estimation must be done independently for each antennas.

The main steps to follow in this session are:

- Update the communication chain to implement the SIMO system on Matlab with the new channel model;
- Assess the bit error rate performance as a function of the number of antennas;
- Discuss the interest of MRC compared to a simple symbol combination;
- Illustrate the benefit of spatial diversity on the obtained BER curves.