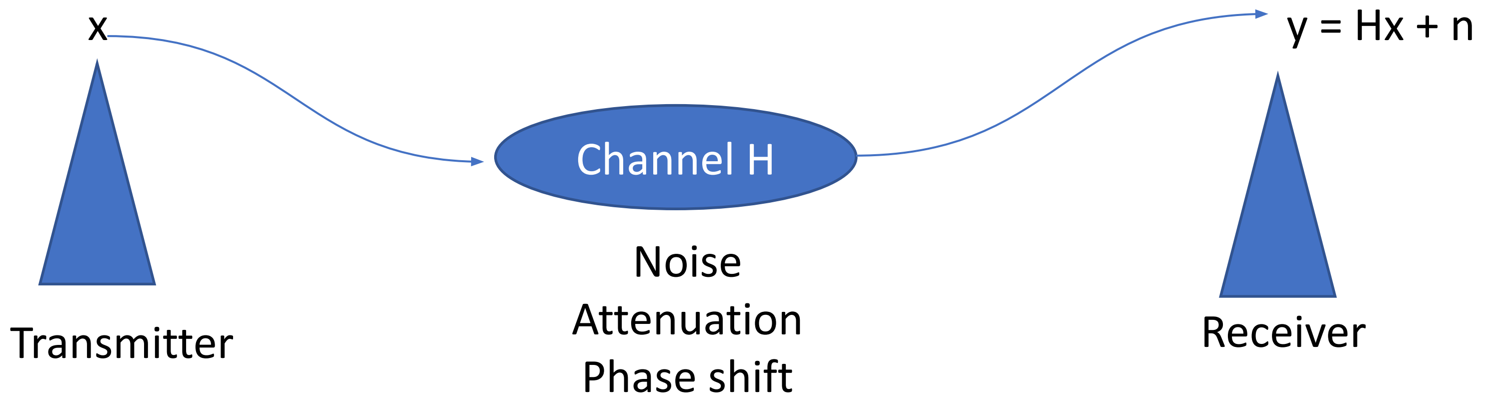
Introduction to Channel Estimation in OFDM systems

March 16th 2023

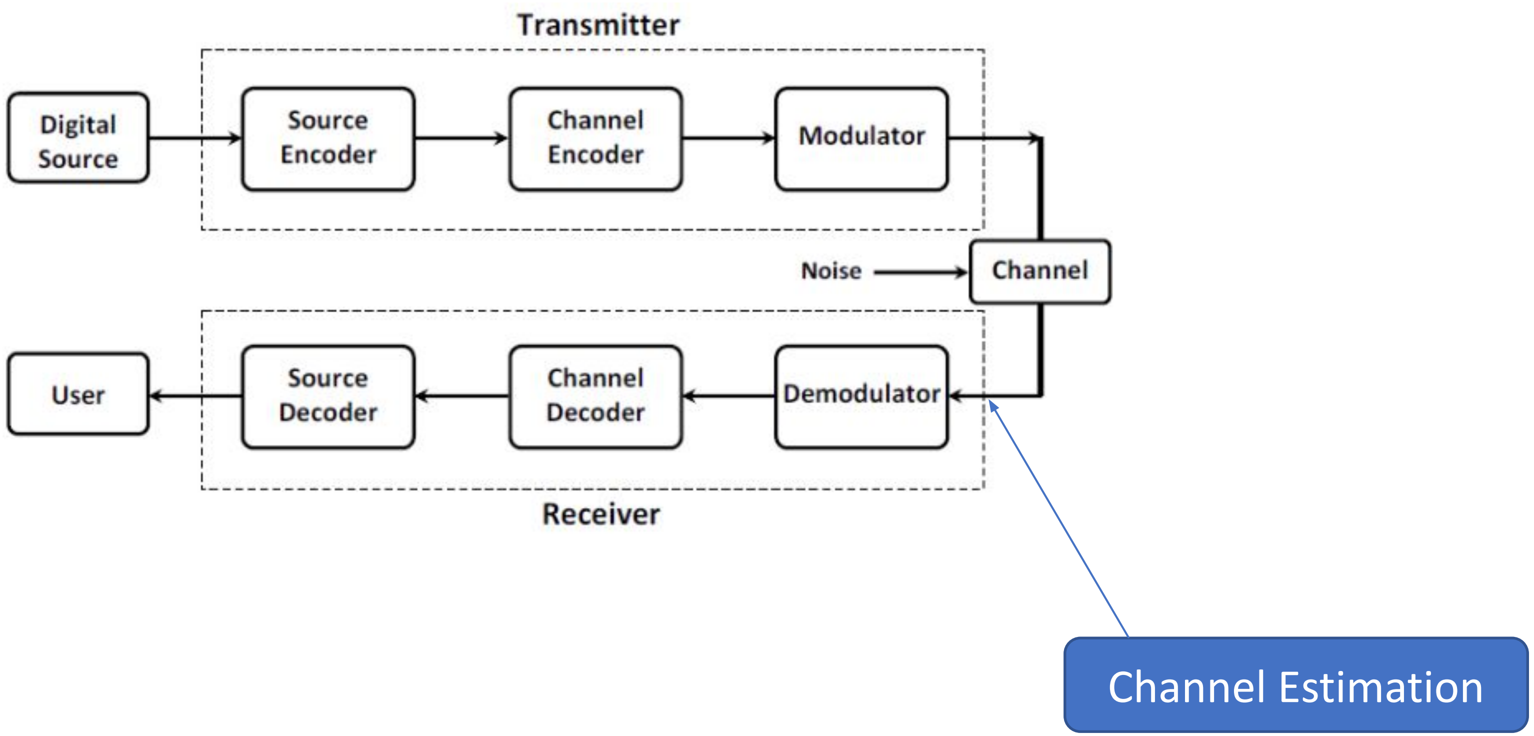
Introduction



- Channel estimation ==> Estimate H

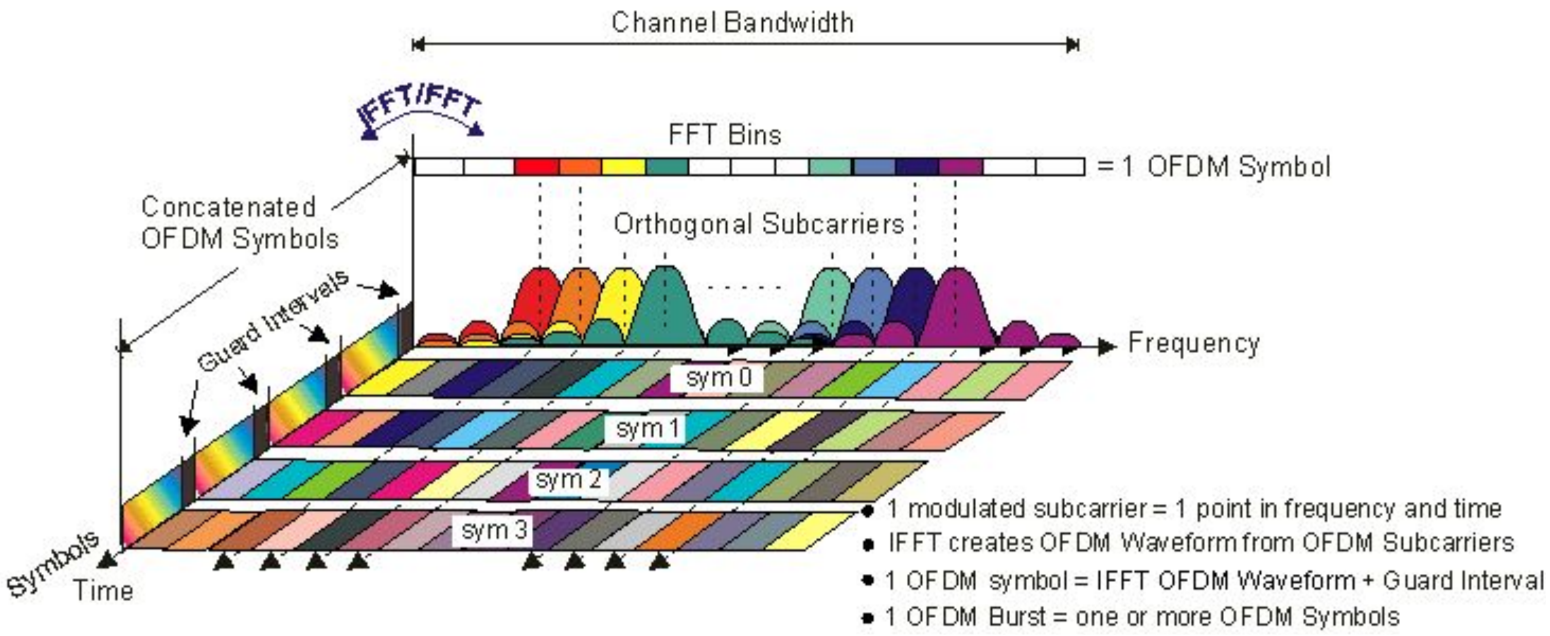
- Pilot-assisted channel estimation in OFDM
    - Uses a set of predefined signal known as pilots (also called reference signals)
    - X is Known at the transmitter and the receiver

A Typical Digital Communication System



Introduction to OFDM systems

- OFDM stands for Orthogonal Frequency Division Multiplexing, which is a method of transmitting data over wireless communication channels.
- In an OFDM system, the available frequency band is divided into multiple subcarriers, which are orthogonal to each other (meaning they don't interfere with each other). Data is modulated onto each subcarrier, and then all the subcarriers are transmitted simultaneously in parallel. This allows for high data rates and efficient use of the available frequency spectrum.
- OFDM is used in many wireless communication standards, including Wi-Fi, digital television, and 4G and 5G cellular networks.



Time-frequency representation of an OFDM signal [Source]

Introduction to OFDM systems

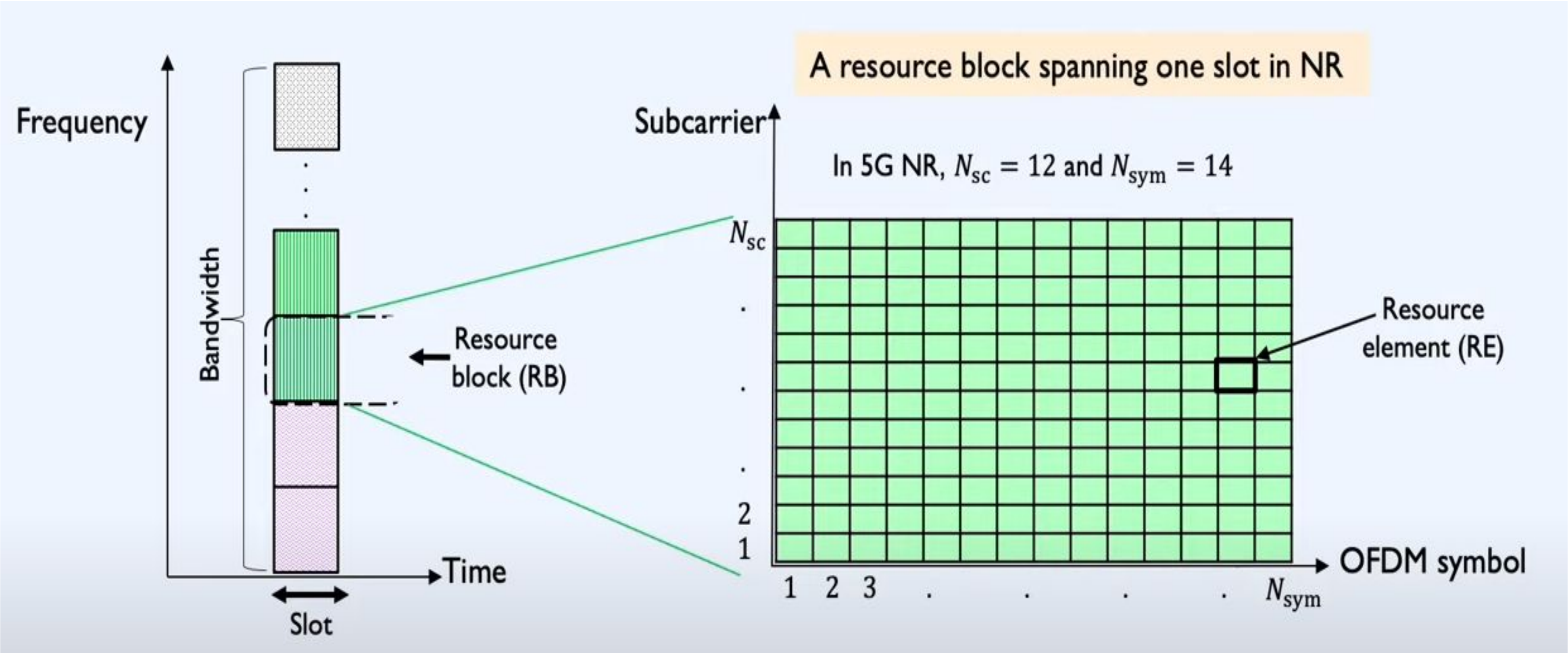


Illustration of a resource block (RB) and a resource element (RE) [Source]

Problem formulation

- H represents a time-frequency response of the channel -> H is a complex matrix with dimension (N_sc,N_sym)

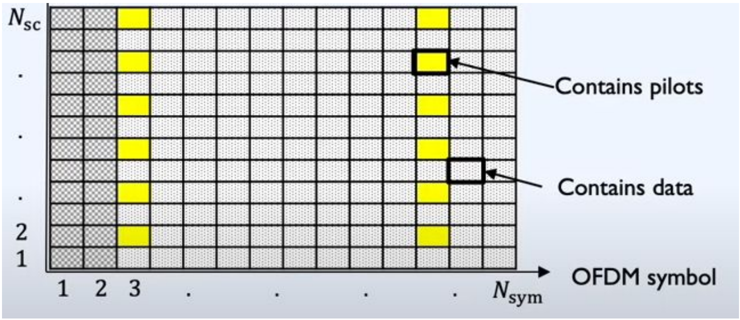
$$\mathbf{Y} = \mathbf{H} \circ \mathbf{X} + \mathbf{W}$$

- Pilots are known sequence of symbols at both receiver and transmitter

$$\mathbf{Y_p} = \mathbf{H_p} \circ \mathbf{X_p} + \mathbf{W_p}$$

- Least-Square (LS): We can estimate H at the pilot positions p (yellow elements in the figure)

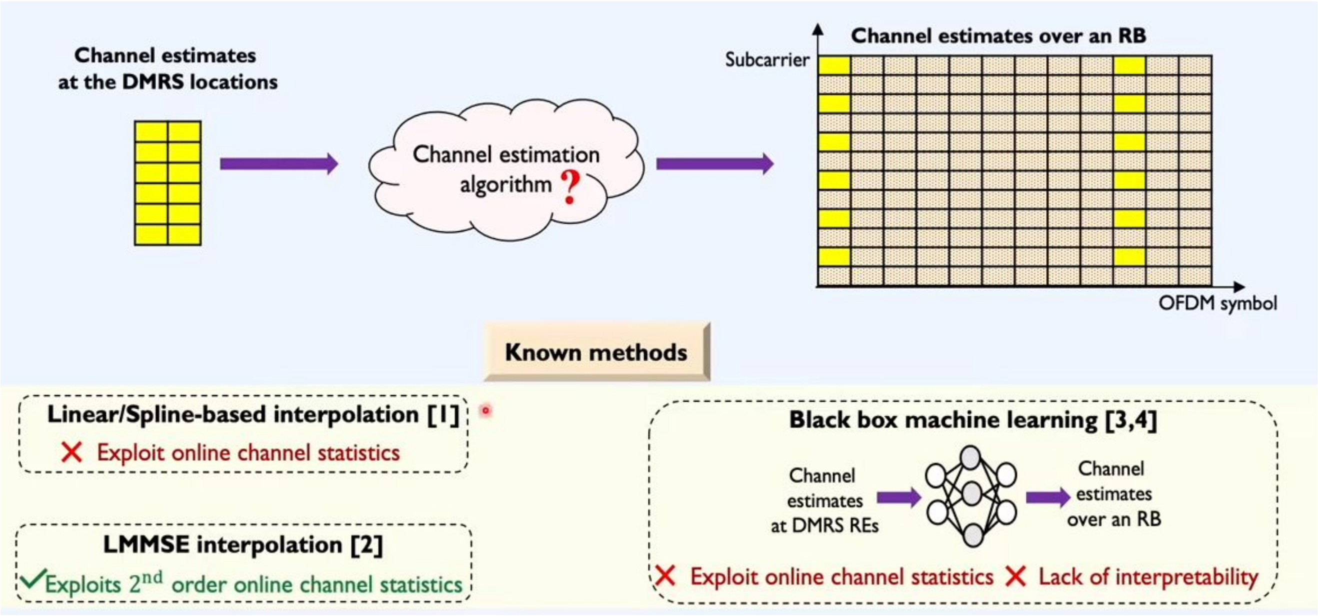
$$\hat{\mathbf{h}}_{\mathbf{p}}^{\mathbf{LS}} = \underset{\hat{h}_p}{\operatorname{argmin}} \|\mathbf{y_p} - \hat{\mathbf{h}}_{\mathbf{p}} \circ \mathbf{x_p}\|_2^2 = \mathbf{y_p} \circ \mathbf{x_p}^{\circ -1}$$



Example of one Resource Block [Source]

Interpolation methods

- The LS method estimates the channel coefficients at pilot positions **only**
- Channel coefficients in other data positions can be interpolated from the estimated coefficients at pilot positions
- The Interpolation is done in frequency, time and space
- Known interpolation approaches :
  - Linear interpolation
  - LMMSE interpolation
  - Deep learning based interpolation



Known interpolation methods [Source]

Traditional interpolation methods

- **Linear interpolation:**
  - Fast, but not very accurate
  - Does not exploit channel statistics or noise statistics

- **Linear minimum mean square error (LMMSE)**
  - Requires second order statistics (frequency, time and space domain correlations)
  - Costly

DL-based interpolation methods

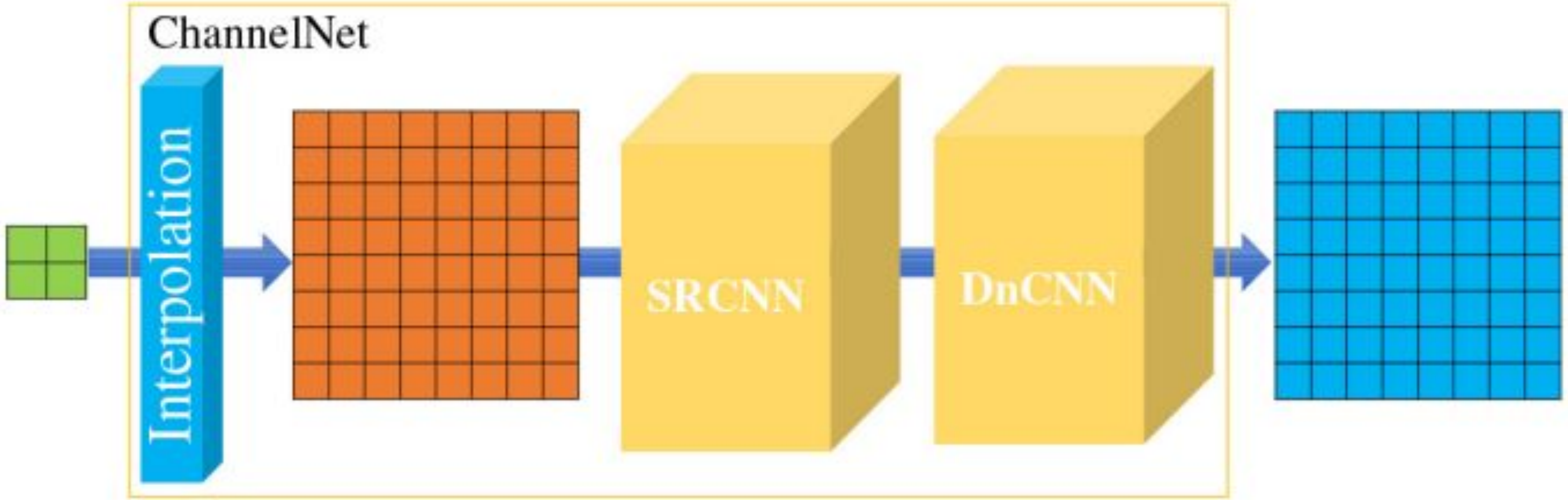
- CE problem == super-resolution (SR) /denoising problem
- The channel matrix at the pilot locations is a low-resolution representation of the whole channel H
- A SR network is learned to reconstruct the high-resolution channel from the low-resolution inputs
- The reconstructed channel can be further denoised using a denoising network

Model	Technique	Architecture	Publication
ChannelNet	SR+denoising	Convolutional	2020
ReEsNet	SR+denoising	Residual/CNN	2020
InReEsNet	SR+denoising	Residual/CNN	2020
MTRE	denoising	Transformer	2020
HA02	SR+denoising	hybrid	2021

List of deep CE methods. This list is **not** exhaustive

ChannelNet

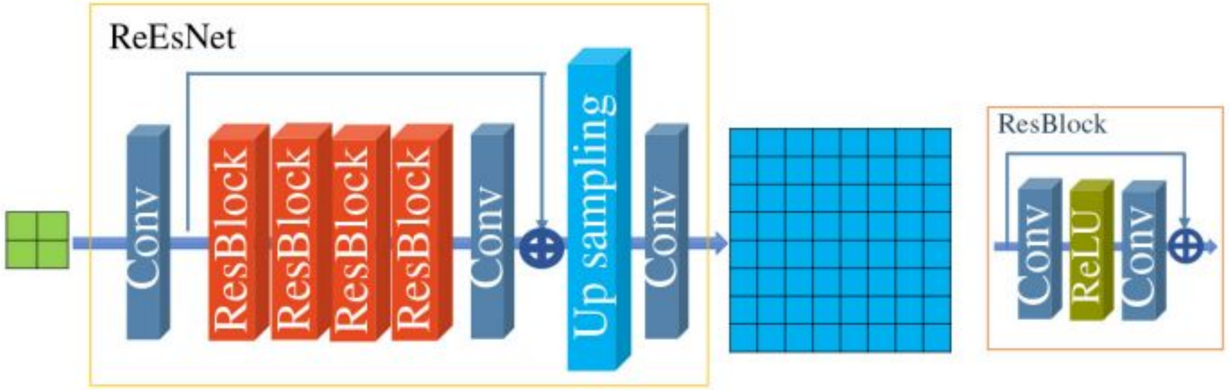
- A pre-sampling SR method that uses SRCNN to upscale the low-resolution inputs
- The upscaled channel is then fed to a denoising CNN (DnCNN)
- The models can be trained separately or in an end-to-end fashion
- The low-resolution inputs are interpolated using a traditional interpolation method before training



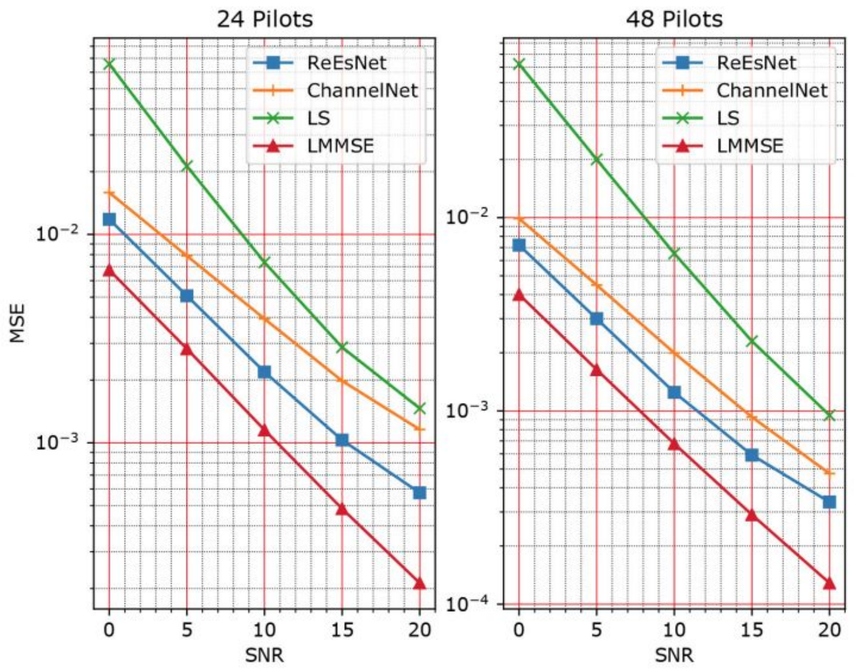
The pipeline of ChannelNet [Source]

ReEsNet

- A post-sampling SR method based on ESDR. Takes the low-resolution channel matrix as inputs
- The output of the SR model are upscaled using a learned deconvolution layer
- Another work replaced the deconvolution layer by a bilinear interpolation layer (not learned)



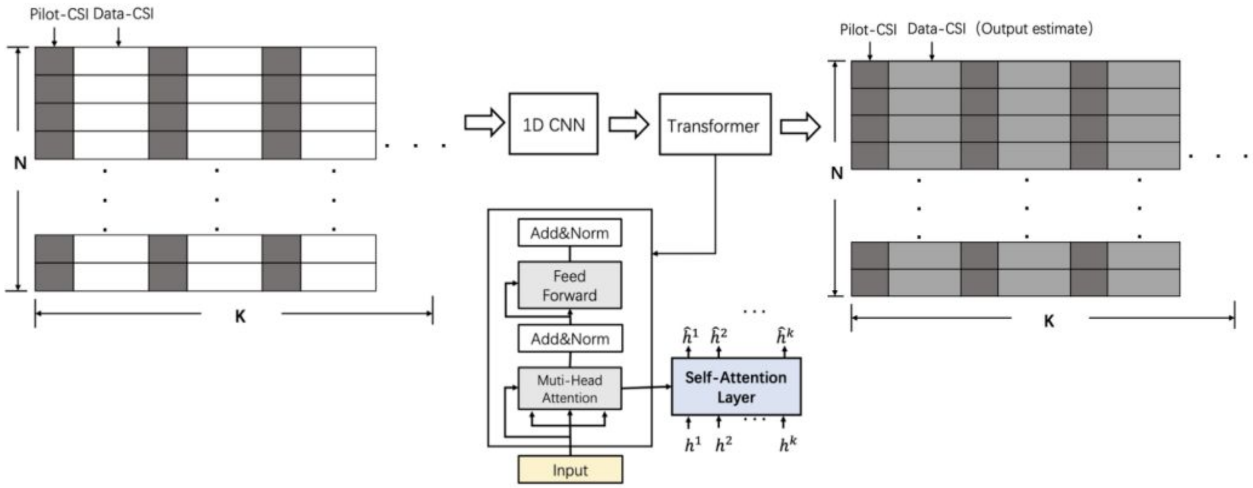
The proposed pipeline [Source]



Transformer/attention based methods

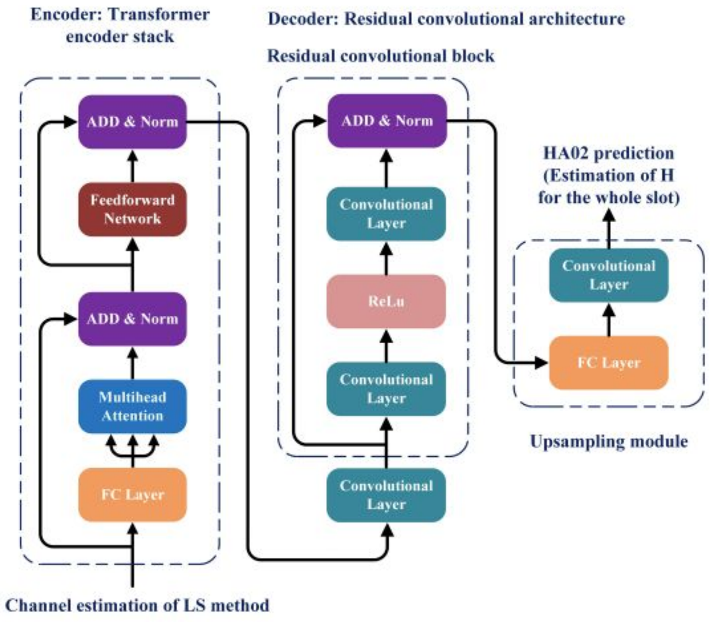
MTRE

- Masked image modeling approach
- Takes a masked matrix where **only** the coefficient at pilot positions are unmasked
- Stack of transformer encoder blocks
- Attention on frequency dimension



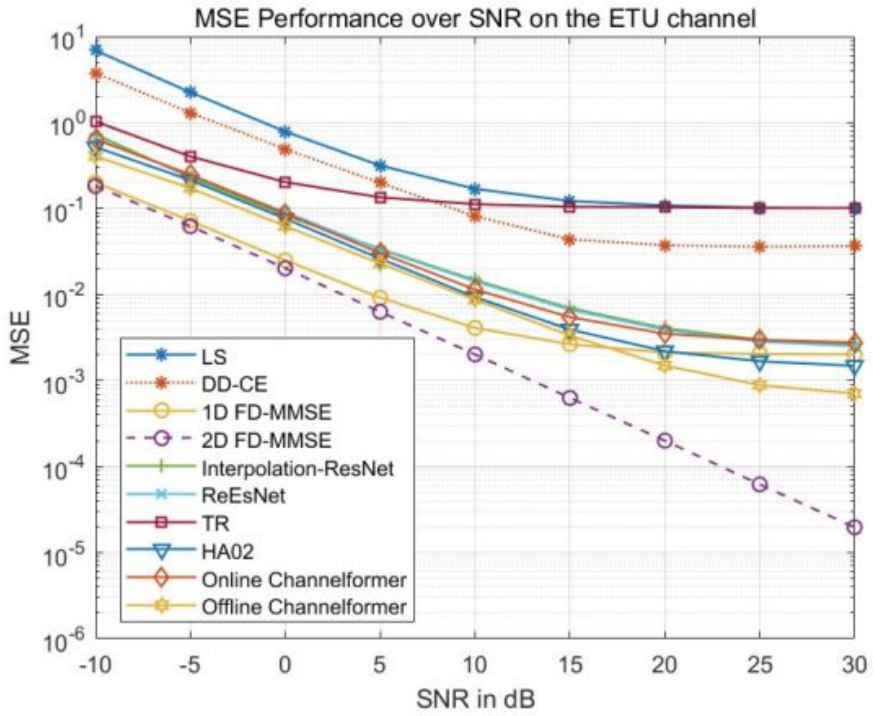
HA02/Channelformer

- Hybrid auto-encoder uses a Transformer encoder and a residual decoder (as in ReEsNet) and an up-sampling module.
- Replaces the transformer decoder by a residual decoder
- Attention on both frequency and time dimensions



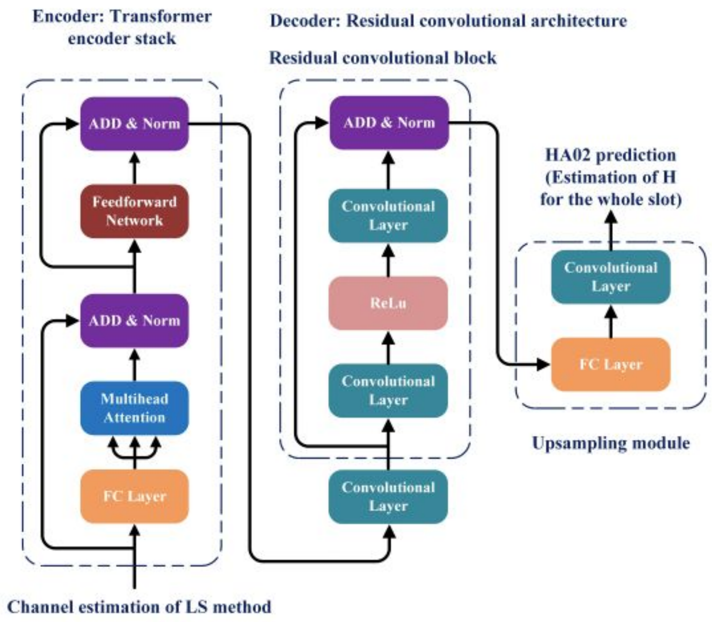
NN-based interpolation methods

- Transformer/attention based



(a) MSE performance over the extended SNR range

HA02/Channelformer

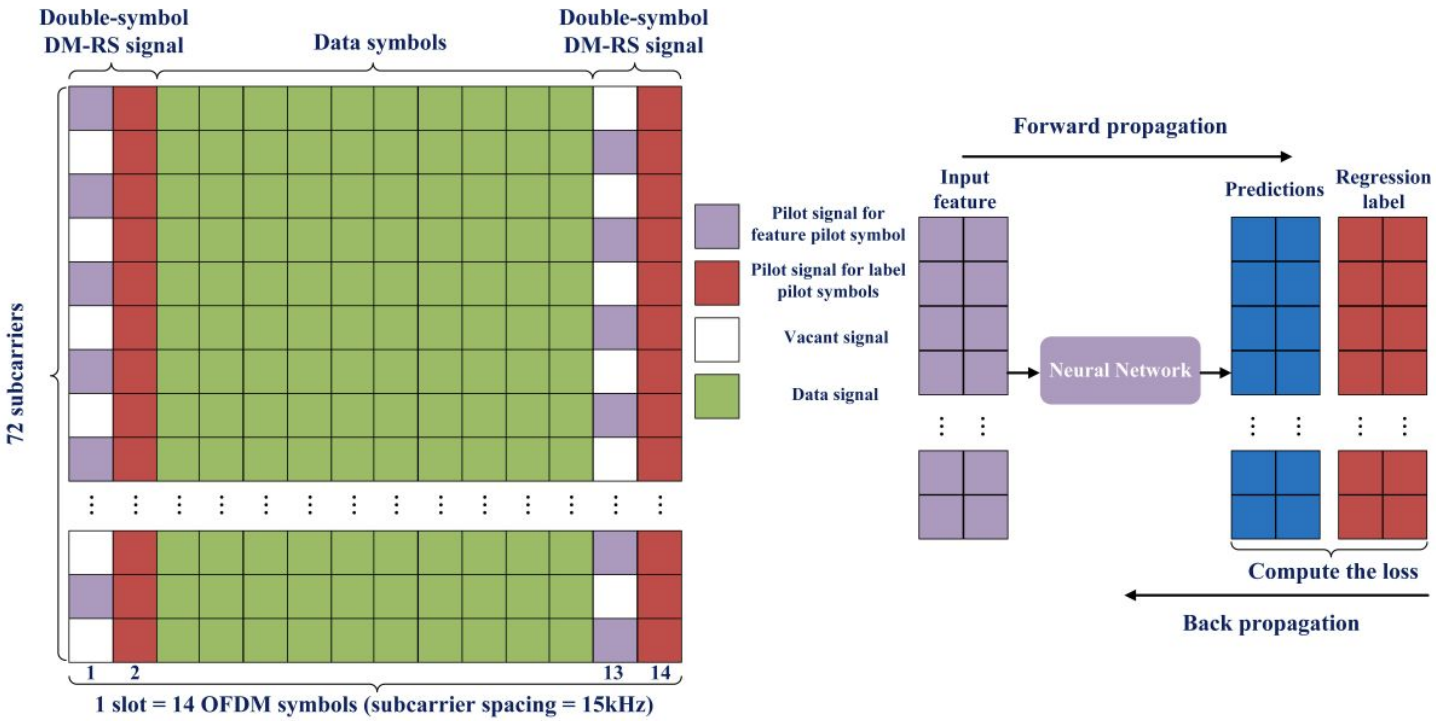


Experiment setup:
-SISO, Extended Typical Urban model
- 5G pilot arrangement
- N_sc = 14, n_sc =72
- Frequency=2.1Ghz
- Model trained on data samples using multiple SNRs

Problems with DL-based interpolation methods

- Supervised learning approaches
  - Require the whole **real** channel matrix of the whole slot
  - Unrealistic in real world

- **Solution 1 : Online learning**

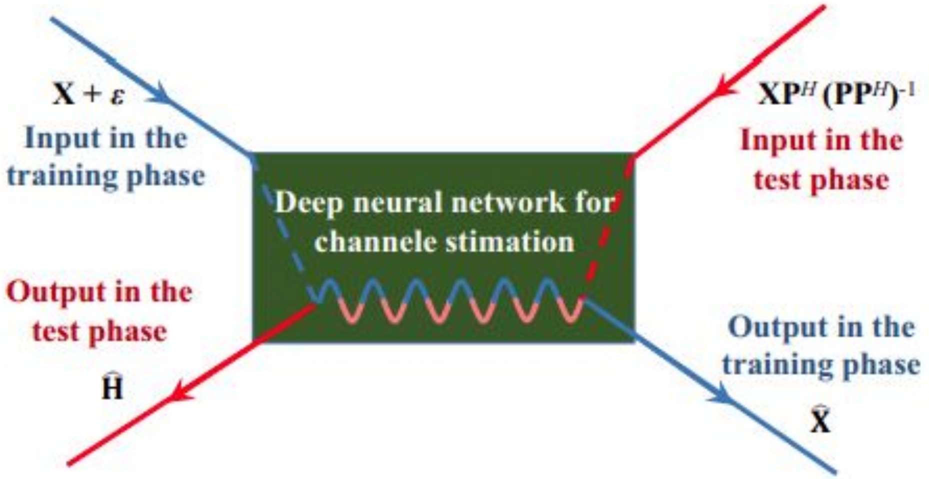


The proposed online learning pipeline from ChannelFormer [Source]

Problems with DL-based interpolation methods

Solution 2 : self-supervised learning

- No ground-truth needed
- The model is learned to denoise the received signal: input is a noisy version of the received signal and the labels are the real received signal.
- At test time, the estimated channel by LS is fed to the learned model and the denoised version is outputted
- This only works when the received signal and the channel matrix have the same dimensions

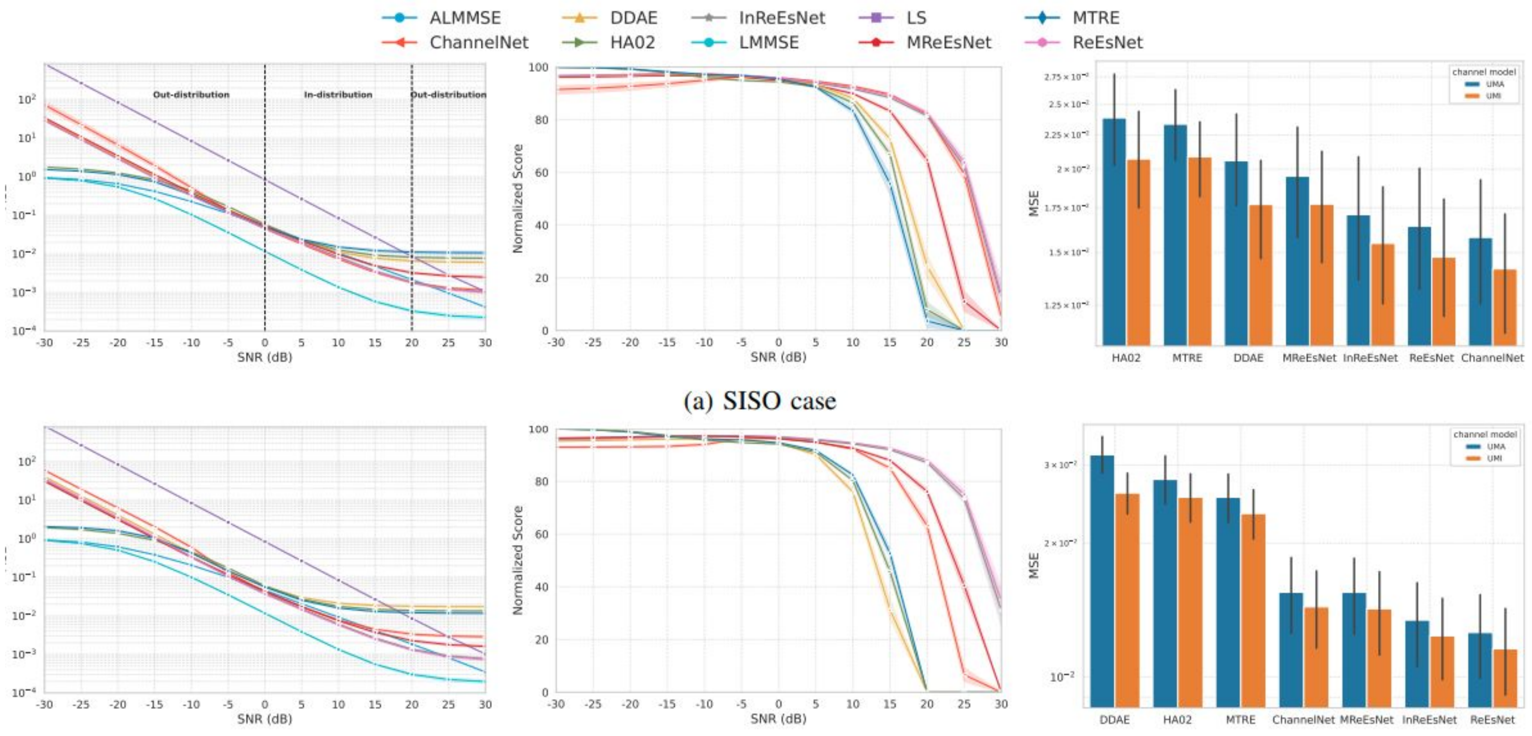


A self-supervised approach for CE [Source]

Problems with DL-based interpolation methods

- Lack of Rigorous and unified empirical analysis:
  - All the previous works use a SISO system model
  - Lack of unified data generation pipeline
  - Lack of standardized evaluation framework

Solution: Our proposed benchmark CeBed [Paper] [Code]



(a) SISO case

(b) SIMO case