5G PHY Layer Part1: Basic Signal Wave-Form Resource and Multiple Access - OFDM

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Disclaimer

All opinions and statements in this presentation are mine and do not in any way represent Ericsson

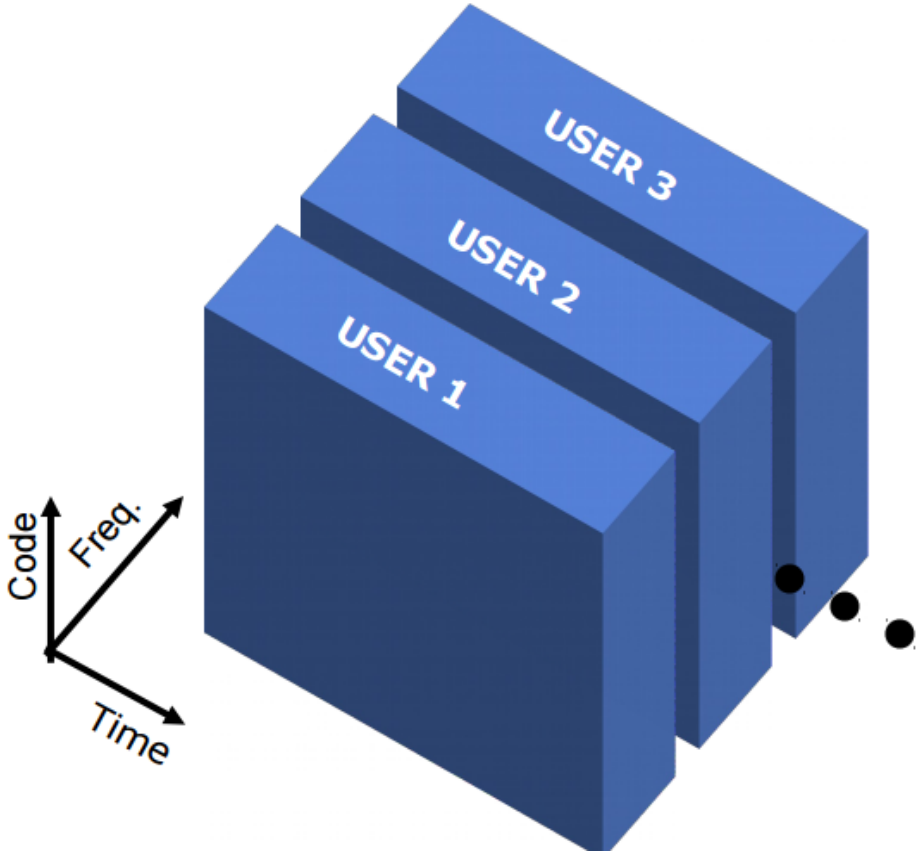
Right before We Introduce

- Usually, math explain itself as code does. But I suppose no one is interested in seeing math...
- No worries, I will explain everything in detail but without(or with a little) math. For any place we have to use math, we use the mathematical conclusion directly rather than derivation.
- If anyone is interested in mathematical derivation, I could explain the details in math as well after this presentation.
- Any question (including math) is welcome.

Overview

1. Everything Starts From FDMA
2. Three More Types of Multiple Access
   - TDMA
   - CDMA
   - SDMA(Space Division Multiple Access)
3. OFDMA
   - Revisit FDMA
   - OFDM
   - Cyclic Prefix: Way to Remove Inter Symbol Interference
4. What ill be the Waveform used for 5G?
   - Why We need other Waveforms rather than OFDM?
   - What are possible Waveforms for 5G?

Everything Starts From FDMA



Users are separated in frequency bands.

Question

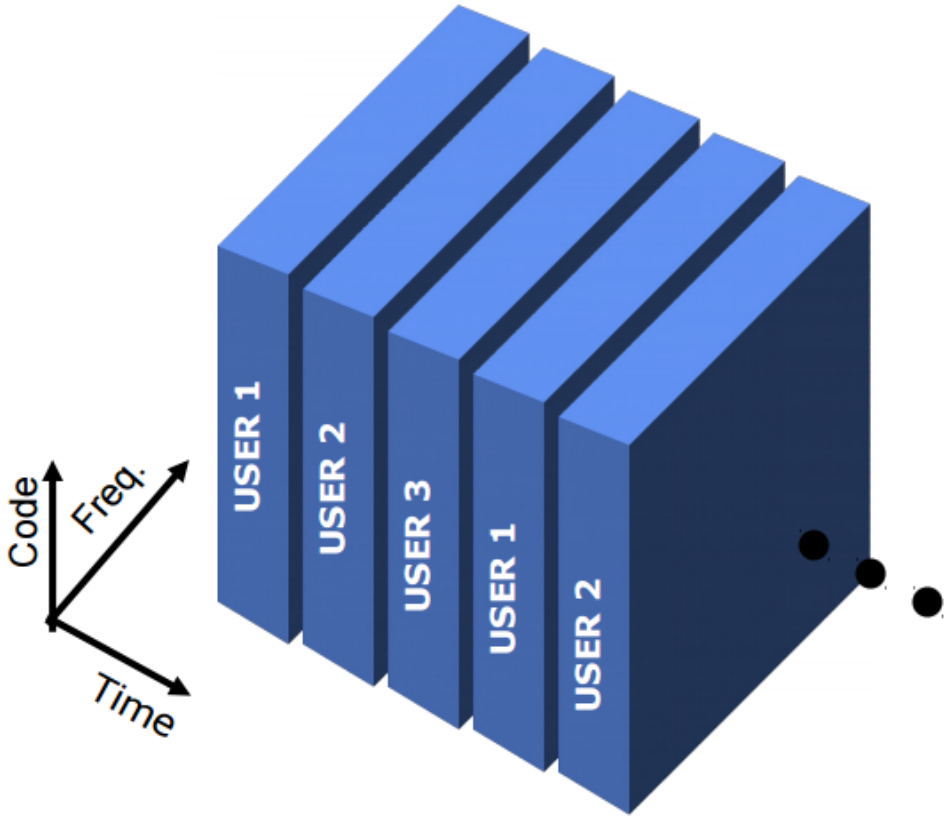
Is frequency the only resource we use to serve users?

Three Types of Multiple Access

Definitely Not

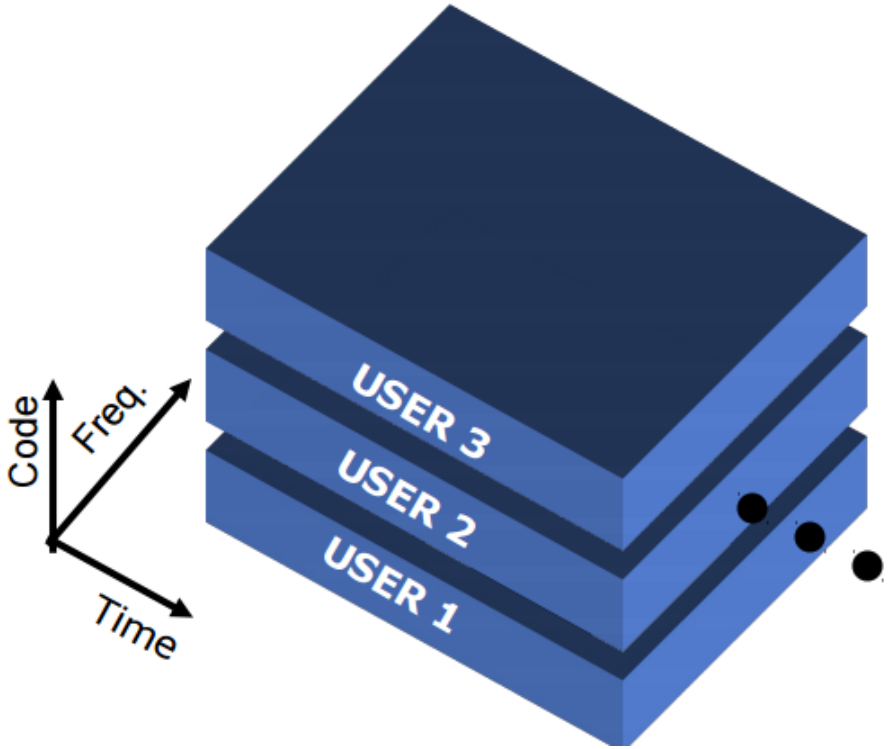
- TDMA
- CDMA
- SDMA(Space Division Multiple Access)

TDMA



Users are separated in time slots.

CDMA



Users are separated by spreading codes.

SDMA(Space Division Multiple Access)

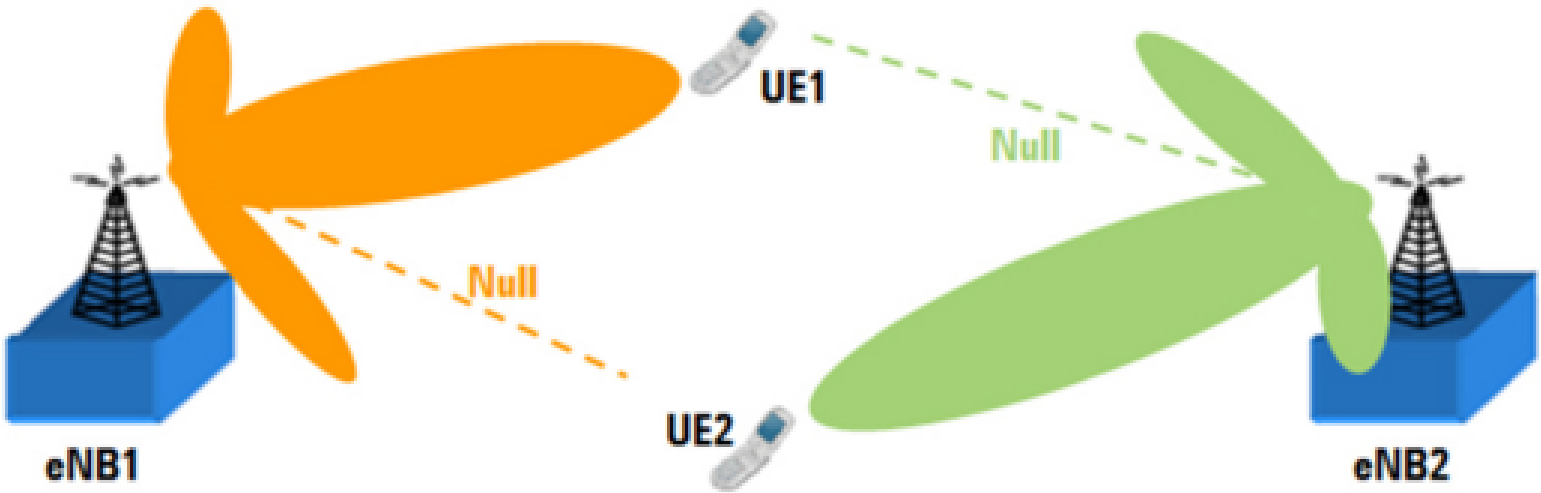


Figure 2: Beamforming improves CNIR by matching antenna gain to UE position.

Remark

SDMA is concept which is same as beamforming

Revisit FDMA

Question

We already explored four (freq, time, code, space) degrees to serve users, what else we can do if we want to serve even more users?

Maybe going back to basic technology, FDMA, to see what we could do

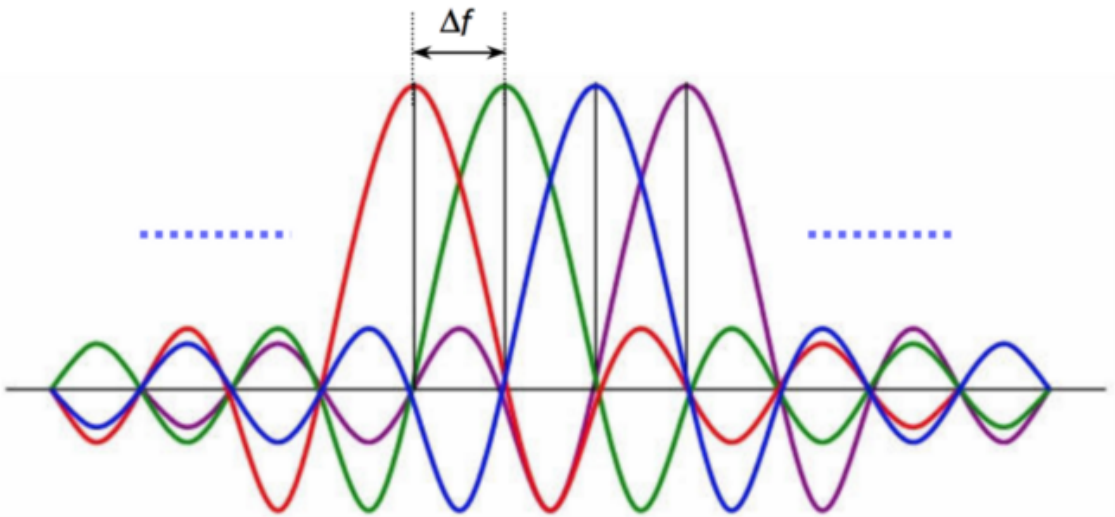
Question

Is any method to improve the frequency efficiency when we use FDMA?

OFDM

Example (Basic Idea)

Yes, using a large number of parallel narrow-band subcarriers instead of a single wide-band carrier(e.g. what we use for FMDA) to transport information



- Frequency separation of subcarriers Δf
- Sampling Time Interval T, where $\frac{1}{\Delta f} = T$

OFDM

Question

How the inter-carrier-interference is removed? It is so obvious there are lots of overlap...

- Mathematically, the complex baseband modulated OFDM symbol is represented as

$$\tilde{x}(t) = \frac{1}{N}\sum_{k=0}^{N-1}\tilde{X}(k)e^{j2\pi kf_0 t}, \quad 0 \le t \le T \text{ and } k = 0, 1, \ldots, (N\text{-}1)$$

$\hat{X}(k)$ is k-th symbol modulating the k-th sub carrier and f_0 is the frequency separation of subcarriers Δf

OFDM

- Let the two sub carriers ϕ_k and ϕ_l considered for investigation has random phases θ_k and θ_l. We will derive the condition for orthogonality in such a scenario.

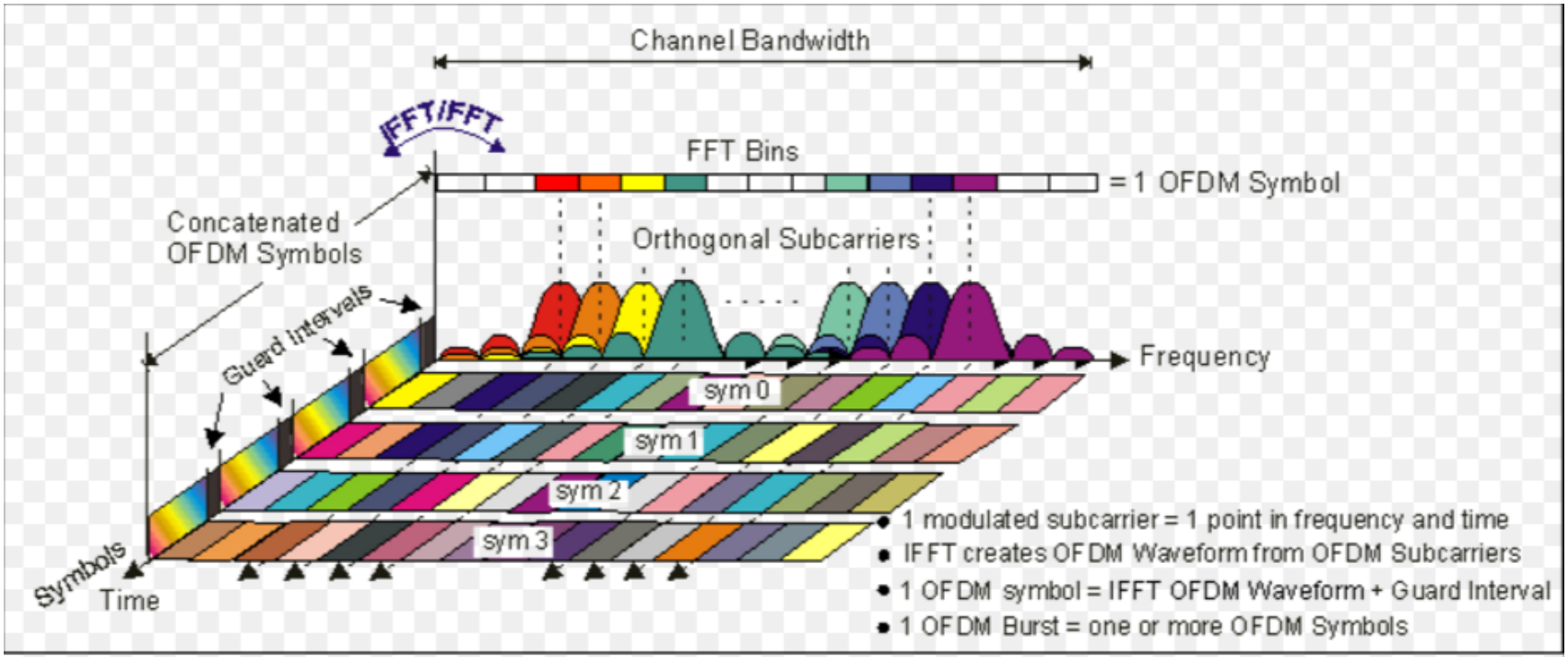
$$
\begin{aligned}
< \phi_k(t), \phi_l(t) > &= \int_0^T \phi_k(t)\phi_l^*(t)dt \\
&= \int_0^T e^{j2\pi f_k t + j\theta_k} e^{-j2\pi f_l t - j\theta_l} dt \\
&= \frac{e^{j(2\pi(f_k - f_l)T + [\theta_k - \theta_l])} - e^{[\theta_k - \theta_l]}}{j2\pi(f_k - f_l)} \leftarrow k \neq l
\end{aligned}
$$

When $2\pi(f_k\text{-}f_l)$T is a multiple of 2π, the right hand side of Eq will be zero for any value of θ_k-θ_k. Thus, when random phase offset is present, the required condition for orthogonality is to have the sub carrier frequencies separated by 1/T in frequency. This is the reason the ICI could be removed by choosing sub carrier spacing equal to 1/T

OFDM

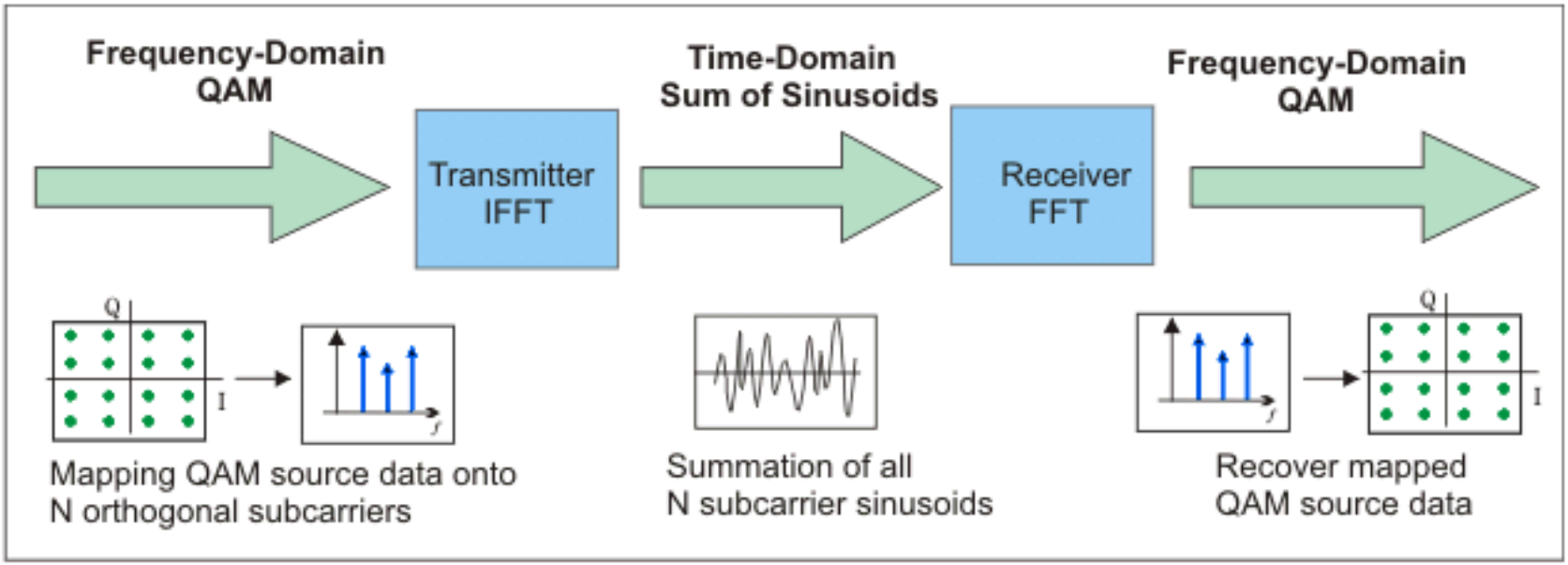
- Clearly, the frequency efficiency has been doubled, twice number of users can be connected compared to FDMA
- No inter-carrier interference between every sub-carrier in frequency, if there is no frequency offset(Frequency separation of subcarriers Δf could be maintained as $\frac{1}{T}$)

So, we could see OFDM resource as below



Frequency-Time Representative of an OFDM signal

OFDM



Simplified OFDM System Block Diagram

That is the reason we see IFFT and FFT block in LTE/5G NX system: We need to convert frequency domain orthogonal sub-carrier signals to time domain signal to be transmitted

OFDM

Question

Any other advantages of OFDM rather than improvements of frequency efficiency?

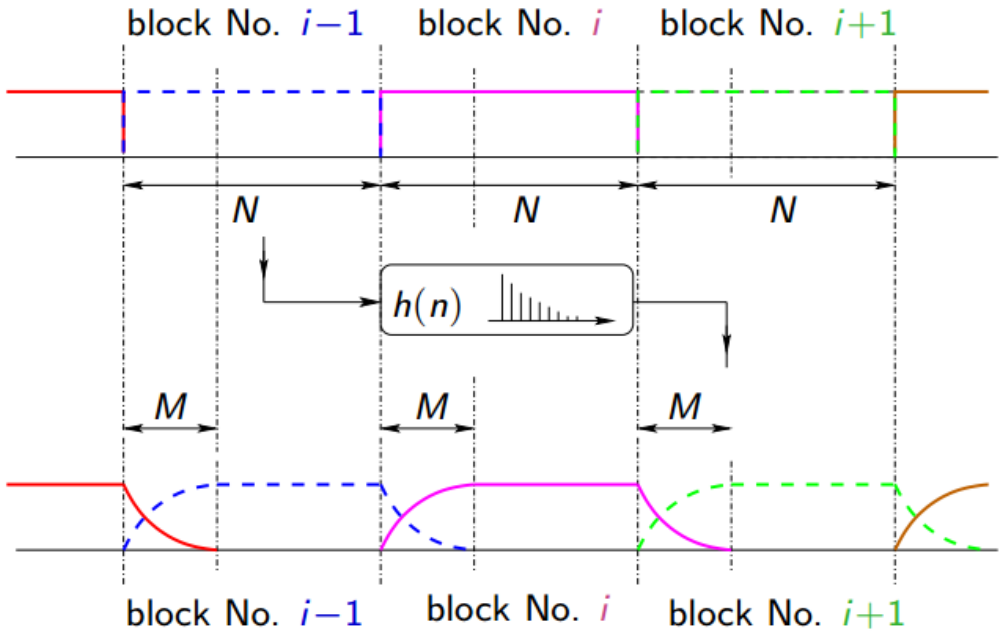
Yes, the Inter Symbol Interference(ISI) could be removed properly in OFDM signal if we add Cyclic Prefix(CP)

Cyclic Prefix: Way to Remove Inter Symbol Interference

Question

What is Inter Symbol Interference? How it has been caused? Why is it negative?

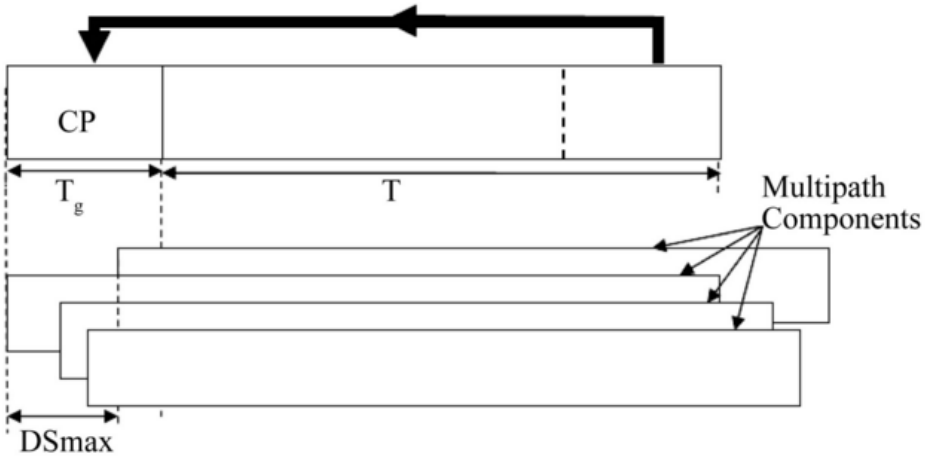
Because of multiple path wireless prorogation, Transmission of length-N symbols over an LTI channel with dispersion M (length M + 1) causes inter-symbol interference (ISI)

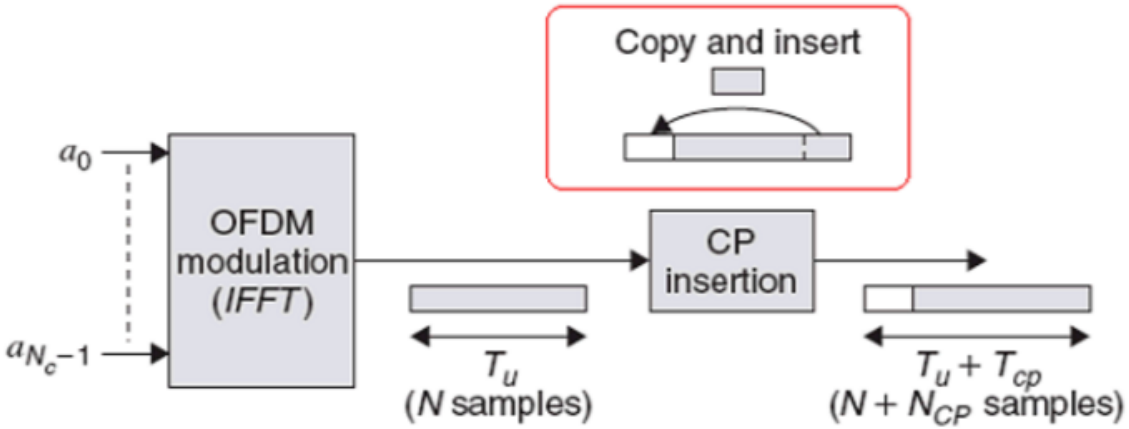


Cyclic Prefix: Way to Remove Inter Symbol Interference

Question

What is Cyclic Prefix? How to remove ISI?





Cyclic Prefix: Way to Remove Inter Symbol Interference

That is reason we see both IFFT and CP adding at transmitter and FFT and CP remove at the other in LTE/NX system.

- Clearly, CP could be added in time domain at transmitter and removed at receiver to guarantee the duration of signal which has been interfered to be removed. Then no ISI

Question

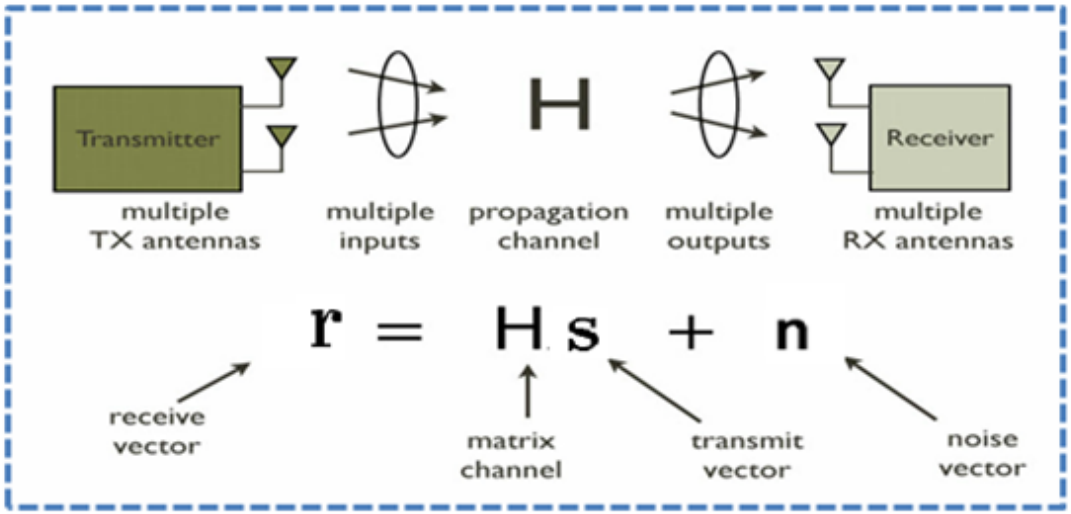
Why do we need CP(copy part of data in the end of symbol to the beginning) rather just filling anything we don't really want to transmit, e.g. artific noise, 0, etc?

Cyclic Prefix: Way to Remove Inter Symbol Interference

- Recall the mathematics of spatial multiplexing, we discussed how SVD has been used to get parralel subchannels without any inter-subchannel interference.
- The same idea, SVD, is used here! But with help of CP, the V matrix and U matrix will become fixed rather than changeable(then we don't need to estimate the S and U)

Cyclic Prefix: Way to Remove Inter Symbol Interference

Recall Spatial Multiplexing(digital beamforming)



$$\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^*$$

$$\tilde{\mathbf{r}} = \mathbf{D}\tilde{\mathbf{s}} + \tilde{\mathbf{n}}$$

where $\tilde{\mathbf{r}} = \mathbf{U}^*\mathbf{r}$, $\tilde{\mathbf{s}} = \mathbf{V}\cdot\mathbf{s}$ and $\tilde{\mathbf{n}} = \mathbf{U}^*\mathbf{n}$

In mathematics, a complex square matrix U is **unitary** if

$$U^*U = UU^* = I$$

where I is the identity matrix and U^* is the conjugate transpose of U.

Decompose the MIMO channel into m several equivalent parallel SISO channels by performing singular value decomposition (SVD) of **H**. Then **U** and **V** are unitary and **D**=*diag*($\sqrt{\lambda_1}$, $\sqrt{\lambda_1}$, … , $\sqrt{\lambda_m}$, 0 , … , 0). m = rank(**H**).
The above equation represents the system as m equivalent parallel SISO eigen- channels with channel distornation given by the eigenvalues λ_1 , λ_2 , … , λ_m.

Cyclic Prefix: Way to Remove Inter Symbol Interference

- Adding the CP on OFDM signal and transmit over fading channel matrix equals mathematically to transmit original OFDM signal over circular channel matrix.

$$\begin{bmatrix} r(0) \\ r(1) \\ \vdots \\ r(N-1) \end{bmatrix} = \begin{bmatrix} h(L) & \cdots & h(1) & h(0) & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & \ddots & & h(1) & h(0) & \ddots & & & & \vdots \\ \vdots & & h(L) & \vdots & h(1) & \ddots & & & & \vdots \\ \vdots & & & h(L) & \vdots & \ddots & \ddots & \ddots & & \vdots \\ \vdots & & & 0 & h(L) & & \ddots & \ddots & \ddots & \vdots \\ \vdots & & & \vdots & \ddots & \ddots & & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & 0 & \cdots & 0 & h(L) & \cdots & h(1) & h(0) \end{bmatrix} \begin{bmatrix} s(-L) \\ \vdots \\ s(-1) \\ s(0) \\ s(1) \\ \vdots \\ s(N-1) \end{bmatrix}$$

$$\underbrace{\begin{bmatrix} r(0) \\ r(1) \\ \vdots \\ r(N-1) \end{bmatrix}}_{\mathbf{r}} = \underbrace{\begin{bmatrix} h(0) & 0 & \cdots & 0 & h(L) & \cdots & h(1) \\ h(1) & h(0) & \ddots & & 0 & \ddots & \vdots \\ \vdots & h(1) & \ddots & & \ddots & \ddots & h(L) \\ h(L) & \vdots & \ddots & \ddots & & & 0 \\ 0 & h(L) & & \ddots & \ddots & & \vdots \\ \vdots & \ddots & \ddots & & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & h(L) & & h(1) & h(0) \end{bmatrix}}_{\ddot{\mathbf{H}}} \underbrace{\begin{bmatrix} s(0) \\ s(1) \\ \vdots \\ s(N-1) \end{bmatrix}}_{\mathbf{s}}$$

Cyclic Prefix: Way to Remove Inter Symbol Interference

- SVD of circular channel matrix will always get IFFT matrix as U matrix and FFT matrix as V^* matrix.

$$\boldsymbol{H}_{\text{CIRC}} = \boldsymbol{F}^{\text{H}} \boldsymbol{\Lambda} \boldsymbol{F}$$

where $\boldsymbol{F} \in \mathbb{C}^{N \times N}$ is the normalized Fourier matrix (unitary in nature i.e. $\boldsymbol{F}\boldsymbol{F}^{\text{H}} = \boldsymbol{I}_N$)

- **FFT matrix**:

$$\boldsymbol{\mathcal{F}} = \frac{1}{\sqrt{N}} \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & W_N & W_N^2 & \cdots & W_N^{N-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & W_N^{N-1} & W_N^{2(N-1)} & \cdots & W_N^{(N-1)^2} \end{bmatrix}$$

  where $W_N = e^{-j2\pi/N}$;

- **IFFT matrix** is given by $\boldsymbol{\mathcal{F}}^H$;
- **Main Properties**: $\boldsymbol{\mathcal{F}}^H \boldsymbol{\mathcal{F}} = \boldsymbol{\mathcal{F}} \boldsymbol{\mathcal{F}}^H = \boldsymbol{I}_N$.

Cyclic Prefix: Way to Remove Inter Symbol Interference

- So the ISI could be removed when we apply IFFT at transmitter and FFT at receiver.

$$\boldsymbol{x}_k = \boldsymbol{F}\boldsymbol{H}_{\text{CIRC}}\boldsymbol{F}^{\text{H}}\boldsymbol{s}_k + \eta_k$$

- Whatever channel H is, the "precoding matrix" and "equlization matrix" will always be IFFT matrix and FFT.

That is the reason why we need copy the same information from end of symbol to the beginning of symbol rather than simply adding something else at the begin of each symbol.

Cyclic Prefix: Way to Remove Inter Symbol Interference

- Recall the equivalent circular matrix

$$\underbrace{\begin{bmatrix} r(0) \\ r(1) \\ \vdots \\ r(N-1) \end{bmatrix}}_{\mathbf{r}} = \underbrace{\begin{bmatrix} h(0) & 0 & \cdots & 0 & h(L) & \cdots & h(1) \\ h(1) & h(0) & \ddots & & 0 & \ddots & \vdots \\ \vdots & h(1) & \ddots & & \ddots & \ddots & h(L) \\ h(L) & \vdots & \ddots & \ddots & & & 0 \\ 0 & h(L) & & \ddots & \ddots & & \vdots \\ \vdots & \ddots & \ddots & & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & h(L) & & h(1) & h(0) \end{bmatrix}}_{\tilde{\mathbf{H}}} \underbrace{\begin{bmatrix} s(0) \\ s(1) \\ \vdots \\ s(N-1) \end{bmatrix}}_{\mathbf{s}}$$

- The length of CP, L, is decided by the delay dispersion of LTI channel in smapling, M. L needs to be at least equal to (or larger than)M which makes the equivalent matrix to be circular matrix.

That is the reason why we can have flexible length of CP for different service/scenarios in NX.

Why We need other Waveforms rather than OFDM?

Ericsson seems like OFDM based 5G, but other companies might NOT want..

Question

OFDM is fantastic waveform, it has been used in WiFi, LTE, Wimax, etc, why do we want another new one?

Because..

- People want even higher efficiency(although OFDM has higher freq efficiency but loss the efficiency in time)
- Inter Carrier Interference (ICI) in OFDM due to frequency offset(say if frequency separation of subcarriers is imperfect so Δf is not exactly equal to $1/T$), it will be even more harmful when 5G mobility
- High peak-to-average power ratio (PAPR), that is reason LTE uplink uses SC-FDMA to replace OFDM cause power amplifier at mobile terminal can NOT handle PAPR

What are possible Waveforms for 5G?

- FBMC, Filter Bank Multi-Carrier: FBMC has gained a high degree of interest as a potential 5G waveform candidate. This waveform scheme provides many advantages
- UFMC, Universal Filtered MultiCarrier: This 5G waveform can be considered as an enhancement of CP-OFDM
- Filtered OFDM uses filtering to provide its unique characteristics. Using f-OFDM, the bandwidth available for the channel on which the signal is to be transmitted is split up into several sub-bands
- Let us move to part2: Signal Wave-Form Resource and Multiple Access Candidates - Beyond OFDM

References

- Ove Edfors, ETIN15 Radio System, Lund University, 2015
- Thomas Magesacher, EIT140 OFDM for Broadband Communication, Lund University, 2011
- Jaakko Vihril, Eeva Lhetkangas, Kari Pajukoski , Natalia Ermolova, Olav Tirkkonen, On the Waveforms for 5G Mobile Broadband Communications, 2015
- Spatial multiplexing, wikipedia.org
- Orthogonal Frequency Division Multiplexing . Rethnakaran.P and Herbert Dawid

Question?

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