Wireless Comm. Basics.

C. Nicolas Barati, Rahman Doost-Mohammady,
Oscar Bejarano and Ashutosh Sabharwal

POWDER

Outline

- **Intro + motivation**
- Basic Wireless System
- OFDM
- Multi-antenna Communication
- Experimentation with POWDER-RENEW

A small intro.

- Why wireless?
  - Extend the range of communication
  - “Freedom of movement”
- Is it easy? NO!
  - Unpredictable medium, interference, mobility, regulations.
  - Need for research, modeling, validation, protocol design etc.

Fundamental performance metrics.

- **Capacity**
  - How much data units per usage can we send/receive?
- Delay
  - How long it takes for the data to get from the sender to the receiver(s)?
- Energy efficiency
  - How much power needed per unit of data?

Capacity.

- Shannon Capacity equation:

$$C = W\log(1 + P/N_0)$$

  - The amount of data we can transmit/receive correctly is function of:
    - W: Bandwidth
    - P/N_0: Signal to Noise Ratio.

How to increase capacity?

$$C = W\log(1 + SNR)$$

- Increase W.
  - Cannot monopolize the entire EM waves spectrum!
  - H/W does not operate over the whole spectrum.
- Increase power.
  - Interference, regulatory boundaries, hardware constraints, e.g., amplifiers.

Is there anything else we can do?

- Use multiple antennas
  - Increase C by combining multiple streams to increase SNR
    - Same data over multiple streams
  - Increase C by sending data in parallel sub-channels
    - $C = C_1 + C_2 + \ldots$
- Still, restrictions
  - H/W size

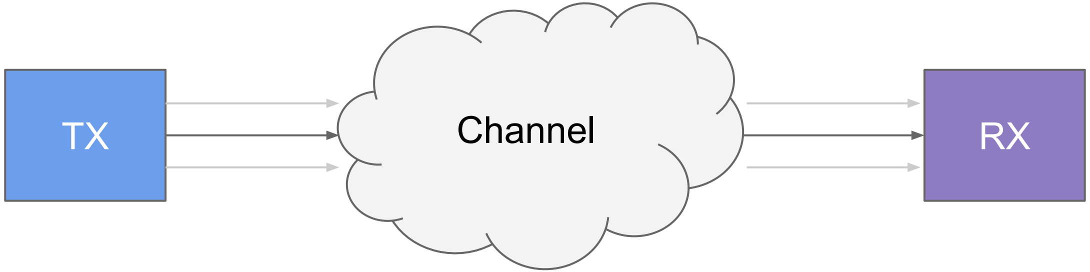
POWDER

Outline

- Intro + motivation
- **Basic Wireless System**
- OFDM
- Multi-antenna Communication
- Experimentation with POWDER-RENEW

POWDER

Wireless system: big picture.



A transmitter, a receiver and a channel between them.

Transmitter.

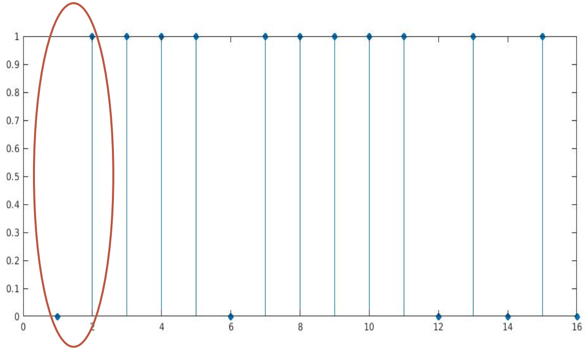
TX

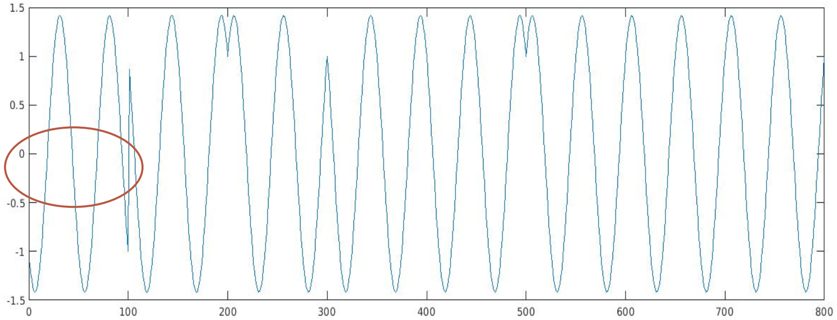
- Bits → Waveforms
  - Encoding
    - Add redundancy (intelligently) to help the receiver to recover the information despite errors. (not covered here.)
  - Modulation
    - Group/map bits into symbols.
    - “Mount” symbols on an analog waveform to be sent over the air.

Transmitter. Modulation. Waveform.

TX

- Generate a basic analog signal and modify it according to the incoming bits and symbols:
  - Modify various aspects: amplitude, frequency or phase
    - AM, FM, Phase *modulation*.





POWDER

Transmitter. Modulation order.

TX

- Defines the number of bits that are mapped to a symbol/signal.
  - With each Mod. order M, we can have up to M different symbols.
    - Mod. order M = 16: every log2(16) = 4 bits are mapped to a symbol.

$$0000 \rightarrow S_1 \quad 0001 \rightarrow S_2 \quad \ldots \quad 1111 \rightarrow S_{16}$$

POWDER

Transmitter. Modulation. Symbols.

TX

- Groups of bits:
  - Can be represented as an integer
    - E.g., 0010 → 2
  - Or, in a different plane as we will see next

Transmitter. Modulation. I & Q.

TX

- A sinusoid signal can be represented by two other orthogonal sinusoids:
  - Inphase: $a\cos(2\pi ft)$
  - Quadrature: $b\sin(2\pi ft)$
    - Create an “orthonormal basis”.
      - A complex 2D plane where any point can be reached through a linear combination of I & Q:

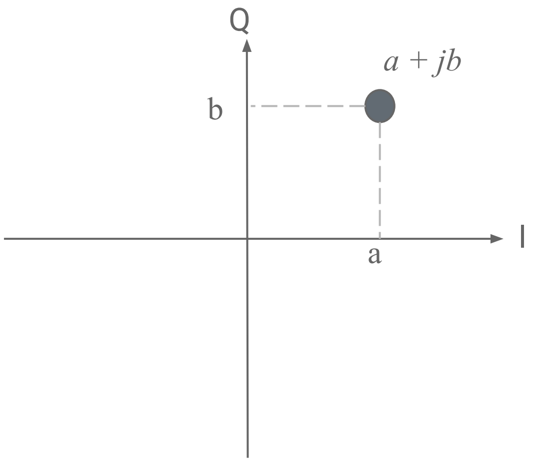
$$v = aI + jbQ$$

POWDER RENEW

Transmitter. Modulation. Constellation.

TX

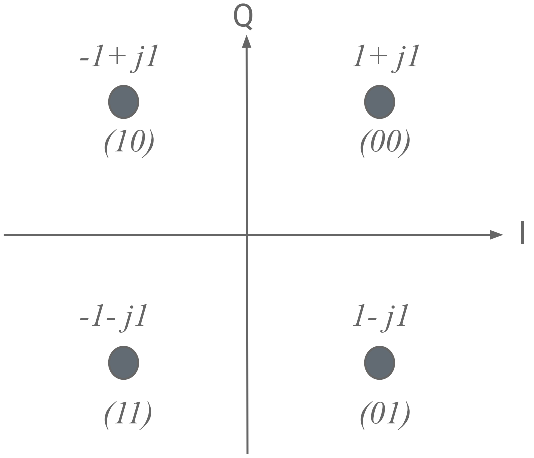
- A 2D representation of symbols along I and Q:
  - Now, we define the symbols as complex numbers in the form of a+jb.
    - I and Q implied.
  - We don't normally choose any a & b.
    - Choose such that the points on the constellation have regular distances.
      - E.g., ±1, ±1j



Transmitter. Modulation. QAM.

TX

- What we saw was Quadrature Amplitude Modulation (QAM).
    - Generate signals through modifying the amplitude of two fundamental signals
    - Map each group of bits to these amplitudes.
    - Most used modulation scheme in modern wireless systems.

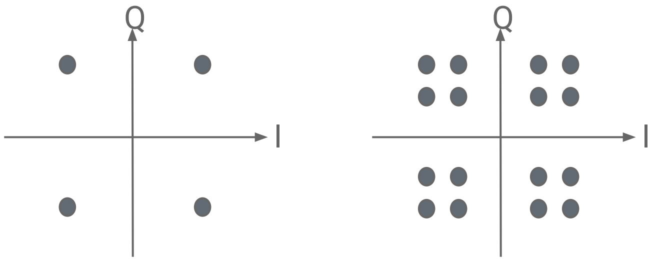


POWDER RENEW

Transmitter. Modulation. More QAM.

TX

- Can send more bits per symbol:
  - Higher modulation orders: 16-QAM, 64-QAM, 256-QAM
- Restricted by transmit power
  - For the same power budget, symbols get packed closer
    - Harder to sort out on the receiver side.



POWDER RENEW

Transmitter. Modulation. Upconversion.

TX

- Suppose we want to transmit a signal, $s_b(t)$.
- We can’t just go ahead and transmit it!
  - Regulations on spectrum usage
- We need to move it to where we’re allowed to transmit.
  - Upconversion:
    - Multiply signal with a carrier sinusoid.
      - Sinusoid with carrier frequency f_c

POWDER RENEW

Transmitter. Passband–Baseband.

- Shift signal in frequency domain around fc.

TX

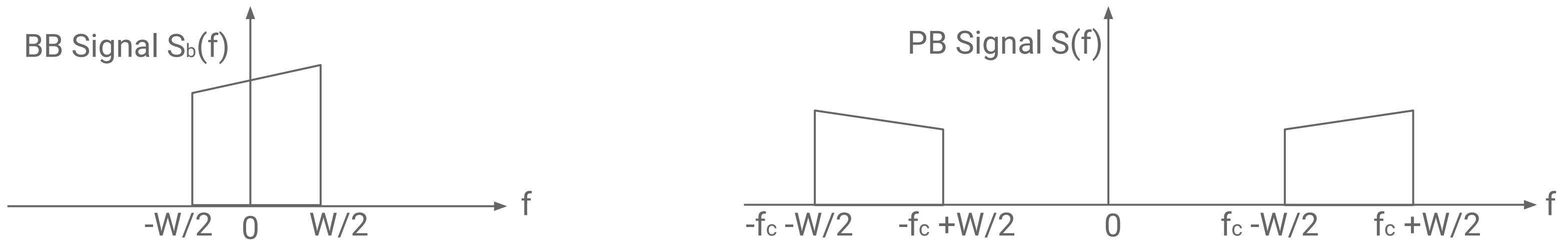
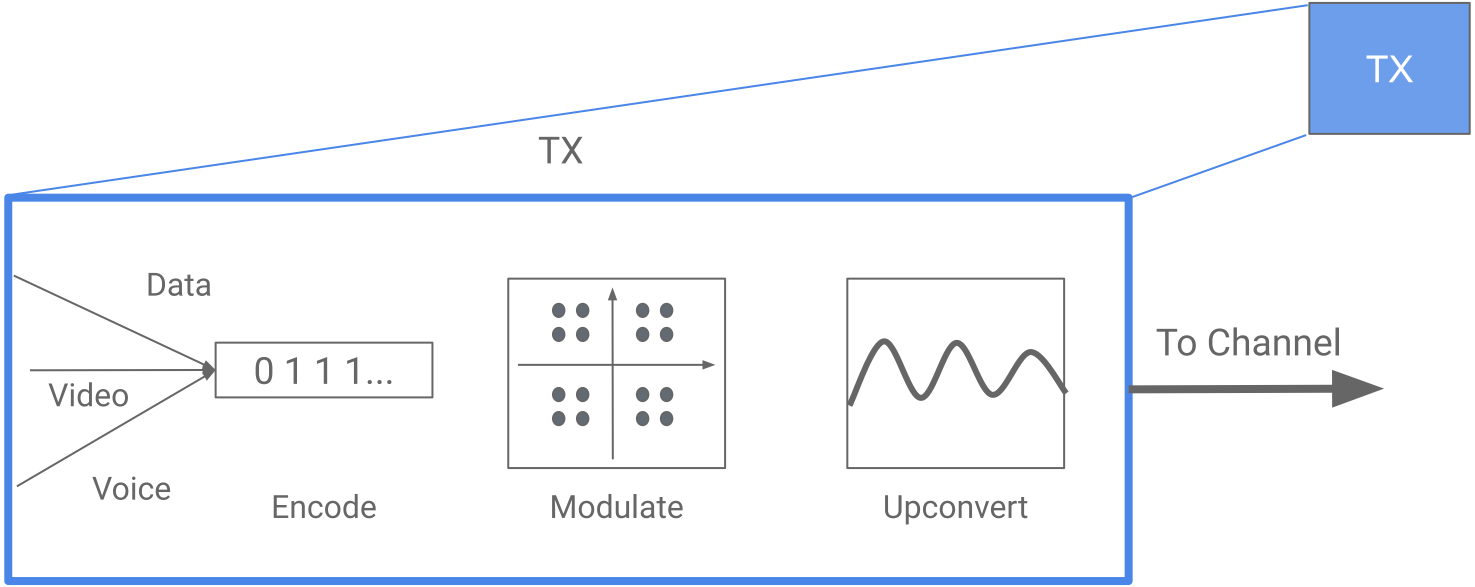


Figure reconstructed from Ch. 2 of Fundamentals of Wireless Communication by D. Tse. & P. Viswanath

POWDER

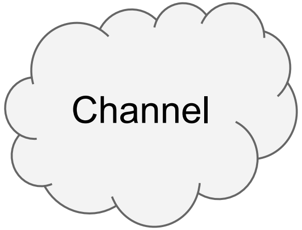
RENEW

Transmitter. Putting all together.



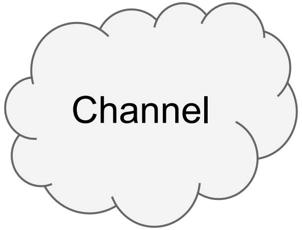
Channel.

- Source of all difficulties in wireless.
  - Effect of the environment on the transmitted signal
    - Pathloss
    - Fading
      - Reflections
    - Doppler shift

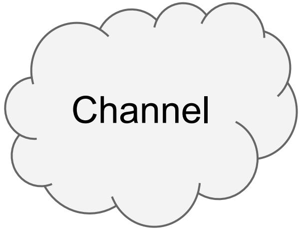


Channel. Baseband equivalent.

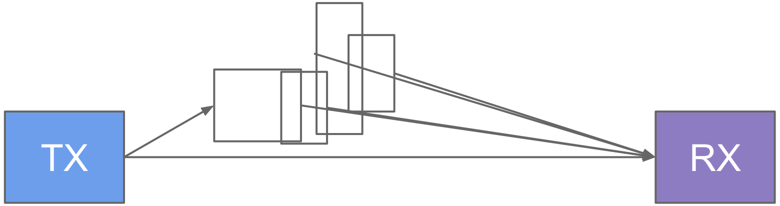
- Signal is transmitted in passband.
- Modulation and signal analysis is done in BB.
- Channel representation in BB.
  - Delays is PB result in constant phase rotation in BB.



Channel. Multipath channel.



- The environment results in signal arriving through different paths
  - Multipath Channel
    - LoS, and NLoS components
    - Each path different delay and different phase.



random path phase

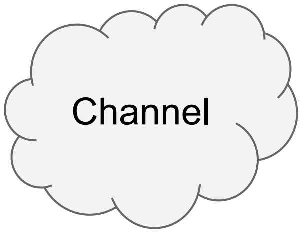
$$r(t) = \sum_{\ell}^{L} a_\ell e^{-j2\pi f_c \tau_\ell + \phi_\ell} s(t - \tau_\ell)$$

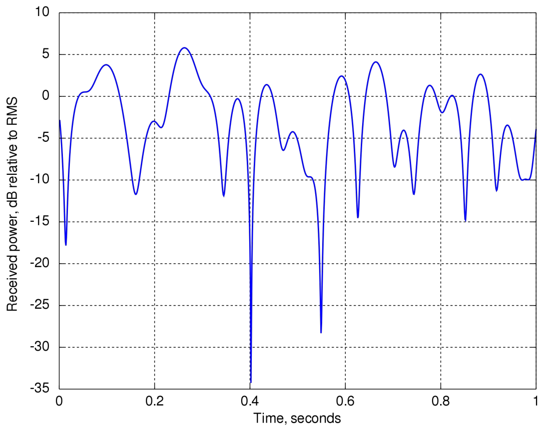
path gain

path delay

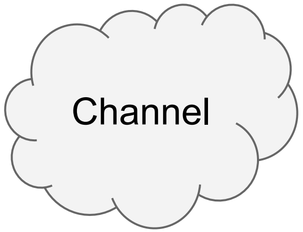
Channel. Fading.

- Small scale fading:
    - Channel power attenuation
    - Caused by destructive addition of paths
        - Sometimes they add constructively
    - Two sources
        - Multipath
        - Doppler



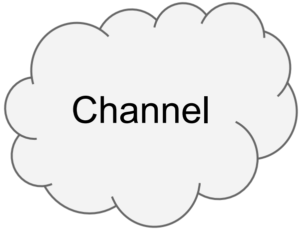


Channel. Modeling.

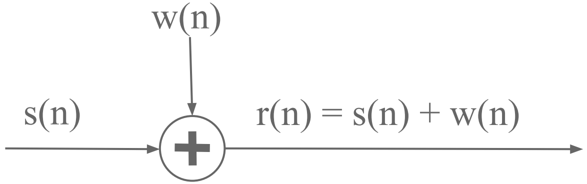


- It’s a random process.
- Modeled by random distributions. Most popular:
  - AWGN
  - Rayleigh
  - Rice
- Also, modeled through measurements and parameter extraction from data

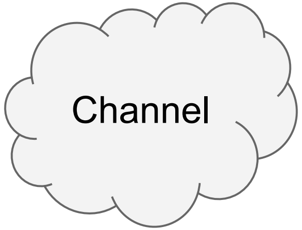
Channel. AWGN.



- The simplest form:
  - No channel.
  - All source of error additive noise.
    - Gaussian random variable.
    - Models thermal vibrations in H/W



Channel. Rayleigh.



- Channel composed of superposition of rays coming from many different paths.
  - No dominant path.
- Modeled as a complex Gaussian r.v.
  - Central limit theorem
  - Magnitude follows a Rayleigh distribution.

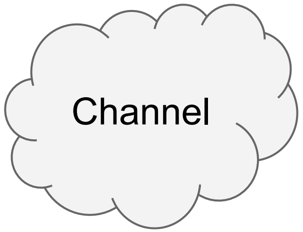
$$R = |H| = \sqrt{H_r^2 + H_j^2}, H \sim CN(0, 2\sigma^2)$$

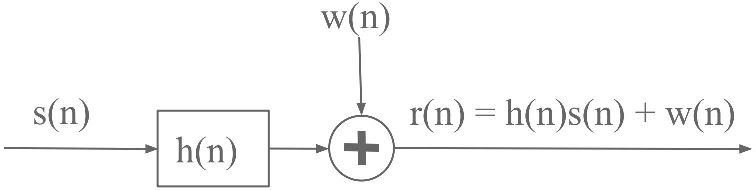
$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$

POWDER

Channel. Rayleigh.

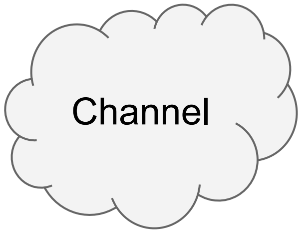
- People often mean i.i.d. Rayleigh fading.
  - Each complex sample multiplied by a complex gaussian r.v.



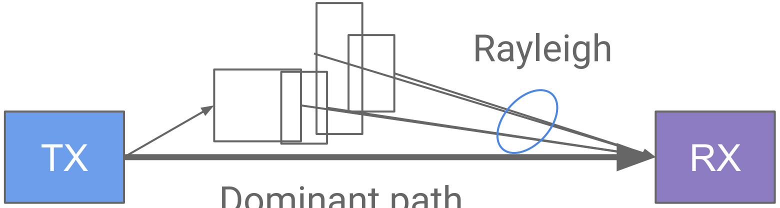


POWDER RENEW

Channel. Rice.

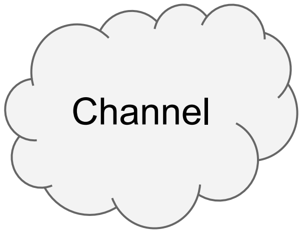


- Two components:
  - Dominant path
  - Rayleigh fading
- Defined by the ratio $K = A^2/2\sigma^2$:
  - Power of the dominant path
  - Power of the Rayleigh fading component



POWDER RENEW

Channel. Multipath clusters.



- Channel composed of rays grouped into clusters
  - Number of clusters/rays defined by environment’s geometry/scenario : Urban, rural etc.
- Random gains, phases, angles and delays drawn from distributions fitted from measurements.
- Versions of it used by standardization bodies s.a. 3GPP.

$$H(t,f) = \sum_{\ell}^{L} \sum_{k}^{K} g_{\ell k} e^{j2\pi(f_{\ell k} t - \tau_{\ell k} f)}$$

Channel. Multipath clusters. Example

Parameter	
Cluster center AoA	From data
Cluster delay	From data
Cluster power	From data
Angular spread/cluster	From data
Delay spread/cluster	From data
AoA /ray	Random: uniform around center within ang. spread
Delay/ray	Random: exponential. mean= delay spread
Gain/ray	$(\sqrt{cluster\ power/num.rays})e^{j2\pi\phi_{\ell k}}$

Channel

Random phase/ray

POWDER RENEW

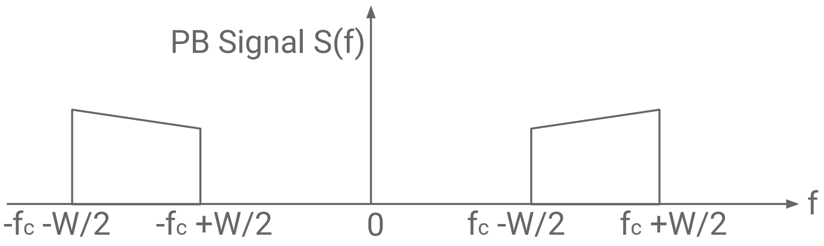
Receiver.

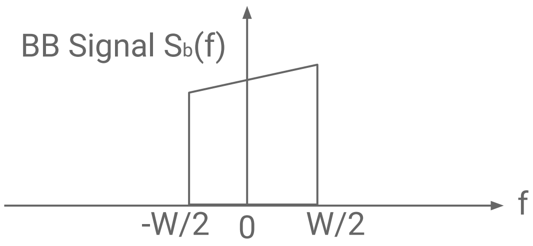
- Waveforms → Bits
  - Downconvert
  - Synchronize
  - Equalize
  - Demodulate

RX

Receiver. Downconvert.

- Mirroring upconversion at the TX
  - Just multiply the received waveform with a sinusoid at the carrier frequency.





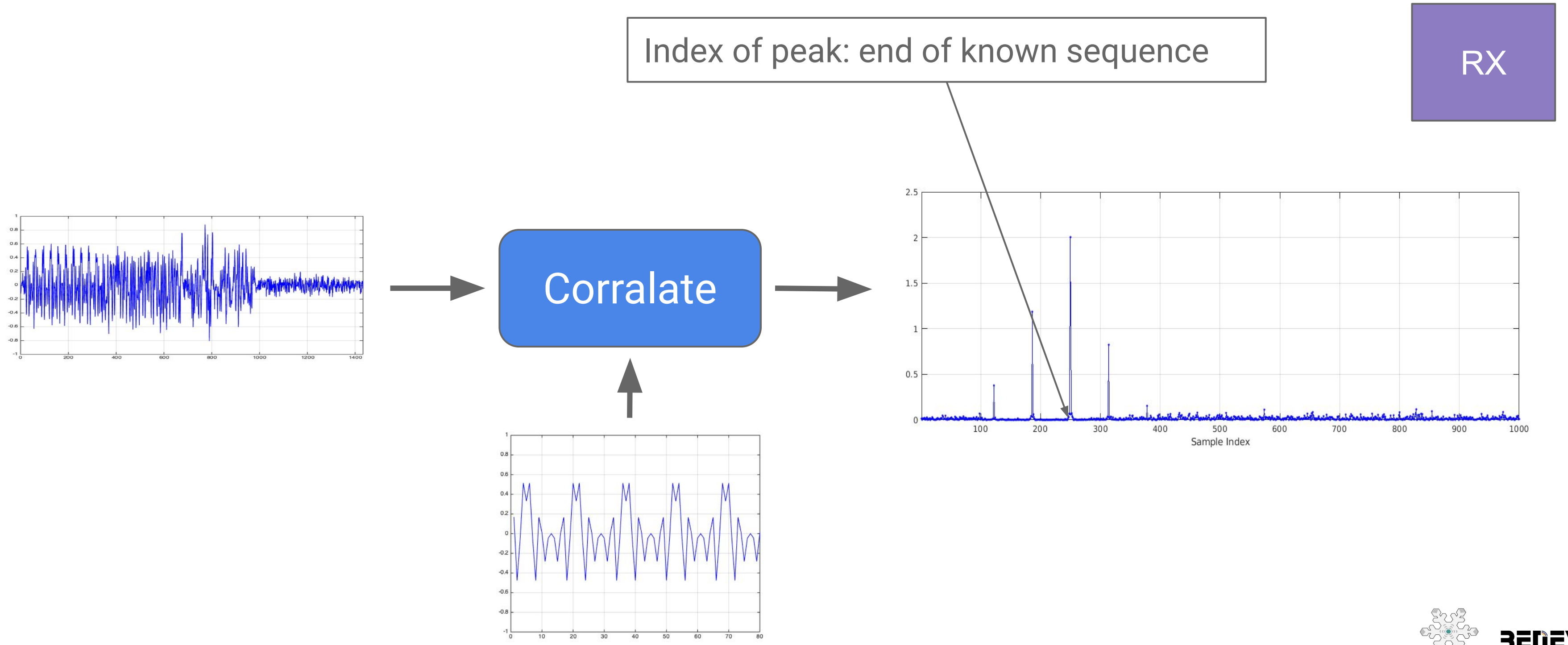
POWDER RENEW

Receiver. Synchronize.

RX

- Before doing anything the receiver needs to first detect the start of a stream/packet/frame of incoming data.
- Correlate with a known sequence (sync. Signal)
    - Make out the start of the data stream relative to the correlation peak
    - Receiver knows *where* and how long the known sequence is

Receiver. Synchronize.



POWDER RENEW

Receiver. Equalize.

RX

- Channel introduces errors.
- Need to offset these errors.
  - Reverse channel effect.
- Use the/a known sequence, called **pilot,** to estimate the channel
  - Remove the pilot. What’s left is channel + noise.
  - Get better estimates by averaging over more sequences.

Receiver. Demodulate.

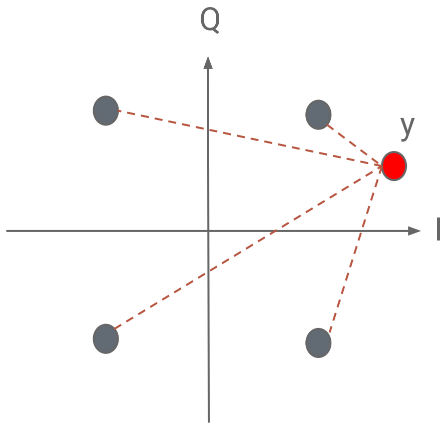
RX

- Decide which symbol, consecutively which bits, were sent.
- Need criteria to decide based on received signal
  - Maximum likelihood
    - Assume x_i was sent (given), what is the probability of observing y_j? → Choose x_i with max. probability.
  - Maximum a posteriori
    - Given observation y_j what is the probability that x_i was sent? → Choose x_i with max. probability.

Receiver. Demodulate. Smallest distance.

- If every symbol has the same probability of being sent, both criteria are the same.
- Smallest distance.
  - Choose the constellation point closer to where the received symbol has landed

RX

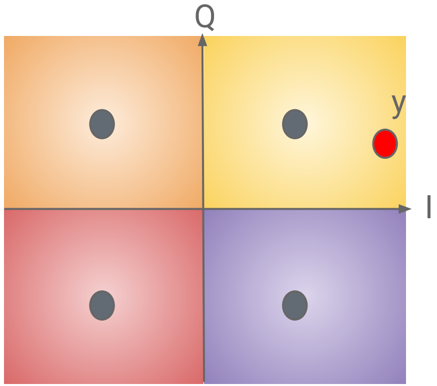


POWDER

RENEW

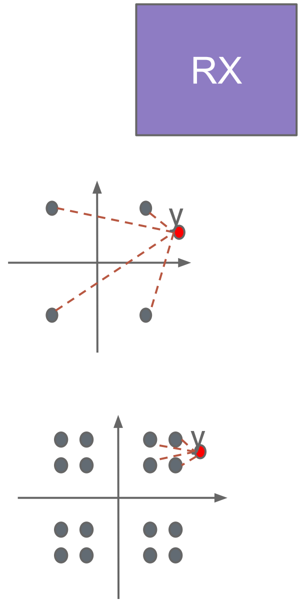
Receiver. Demodulate. Decision regions.

- These criteria define decision regions
  - Areas around each constellation point xi, where each point is closer to x_i than any other constellation point x_j.
  - Very regular for QAM
  - Decide based on which region y lands on



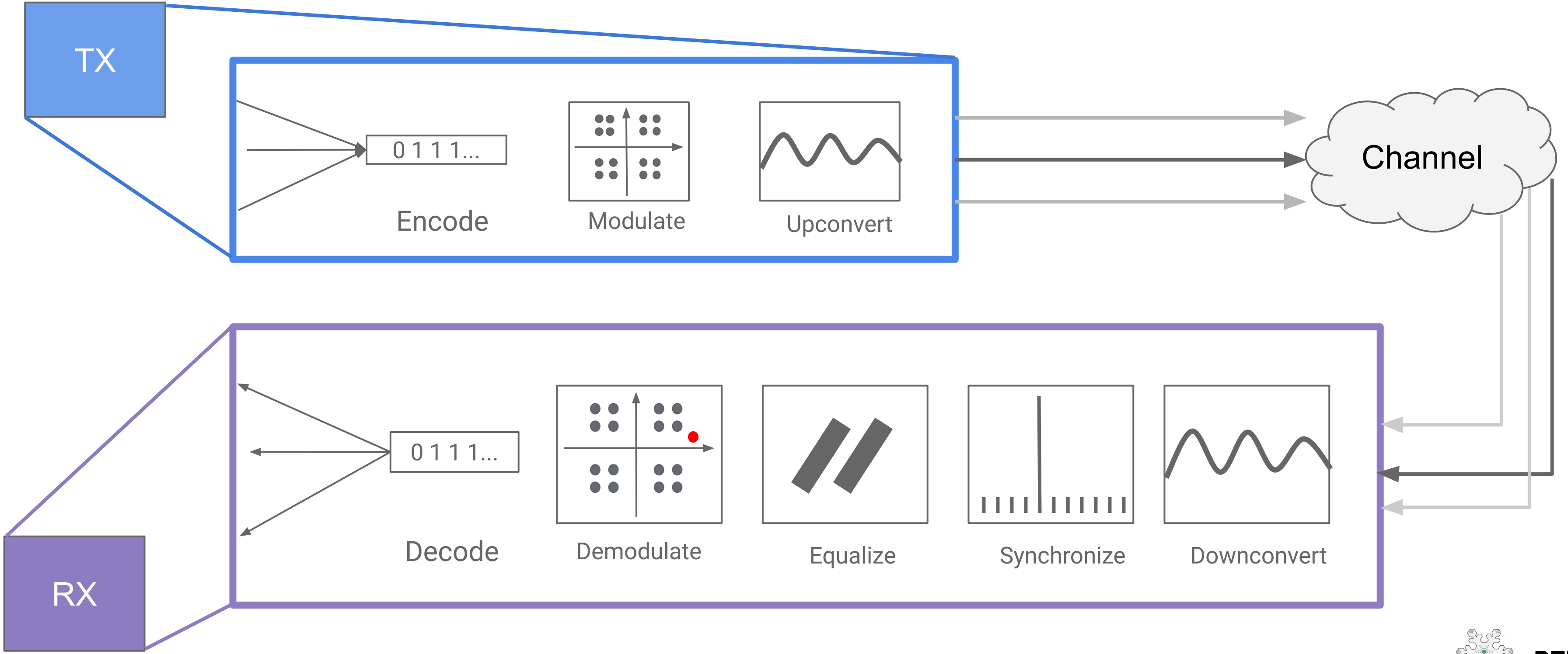
Receiver. Demodulate. Errors.

- Packing more symbols on the constellation increases rate.
  - More bits/channel use.
- Leads to more errors
  - Smaller distances/decision regions for same power
- Higher constellation orders need higher **SNR**
  - Makes the received symbol to land closer to the correct point.



POWDER RENEW

Wireless system: Putting all parts together.



Performance Metrics.

- SER
    - Average number of incorrect received complex symbols
- BER
    - Average number of incorrect received bits
- EVM
    - Average distance between constellation points and where received symbols have landed
    - Effective SNR: inverse of the square of EVM
        - Average distance is a function of SNR

Outline

- Intro
- Basic Wireless System
- **OFDM**
- Multi-antenna Communication
- Experimentation with POWDER-RENEW

OFDM. Why?

- As BW grows, channel estimation / equalization becomes harder.
- Inter-symbol interference (ISI)
  - Delayed versions of successive symbols interfere with each other
  - Large BW → small symbol duration → ISI destroys larger part of the symbol

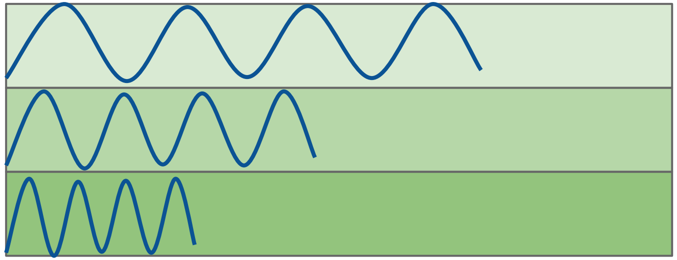
OFDM. What does it solve?

- What if we divided the BW into smaller chunks?
  - Channel can be assumed “flat” across each small frequency chunk
    - Described by only a scalar
  - Each chunk is narrow band → larger symbol duration
    - ISI with smaller portion of symbols

POWDER

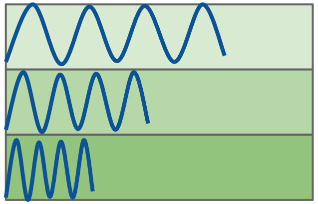
OFDM. Principles.

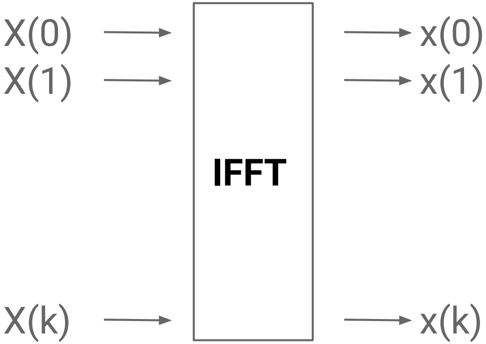
- Take QAM symbols and modulate them on the chunks.
  - Called subcarriers (SC)
  - Each with a frequency different than the other by an integer
- Combine the outputs of the SC into a single output.



OFDM. IFFT.

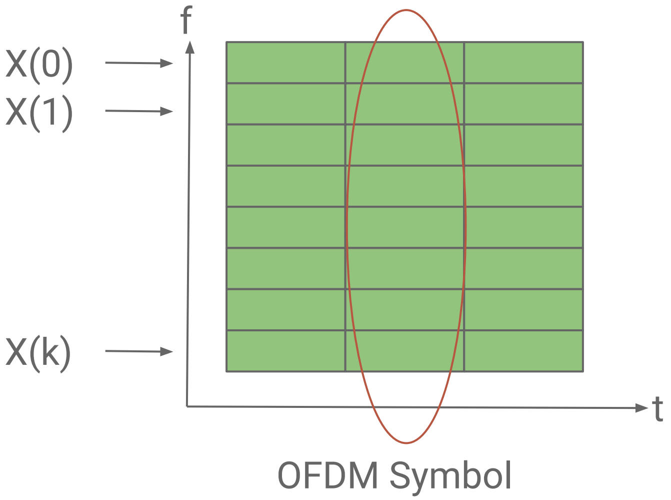
- SC modulation done through *IFFT*
  - Original QAM symbols in frequency domain (FD)
  - IFFT produces time-domain (TD) samles
  - Each TD sample contains parts of all the FD QAM symbols.





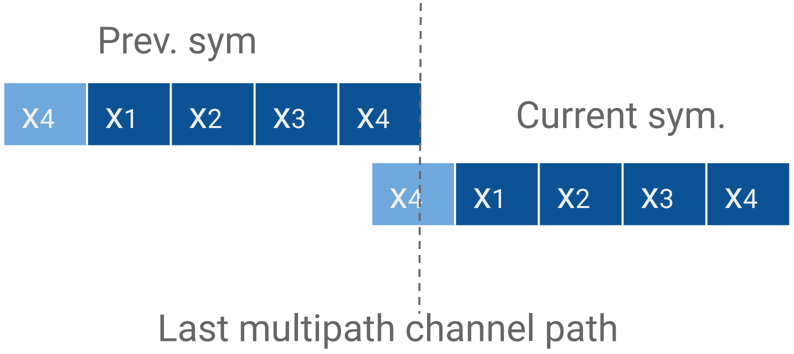
POWDER

OFDM. Time-frequency grid.



OFDM. Cyclic prefix.

- An OFDM symbol still faces ISI.
  - Although less severe
- Cyclic prefix CP:
  - Create a “safe interval” by copying a small part of the end of the OFDM symbol and attaching it to the beginning
- ISI will affect the repeated part



OFDM. Reception.

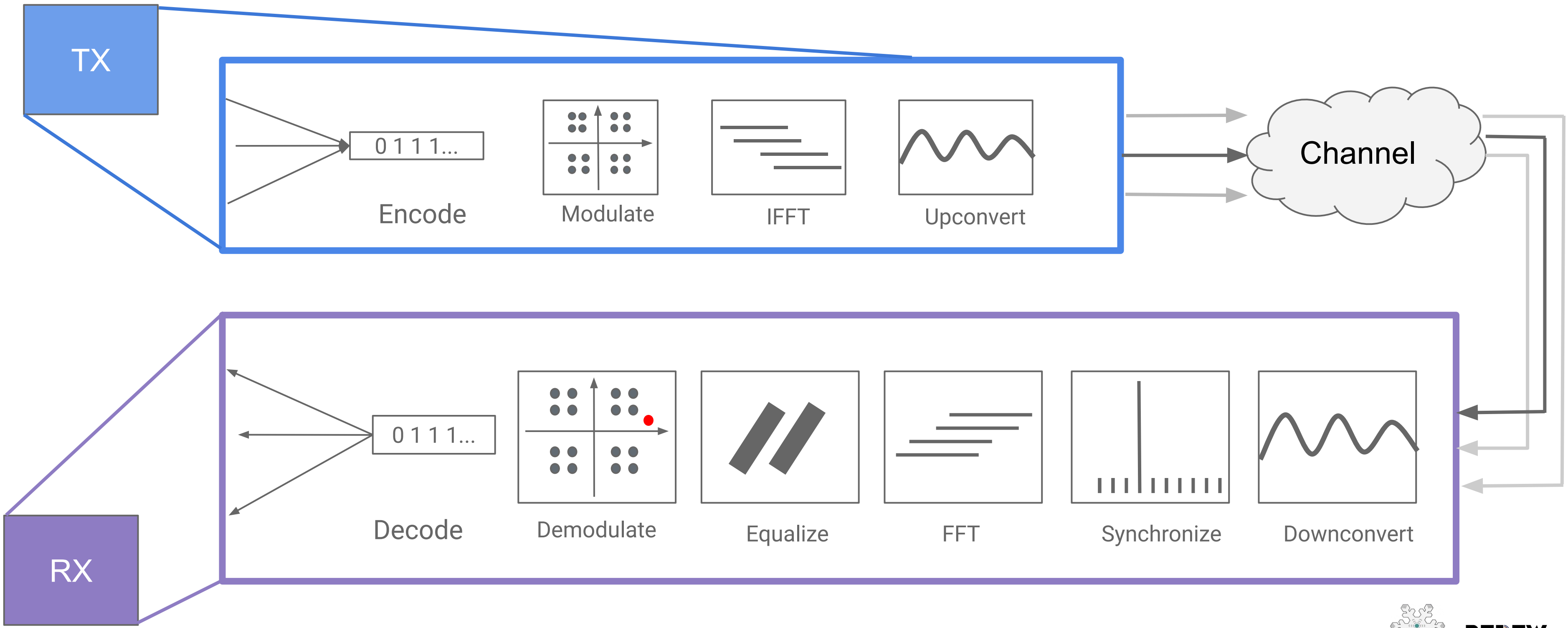
- The receiver repeats the same steps as before
  - Down conversion
  - Sync.
  - Equalization (per sub-carrier)
  - Demodulation
- With one addition:
  - After synchronization, use FFT to demultiplex the OFDM symbols and retrieve FD QAM symbols.

OFDM. Equalization.

- The TD signal is *linearly* *convolved* with the channel
- By adding CP it is now *circularly* convolved
- In FFT domain (FD), a circular convolution in time-domain becomes just a multiplication!
  - Equalize each SC in FD by *a simple scalar division*
    - Estimate channel by taking out the **pilot** (and averaging).
    - Divide QAM symbols on each SC by the estimated channel.

POWDER RENEW

OFDM system: Putting all parts together.

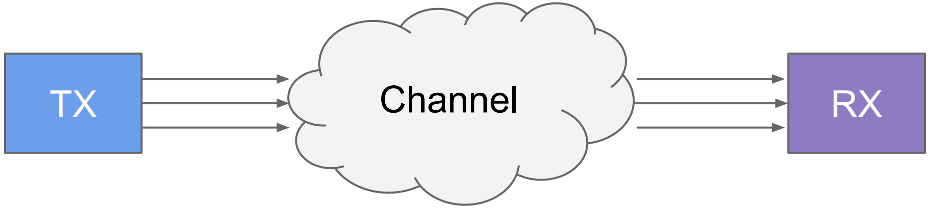


Outline

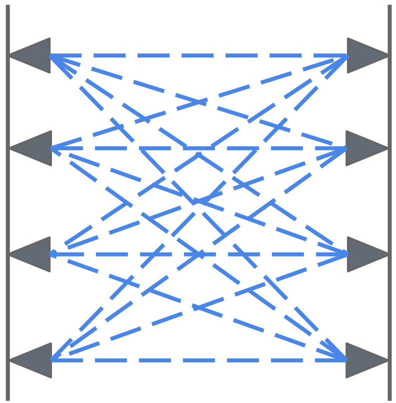
- Intro
- Basic Wireless System
- OFDM
- **Multi-antenna Communication**
- Experimentation with POWDER-RENEW

MIMO.

- Multiple input multiple output
  - Increase capacity
    - Using the same BW and time resources
  - Receive/transmit in multiple spatial streams
    - Array of antennas.
  - Variations
    - SIMO, MISO



MIMO. MIMO spatial channel.



$$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1m} \\ \vdots & \vdots & \ddots & \\ h_{n1} & h_{n2} & \dots & h_{nm} \end{bmatrix}$$

POWDER RENEW

MIMO. Beamforming/Precoding.

- Received signal: $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$
- Given $\mathbf{H}$, we can process the transmitted and received signal to increase capacity:
  - Combine sub-channels power to increase SNR
  - Create parallel streams
  - Suppress interference

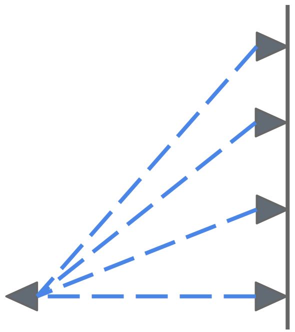
$$\mathbf{y} = \underbrace{\mathbf{W}_{RX}}_{\text{RX BF}}\ \mathbf{H}\ \underbrace{\mathbf{W}_{TX}}_{\text{TX BF/ Precoding}}\ \mathbf{x} + \tilde{\mathbf{n}}$$

MIMO. SIMO. RX BF.

- Single TX antenna, multiple RX antennas.
- Channel is a vector: $\mathbf{H} \rightarrow \mathbf{h}$
- $\mathbf{w}_{\mathrm{RX}}$ maximizing SNR (also a vector):

$$\mathbf{w}_{\mathrm{RX}} = \mathbf{h}^*$$

$$\mathrm{SNR} = \frac{1}{N_0} \sum_{n}^{N} |h_n|^2 = \sum_{n}^{N} \mathrm{SNR}_n$$

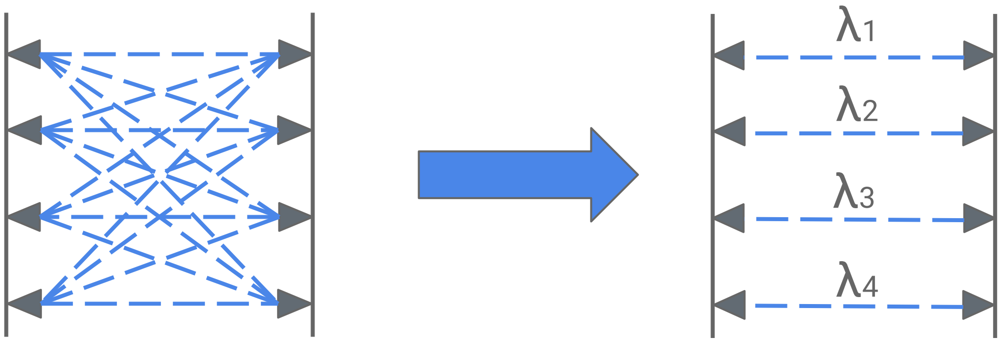


- Called Maximal Ratio Combining (MRC)

POWDER RENEW

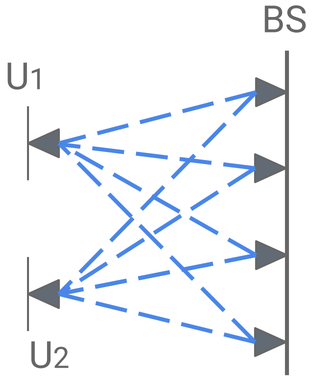
MIMO. Single user MIMO.

- When both sides are equipped with multiple antennas, we can create multiple parallel channels.
- $\mathbf{W}_{RX}$ and $\mathbf{W}_{TX}$, left and right singular vectors
- N parallel channels, each with power equal to the square of the eigenvalues of $\mathbf{H^*H}$



MIMO. Multi user MIMO

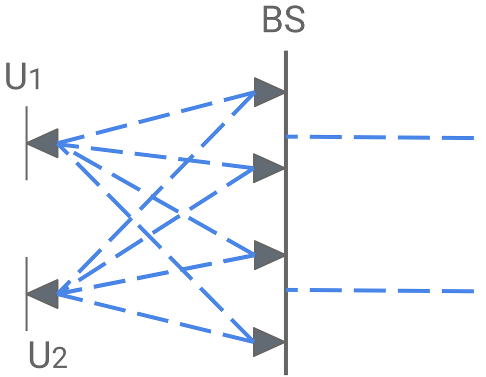
- Usually assume single-antenna users.
- We want to transmit M parallel signals to M users
- Problem:
  - Signal streams transmitted at the same time
  - Need a scheme to demultiplex the M received signals.
    - What W_{Rx} need to be to achieve that?



POWDER RENEW

MIMO. Multi user MIMO. Zero Forcing.

- Decouples the streams by transforming it to a MxM identity matrix.
  - $\mathrm{W_{RX}}$ is the pseudo-inverse $(\mathbf{H}^{\dagger})$ of the channel:

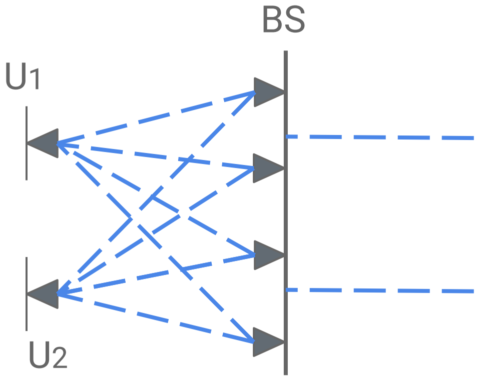


$$\begin{aligned} \mathbf{y} &= \mathbf{W}_{RX}\mathbf{H}\mathbf{x} + \mathbf{W}_{RX}\mathbf{n} \\ &= (\mathbf{H}^*\mathbf{H})^{-1}\mathbf{H}^*\mathbf{H}\mathbf{x} + \underbrace{(\mathbf{H}^*\mathbf{H})^{-1}\mathbf{H}^*}_{\mathbf{H}^{\dagger}}\mathbf{n} \\ &= \mathbf{x} + \tilde{\mathbf{n}} \end{aligned}$$

POWDER RENEW

MIMO. Multi user MIMO. Zero Forcing.

- Doesn't always work well.
  - In low SNR it amplifies noise:
    - Take the SISO channel equivalent:
      - $y = x + n/h$
  - When users are close to each other, or more generally, in the same scattering environment their channels become correlated.
    - Noise is amplified by being divided by a very small singular value.

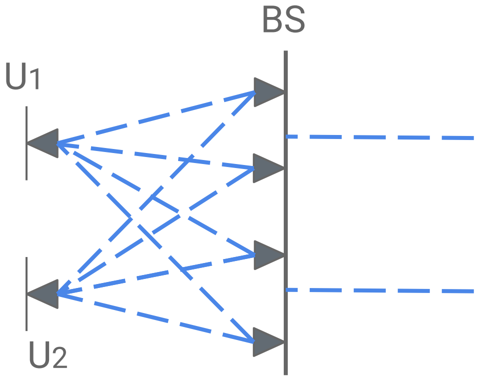


MIMO. Multi user MIMO. MMSE.

- Can mitigate the ZF drawbacks by using the SNR ρ as a regularization term.

$$\mathbf{W}_{RX} = \rho(\mathbf{I}+ \quad \rho\mathbf{H}^{*}\mathbf{H})^{-1}\mathbf{H}^{*}$$

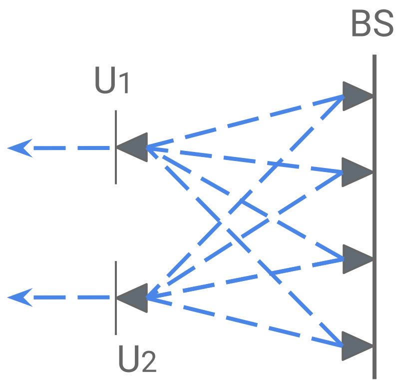
- More complicated.
- Not used widely.



MIMO. Multi user MIMO. UL /DL.

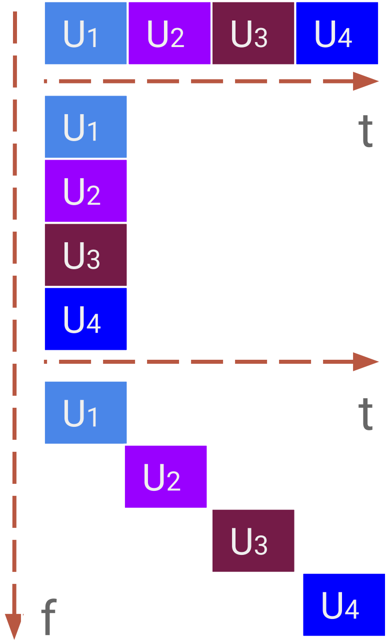
- If the channel is reciprocal, as in TDD systems, the same matrices can be used in downlink.

$$\mathbf{W}_{TX} = \mathbf{W}^{*}_{RX}$$



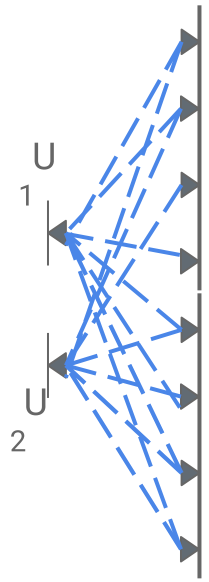
MIMO. Multi user MIMO. Channel estimation.

- Applying WRX and WTX requires knowledge/estimate of the channel.
- Same principles as in SISO
    - In a *higher dimension* though
    - Per user per SC (or group of SCs) in OFDM.
- Done with *pilots*.
    - Requirement: pilots have to be **orthogonal**
    - Otherwise, BF/Precoding in a direction that is a combination of two or more users channels!



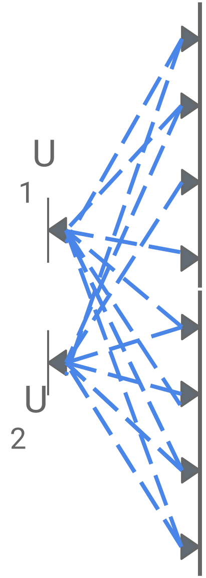
MIMO. Massive MIMO.

- The promise:
  - *If the entries of the channel matrix* $\boldsymbol{H}$ *are iid complex Gaussian r.v.s (Rayleigh fading), then as the ratio of the number of antennas to the number of users goes to infinity the entry vectors of the matrix become orthogonal.*



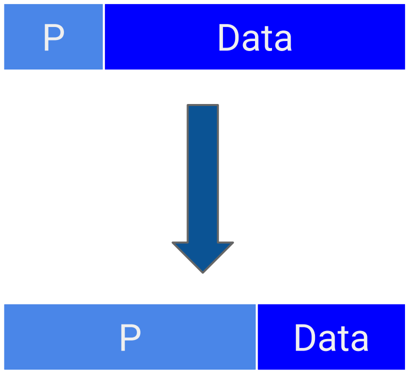
MIMO. Massive MIMO. Conjugate BF.

- Thus, demultiplexing becomes easy.
  - Just use the (normalized) conjugate transpose of the channel as $\mathbf{W}_{RX}$.
  - The cross terms go to 0 due to orthogonality.
  - A generalization of MRC.
    - High SNR, low interference channels.
    - Holy Grail of wireless!



MIMO. Massive MIMO. Practical issues.

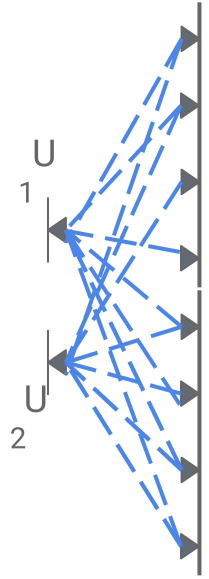
- Channel estimation:
  - Need for orthogonal pilots
  - As the number of users grow, more resources to pilots.
    - Even worse in a multi-cell setting.
  - Alternative: re-use pilots
  - Leads to *pilot contamination*
    - Interference of pilots → wrong BF/Precoding



POWDER

MIMO. Massive MIMO. Channel correlation.

- The promise of orthogonal channel vectors is not always true.
- Depends on the environments geometry
- If users are affected by the same scatterers, some correlation will still exist.
    - Can’t use Conjugate BF
    - Can use ZF depending on how bad the correlation is.

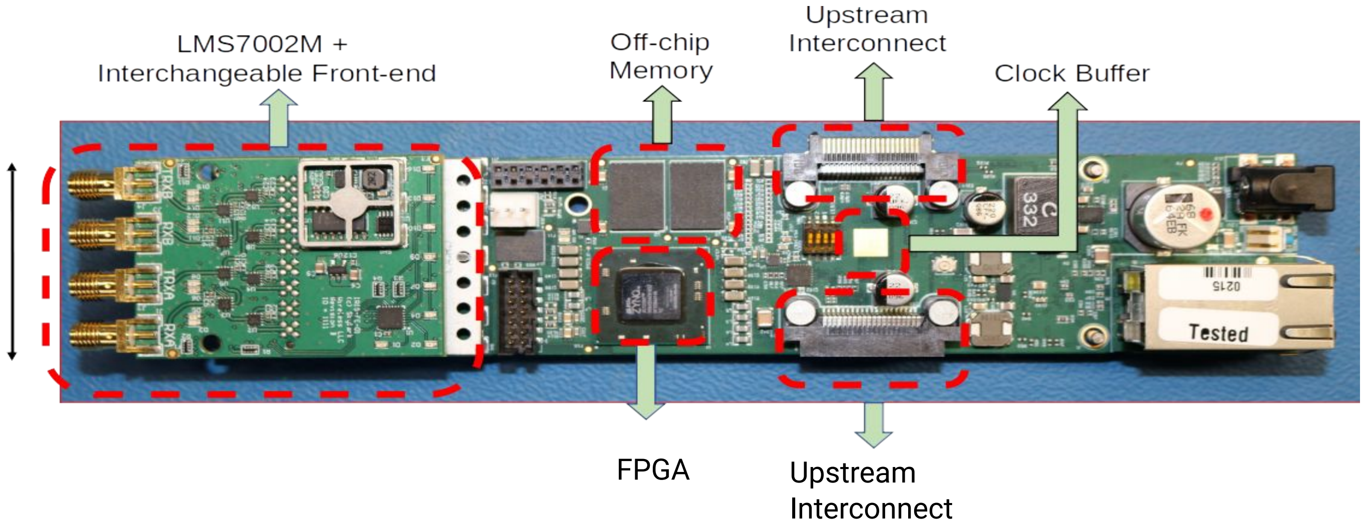


Outline

- Intro
- Basic Wireless System
- OFDM
- Multi-antenna Communication
- **Experimentation with POWDER-RENEW**

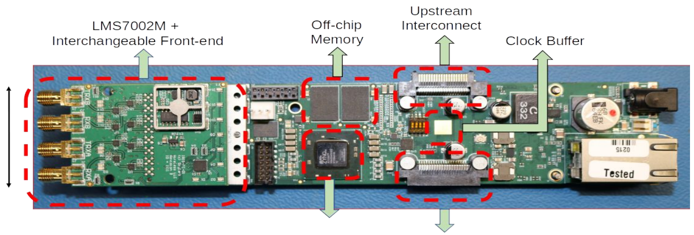
Hardware. Iris board.

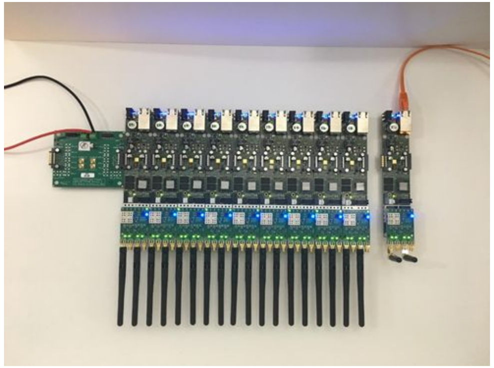
- Basic building block of our wireless experimentation platform.



Hardware. Iris chain.

- 2x2 SDR Transceiver 50-3800 MHz RF range 58 MHz BW.
    - Interchangeable frontend
- Software-defined and frequency agile
- Can be daisy-chained to create a high-dimension system
    - Each user considered a single Iris board in our setup

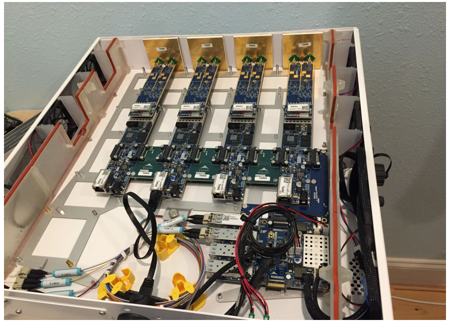


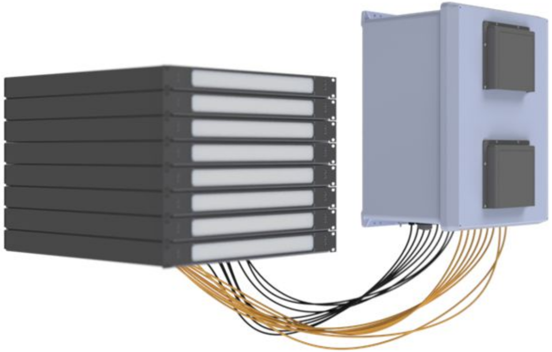


POWDER

Hardware. Faros® BS.

- Comprised of multiple chains
    - Iris boards daisy chained
    - Chains connected to each other through a hub
- Time synchronization mechanism
    - Iris measures delay relative to end of chain
    - Trigger will propagate the offset

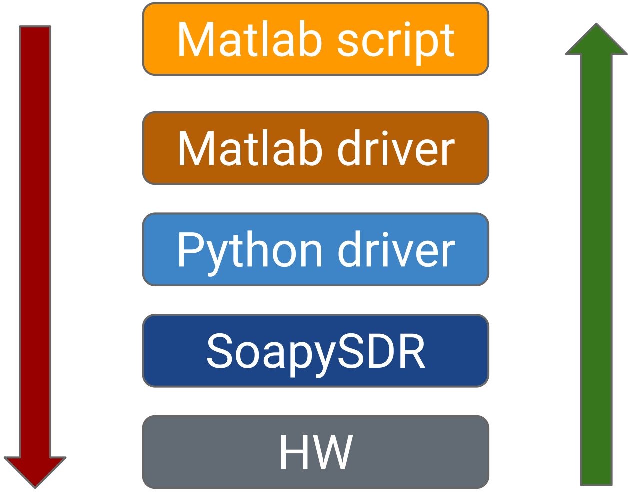




POWDER

Software.

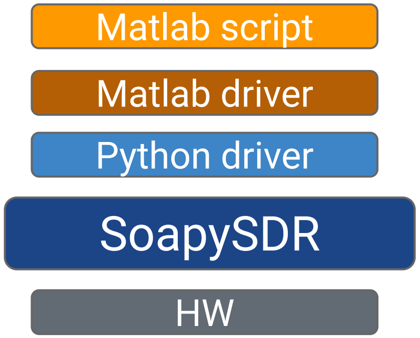
- Our framework is based on the following abstraction for interacting with the HW:



POWDER RENEW

Software. SoapySDR.

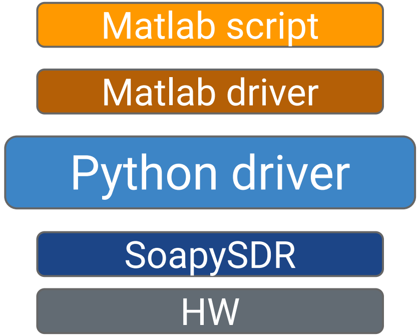
- SDR abstraction framework
    - Configure HW parameters s.a. gains, TDD frame schedule etc.
    - Has handles to Python and C++
        - Allows python and C++ programs to access HW.



POWDER

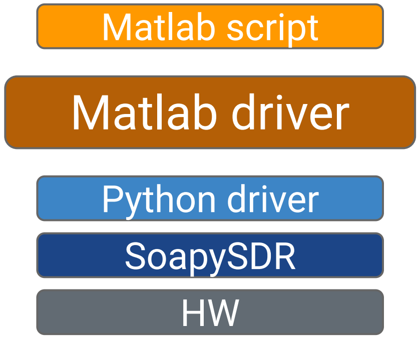
Software. Python driver.

- An object-oriented layer between Matlab and SoapySDR
    - Soapy configuration packaged into objects and methods
        - Takes parameters from Matlab and execute them on HW through SoapySDR handles
    - Can run as a standalone script



Software. Matlab driver.

- A layer between experimenter's Matlab scripts and Python
- A set of Matlab functions.
    - Scripts call these functions, driver hands input and parameters to Python driver
    - Driver sends back output returned by Python to the caller scripts.
- More details in your lab handouts.



POWDER RENEW

Further material.

The following list is a good source for material on wireless communication and MIMO:

- D. Tse & P. Viswanath, Fundamentals of Wireless Communications
- A. Goldsmith, Wireless Communications
- Aditya K. Jagannatham, IIT Kanpur Video Lectures:




- Web-site: https://renew-wireless.org
- Git: https://gitlab.renew-wireless.org/renew/renew-software
- Support: nicobarati@rice.edu, doost@rice.edu, ob4@rice.edu

The end.

Backup.

POWDER

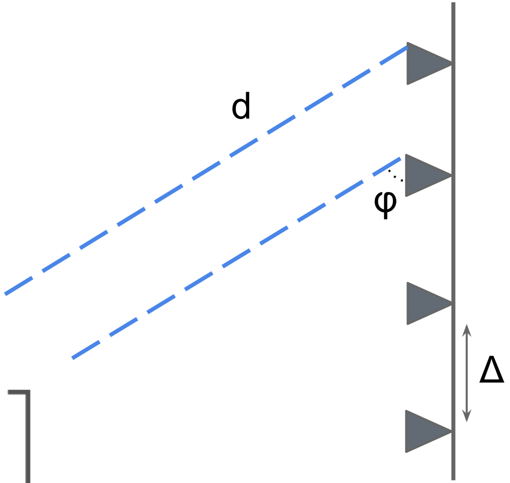
MIMO. Array response. RX.

- Array response vector (spatial signature)
  - BB response at each antenna function of the distance d, antenna separation Δ and incidence (arrival) angle φ.

cos (φ)

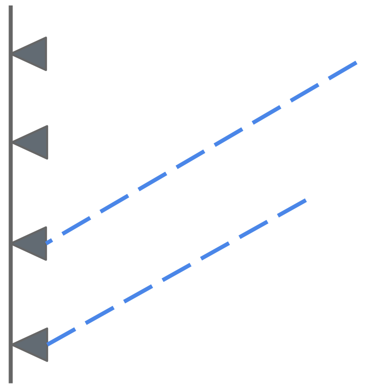
$$g\begin{bmatrix}1\\ e^{-j2\pi\Delta\Omega}\\ \vdots \\ e^{-j2\pi(i-1)\Delta\Omega}\end{bmatrix}$$

Complex gain



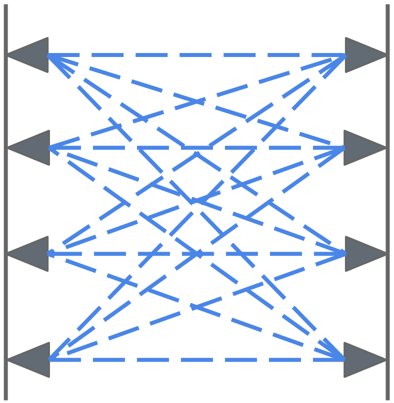
MIMO. Array response. TX.

- A reciprocal vector for TX
  - φ: angle of departure
  - No complex gain g



MIMO. MIMO spatial channel.

- Call Rx response $\mathbf{u}(\varphi)$ and Tx reponse $\mathbf{v}(\varphi)$
- The (spatial) MIMO channel is a matrix that connects $\mathbf{u}(\varphi)$ and $\mathbf{v}(\varphi)$:



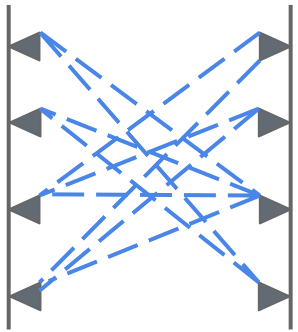
$$\mathbf{H} = g\ \mathbf{u}(\varphi)\ \mathbf{v}(\varphi)^*$$

$$\mathbf{H} \quad = \begin{bmatrix} g_\ell u_1(\phi)\mathrm{v}_1^*(\phi) & g_\ell u_1(\phi)\mathrm{v}_2^*(\phi) & \cdots & g_\ell u_1(\phi)\mathrm{v}_m^*(\phi) \\ g_\ell u_2(\phi)\mathrm{v}_1^*(\phi) & g_\ell u_2(\phi)\mathrm{v}_2^*(\phi) & \cdots & g_\ell u_2(\phi)\mathrm{v}_m^*(\phi) \\ \vdots & \vdots & \cdots & \vdots \\ g_\ell u_n(\phi)\mathrm{v}_1^*(\phi) & g_\ell u_n(\phi)\mathrm{v}_2^*(\phi) & \cdots & g_\ell u_n(\phi)\mathrm{v}_m^*(\phi) \end{bmatrix}$$

MIMO. MIMO spatial channel.

- With multipath, we will a matrix $\mathbf{H}_\ell$ per sub-path ℓ and $\mathbf{H}$ is the summation of these $\mathbf{H}_\ell$:

$$\mathbf{H} = \sum_{\ell}^{L} g_\ell \mathbf{u}_\ell(\phi)\ \mathbf{v}_\ell^*(\phi)$$



POWDER

RENEW