Wireless Communication Project

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Outline

Outline

Context

The goal is to simulate a reliable OFDM communication system

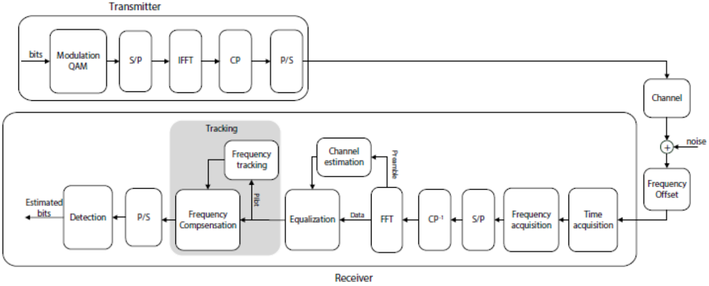


Figure: OFDM communication

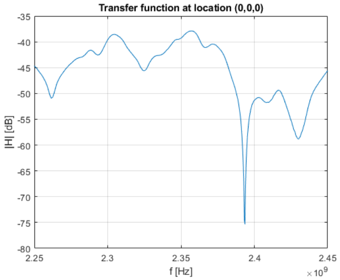
Outline

Channel transfer function

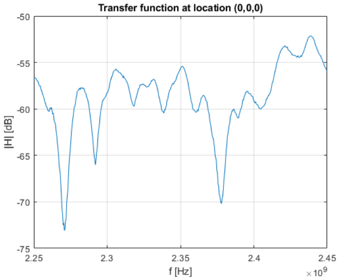
The transfer function of channel is measured over a BW of 200MHz

⟶ Some frequency components vanish

⟶ The channel is frequency selective



(a) LOS



(b) NLOS

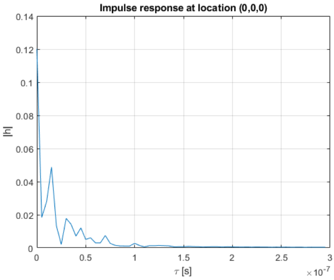
Figure: Transfer function of Channel at location $(0, 0, 0)$

Channel impulse response

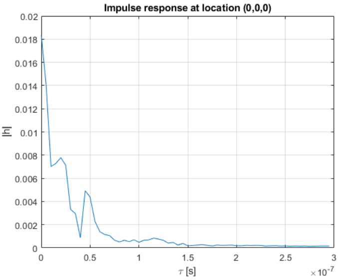
The channel impulse response is obtained after applying an IFFT on the transfer function

$\longrightarrow$ The channel is time-dispersive, this is due to frequency selectivity

$\longrightarrow$ This gives rise to ISI, if not compensated



(a) LOS



(b) NLOS

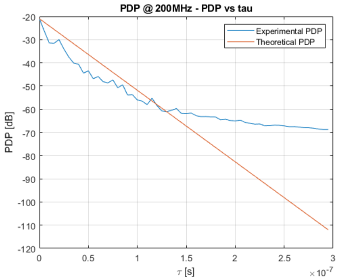
Figure: Impulse response of the 200*MHz* channel at location $(0, 0, 0)$

Power delay profile

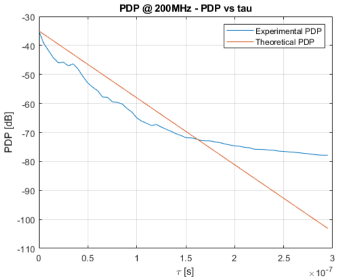
The PDP of the channel can be computed from the impulse response

Before reaching the noise floor, the PDP drops exponentially:

$$P(\tau) = P(0)\, e^{-\tau/\sigma_\tau} \tag{1}$$



(a) LOS



(b) NLOS

Figure: Impulse response of the 200MHz channel at location $(0, 0, 0)$

Delay spread

The delay spread σ_τ measures the time dispersion of the channel

$$\sigma_\tau = \sqrt{\frac{1}{P_T}\int_0^\infty \tau^2 P(\tau) d\tau - \tau_m^2} \tag{2}$$

- σ_τ is the delay where the PDP reaches the noise floor
- The higher σ_τ, the longer the symbol period T_S to avoid ISI

	LOS	NLOS
σ_τ	$12.55\ ns$	$17.44\ ns$

Table: Delay spread for $BW = 200MHz$

Coherence bandwidth

In the frequency domain, the dual quantity is the coherence bandwidth Δf_c

$$\Delta f_c = \frac{1}{2\pi\sigma_\tau} \tag{3}$$

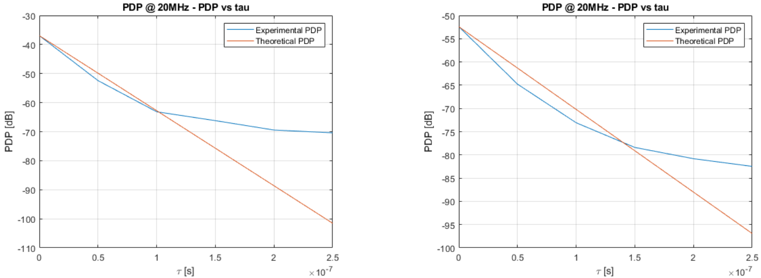
- The channel can be considered as flat if $BW << \Delta f_c$, if this true we can model the channel as narrowband
- Else, a wideband channel must be considered

	LOS	NLOS
Δf_c	$12.68\ MHz$	$9.12\ MHz$

Table: Coherence bandwidth for $BW = 200MHz$

Impact of bandwidth reduction

We analyze the effect of a bandwidth reduction to $20MHz$



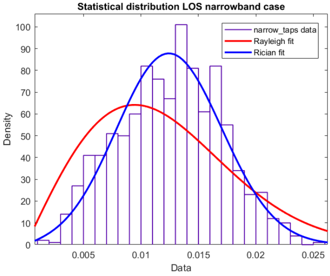
(a) LOS (b) NLOS

Figure: PDP of the system with $BW = 20MHz$

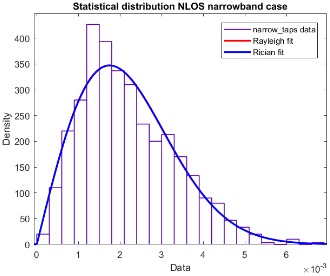
	σ_τ	Δ_{fc}
NLOS	$18.99\ ns$	$8.38\ MHz$
LOS	$12.75\ ns$	$12.48\ MHz$

Narrowband channel model (1/2)

- The receiver cannot distinguish all the MPC ⟶ All the echos of the signal are falling into a single tap
- The channel impulse response is characterized by a Rayleigh distribution in NLOS case and by a Rice distribution in LOS case



(a) LOS



(b) NLOS

Figure: Statistical distribution for the narrowband case

Narrowband channel model (2/2)

- One interesting parameter of the Rice distribution is the K factor. It expresses the relative power of the LOS component compared to the power of the MPCs

$$K = \frac{a_0^2}{\sum_{i=1}^{N} a_i^2} \tag{4}$$

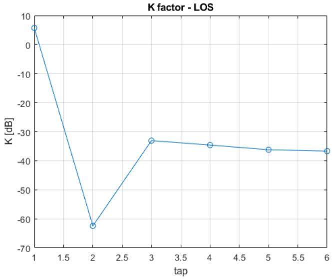
- In the NLOS case, K is nearly 0 $\longrightarrow$ Rice distribution converges to Rayleigh distribution

	LOS	NLOS
K [dB]	4.76	−10.51

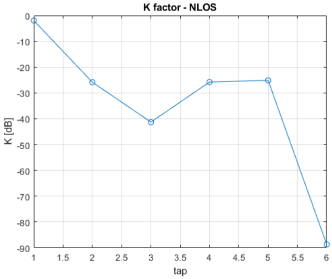
Table: K factor - narrowband model

Wideband channel model

- The receiver can distinguish some MPC $\longrightarrow$ Echos of the signal are falling into 6 taps, each spaced in time by 50ns
- Each tap follows a Rayleigh distribution (in NLOS) or a Rice distribution (in LOS)



(a) LOS



(b) NLOS

Figure: Evolution of the K factor with the delay

Outline

OFDM

Channel equalization is not trivial on frequency selective channels. In OFDM, the channel bandwidth is divided into *N* flat sub-channels. Data symbols are transmitted in parallel on each narrowband sub-channel. The sub-carriers of each sub-channel are chosen to be orthogonal from one another

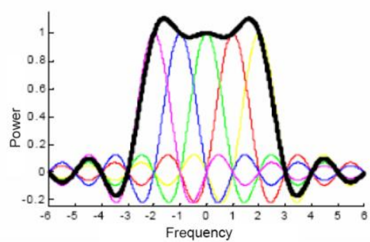


Figure: OFDM sub-channels

Equalization

In the time domain, the received QAM symbols $r(n)$ is:

$$r(n) = h(n) * s(n) + w(n) \tag{5}$$

On each sub-carrier k, the received symbol is expressed in the frequency domain by:

$$R(k) = H(k)S(k) + W(k) \tag{6}$$

The sent frequency symbols $S(k)$ are recovered using zero-forcing equalization:

$$\frac{R(k)}{H(k)} = S(k) + \frac{W(k)}{H(k)} \tag{7}$$

Cyclic prefix (1/2)

For the FFT to be valid, the discrete symbols $s(n)$ should be periodic

- We introduce a CP at the beginning of each block of symbol to simulate periodicity of the input signal $s(n)$
- This CP will also prevent IBI $\longrightarrow$ choose size CP to "shield" the block symbols for at least σ_τ

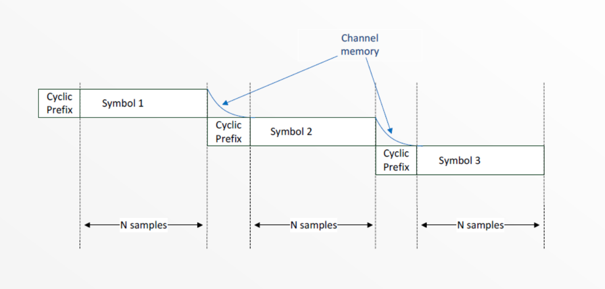


Figure: Cycle prefix

Cyclic prefix (2/2)

The benefits of the cyclic prefix is illustrated in the following BER curve:

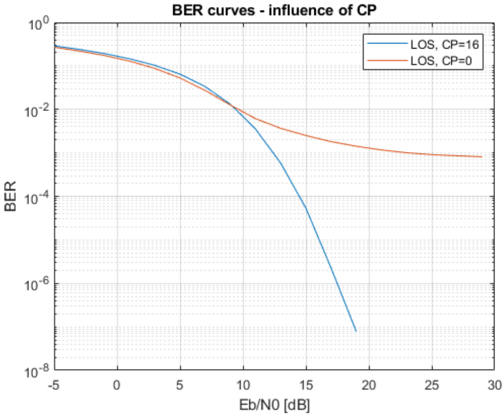


Figure: Impact of CP on BER

Result of equalization

Considering the channel frequency response of each sub-carrier $H(k)$ as known, the following BER are obtained

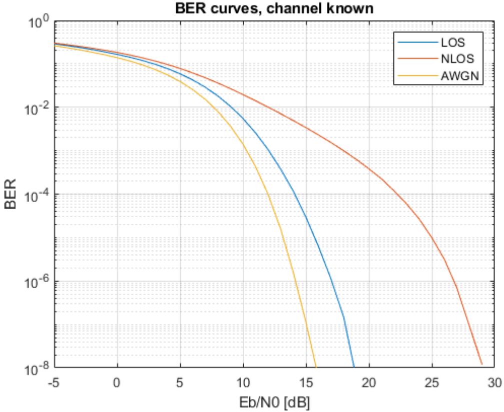


Figure: Impact of CP on BER

Outline

Channel estimation

The effect of the channel on the symbols is represented in the following equation

$$\frac{R(k)}{H(k)} = S(k) + \frac{W(k)}{H(k)} \tag{8}$$

The channel $H(k)$ must be estimated with known preamble symbols.

$$\hat{H}(k) = \frac{R'(k)}{S'(k)} = H(k) + \frac{W(k)}{S'(k)} \tag{9}$$

Error introduced by the estimation of the channel.

Channel estimation

We assume that the channel stays constant during a frame of multiple symbol blocks. $\mapsto$ One preamble at the beginning of the frame is sufficient to calculate $H(k)$.

Two identical preamble are sent in the channel at the top frame. $H(k)$ is calculated with these two preamble and the two results are averaged.

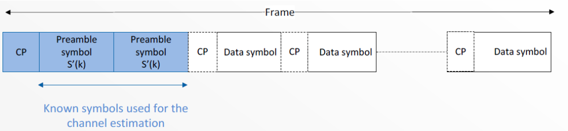
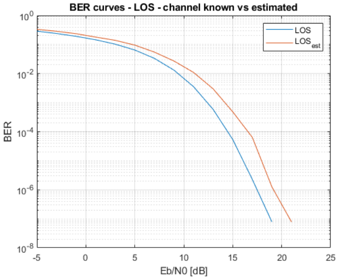


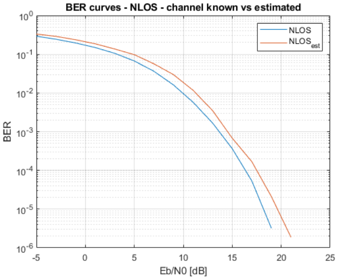
Figure: Frame structure

Channel estimation

Using the estimated channel degrades the BER performance.



(a) LOS



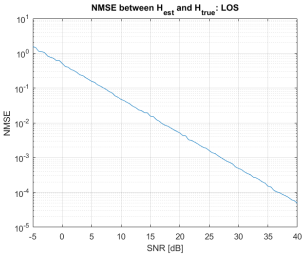
(b) NLOS

Figure: BER curves comparison with known channel and estimated channel

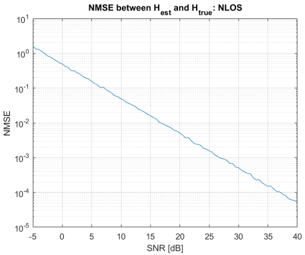
Channel estimation

A way to assess the impact of the noise is to calculate the normalized mean square error between known channel and estimated channel.

$$NMSE = \frac{\sum_k |\hat{H}(k) - H(k)|^2}{\sum_k |H(k)|^2} \qquad (10)$$



(a) LOS

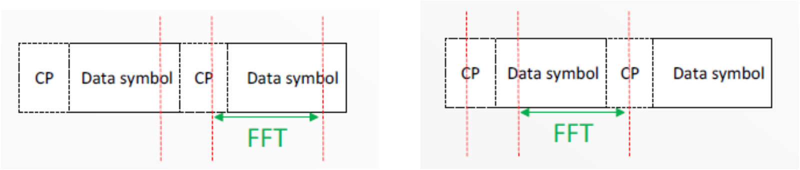


(b) NLOS

Figure: NMSE LOS and NLOS

Outline

ToA effect



(a) Early (b) Late

Figure: ToA estimated too early and too late

$$s(n - n_0) \longmapsto S(k)e^{-j2\pi\frac{k}{N}n_0} \tag{11}$$

$$\hat{H}(k) = \frac{H(k)S'(k)e^{j\Phi(k)} + W(k)}{S'(k)} = H(k)e^{j\Phi(k)} + \frac{W(k)}{S'(k)} \tag{12}$$

ToA effect

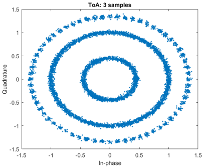


Figure: ToA = 3 samples

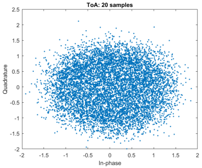


Figure: ToA = 17 samples

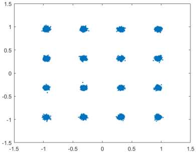


Figure: ToA = 0 samples

Figure: Constellation for different values of ToA

ToA estimation

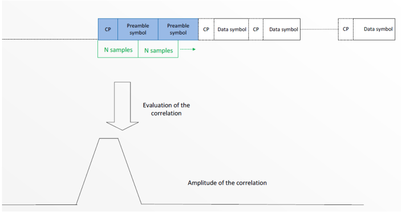
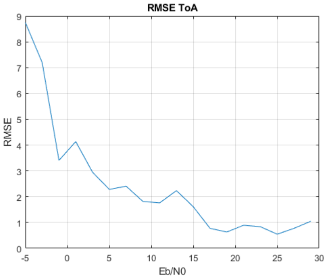


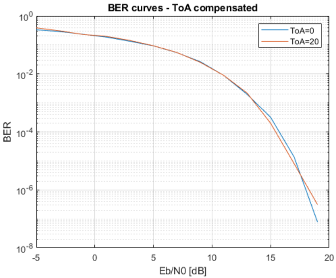
Figure: Correlation to find ToA

$$\hat{n} = \max_{n} \sum_{l=0}^{N-1} r^{*}_{n+l+N} \, r_{n+l} \tag{13}$$

ToA estimation



(a) RMSE on ToA estimation



(b) BER with ToA compensated

Figure: ToA acquisition

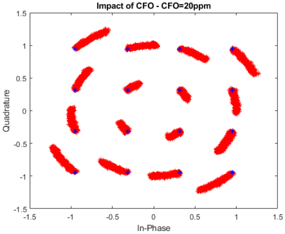
CFO effect

Finite accuracy of oscillators $\mapsto$ receiver frequency f_{RX} differs from carrier frequency f_{Tx}

$$r(t) = s(t)e^{j2\pi f_{TX}t}e^{-j2\pi f_{RX}t} \tag{14}$$

Δf is the difference between f_{TX} and f_{RX}. After the sampling:

$$r(n) = s(t)e^{j2\pi\Delta f \; nTs} \tag{15}$$

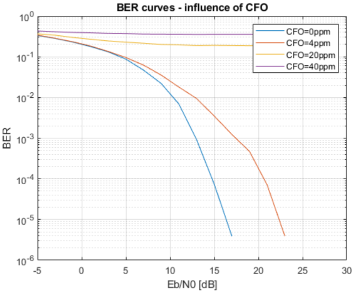


Frequency acquisition

Estimation of CFO

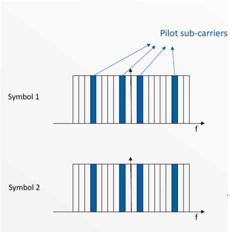
Average of phase differences between symbols of preamble r_1 and preambe r_2

$$CFO = \frac{\angle r2^* r1}{2\pi N T_s} \tag{16}$$

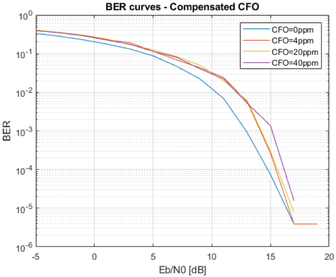


Frequency tracking

Frequency tracking is performed by averaging the phase shift



(a) average of pilot symbols phases



(b) BER with CFO compensated

Figure: CFO tracking

Outline

Objective

The objective is to mitigate the fading at the receiver by combining the signals arriving at the antennas.
The positions of the antennas must be determined to make the system efficient.
The evaluation of spatial correlation is needed.

The angular distribution is needed to evaluate the spatial correlation in the local area.

$$a_n(\theta,\phi) = \frac{\sum_i h_i(n) B_i^*(\theta,\phi)}{\sum_i |B_i(\theta,\phi)|^2} \tag{17}$$

$$B_i(\theta,\phi) = e^{-j\vec{\beta}\vec{r}_i} = e^{-j\frac{2\pi}{\lambda}(X_i\ sin\theta\ cos\phi + Y_i\ sin\theta sin\phi + Z_i\ cos\theta)} \tag{18}$$

Angular spectrum

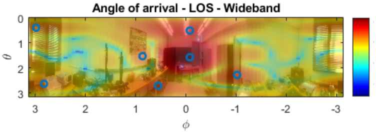


Figure: Angular spectrum LOS

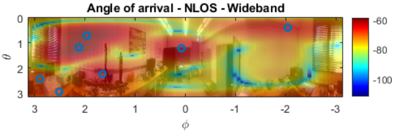


Figure: Angular spectrum NLOS

Figure: Angular spectrum wideband Tap 1

Spatial correlation

The spatial correlation along z, y and x axis are:

$$R(\Delta z, n) = \sum_{i=1}^{N} |a_{z,n}(\theta)|^2 e^{j\beta cos\theta \Delta z} \tag{19}$$

$$R(\Delta y, n) = \sum_{i=1}^{N} |a_{y,n}(\theta)|^2 e^{j\beta sin\theta sin\phi \Delta y} \tag{20}$$

$$R(\Delta x, n) = \sum_{i=1}^{N} |a_{x,n}(\theta)|^2 e^{j\beta sin\theta cos\phi \Delta x} \tag{21}$$

Spatial correlation

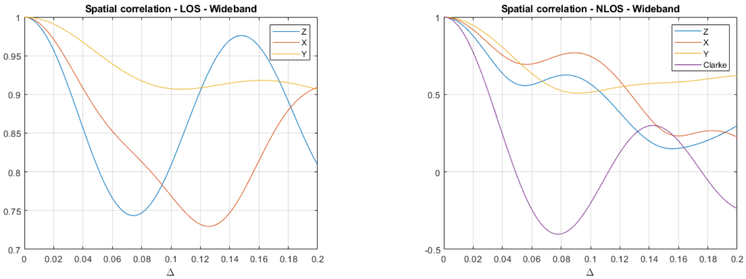


Figure: Spatial correlation in local area as a function of x, y and z

New channel model

From the angular spectrum, one can evaluate channel impulse response at a position i.

$$\hat{h}_i(n) = \sum_{(\theta,\phi)} a_n(\theta,\phi) e^{j(\phi_i - \vec{\beta}_k \vec{r}_i)} \tag{22}$$

SIMO implementation

We now have N antennas that are used for SIMO communication. N channels are estimated

Naive way to compute received symbols.

$$\hat{S}(k) = \frac{1}{N}\sum_{i=1}^{N}\frac{R_i(k)}{H_i(k)} = \frac{1}{N}\sum_{i=1}^{N} S_i(k) + \frac{W_i(k)}{H_i(k)} \tag{23}$$

Noise more attenuated on some channels than the others.

Maximum Ratio Combining

This method consists in a weighed sum where a term relative to a channel with attenuated noise has more importance.

$$\hat{S}(k) = \sum_{i=1}^{N} \frac{H_i(k)^* R_i(k)}{\sum_{j=1}^{N} |H_i(k)|^2} \tag{24}$$

$$\hat{S}(k) = \sum_{i=1}^{N} \frac{H_i(k)^* H_i(k) S(k)}{\sum_{j=1}^{N} |H_j(k)|^2} + \frac{H_i(k)^* W_i(k)}{\sum_{j=1}^{N} |H_j(k)|^2} \tag{25}$$

Performance gain

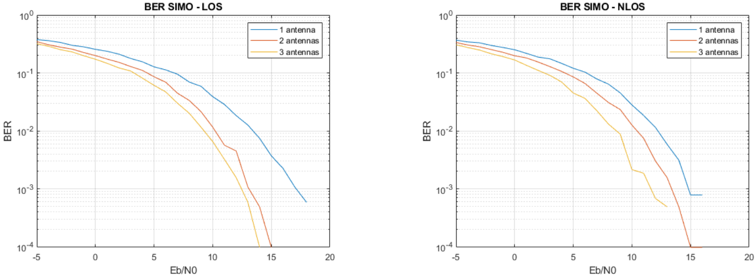


Figure: BER gain for different number of antennas

Thank you for your attention