Simulation Techniques for 5G Transmission

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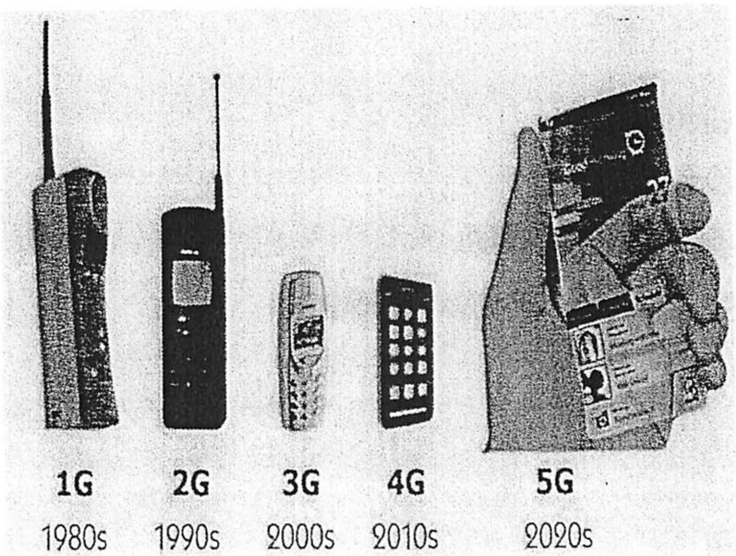
Content

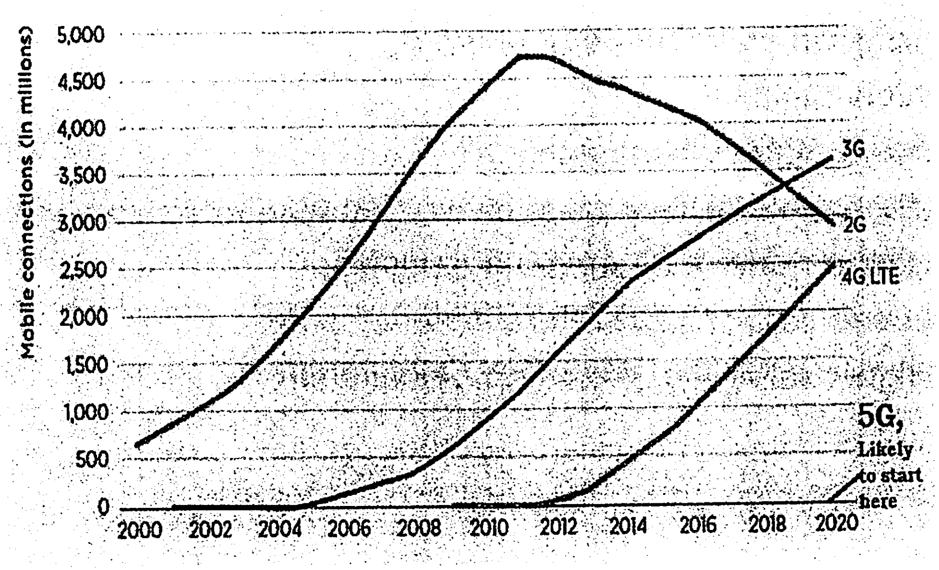
1. Introduction to 5G
2. Introduction to OFDM
3. F-OFDM and W-OFDM
4. Mini-meter wave communication

Introduction to 5G

- Wireless communication has experienced a rapid growth and evolution since 1980s (1G, …4G, or now 5G).

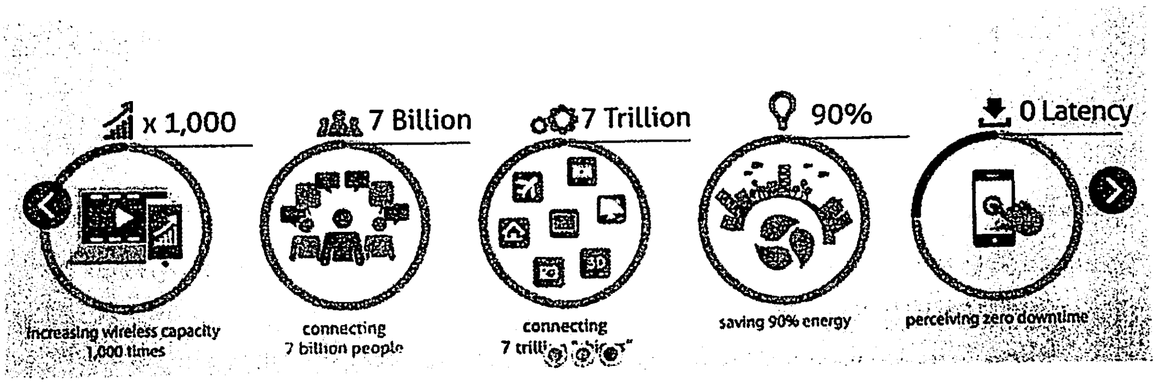


- Evolution:



- What is 5G?
  - 5G is the fifth generation technology, and it has many advanced features potential enough to change our life dramatically.

- Targets:



https://5g-ppp.eu/#

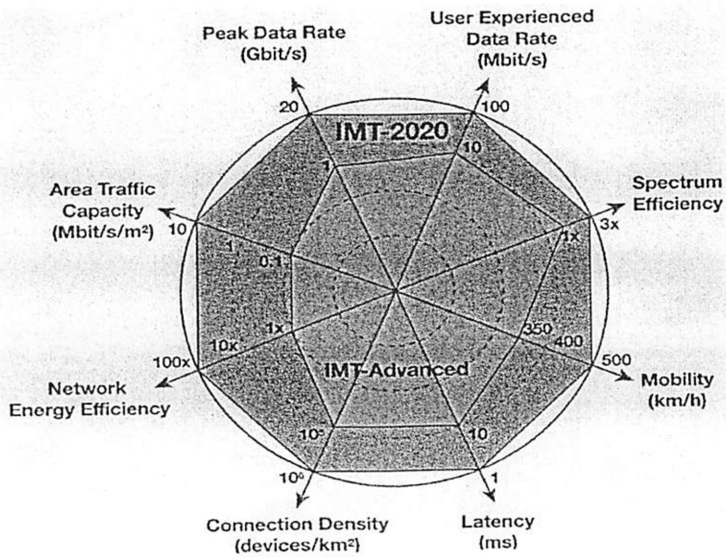
- Features:
  - High increased peak bit rate
  - Larger data volume per unit area
  - High capacity
  - Lower battery consumption
  - Better connectivity irrespective of the geographic region
  - Larger number of supporting devices
  - Lower cost of infrastructural development
  - Higher reliability of the communications

- How to increase the capacity by 1000 times?

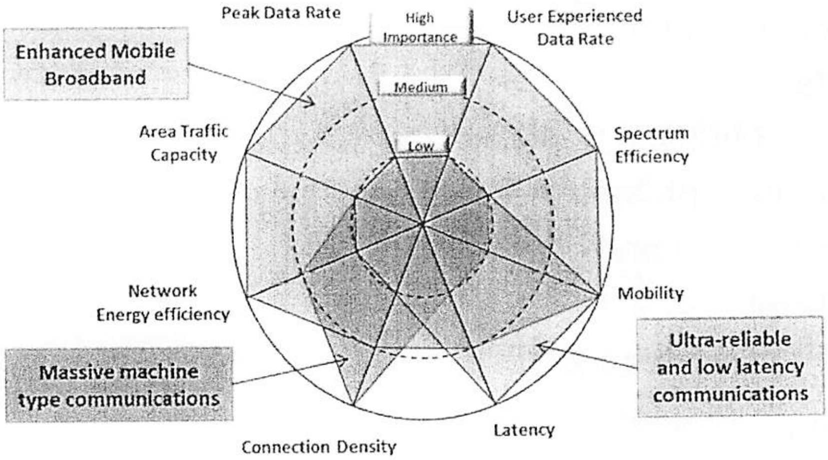
- Better spectral efficiency (4):
  - Spectral efficiency: 30 bps/Hz →?
  - Key enabling technology, MIMO, ...
- Larger spectrum (5):
  - Carrier bandwidth Increase: 100MHz →500MHz/1GHz
  - Spectrum availability?
    - Higher band: millimeter wave (mmWave)
    - Spectrum sharing
    - Unlicensed bands
- More cells, network densification (50):
  - Greatly reduce the coverage of a cell, i.e., dramatically increase the cell number
  - Key enabling technology, ultra-dense small cells

- Technology challenges:
  - Authorized shared access
  - Unlicensed bands
  - mmWave
  - Massive MIMO
  - Phase antenna array
  - Beam-forming and beam-tracking
  - Small cell
  - Interference management
  - Full duplex radios
  - SDN and NFV
  - ...

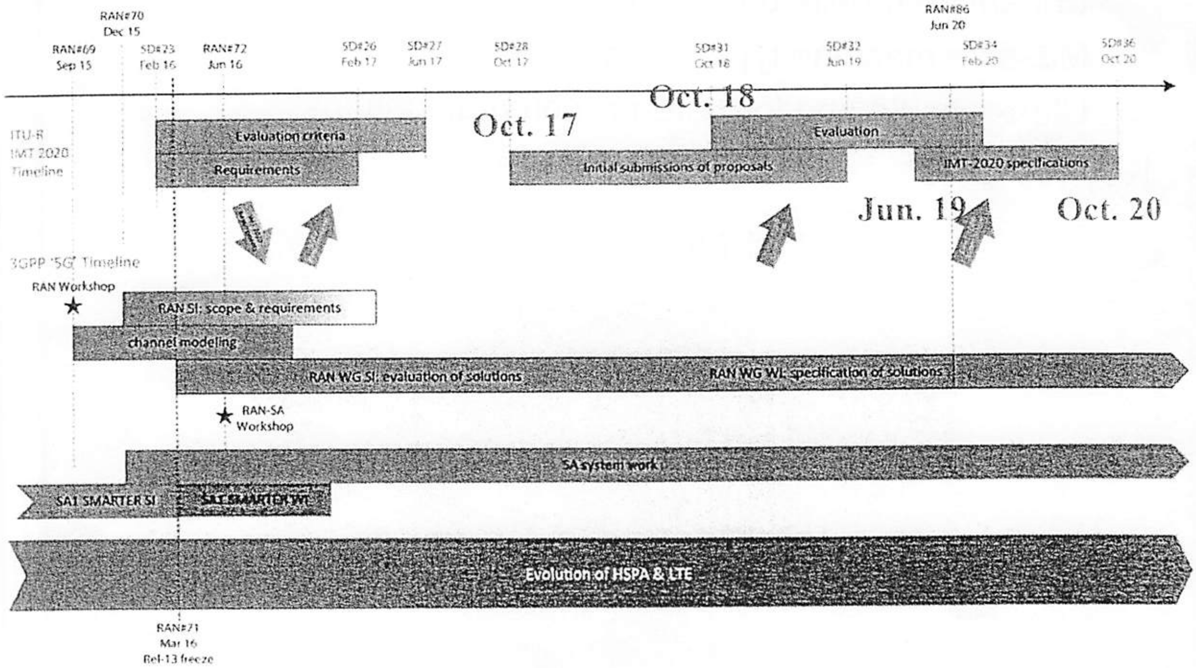
- ITU has defined three usage scenarios in 5G
  - Enhanced mobile broadband
  - Massive machine type communications
  - Ultra-reliable and low latency communications
- Key features:



- Three scenarios:

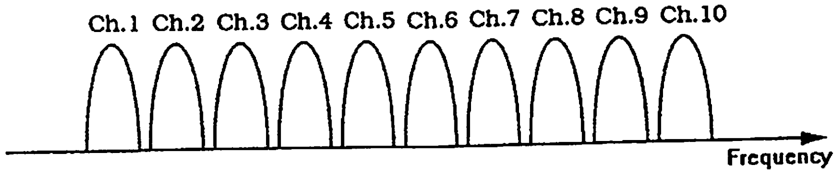


- 3GPP RAN workshop on 5G (9/18/2015):



Introduction to OFDM

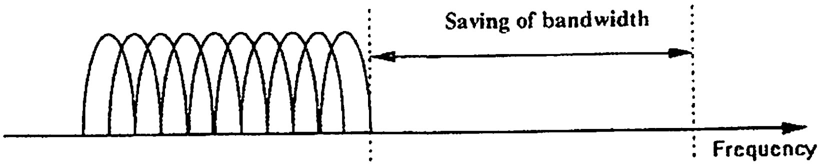
- OFDM can also be defined with the framework of frequency-division-multiplexing (FDM).
- FDM : Split a high-rate data-stream into a number of lower rate streams transmitted simultaneously over a number of carriers.



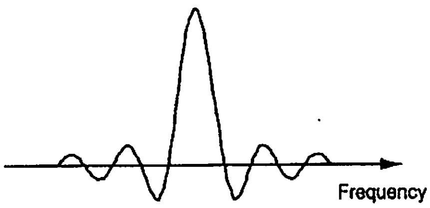
(a)

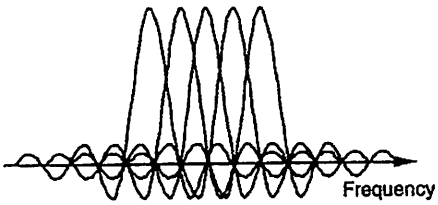
- Since the symbol duration increases for low rate carriers, the channel dispersion is decreased.
- Drawback: Guard bands make this approach inefficient.

- Remedy: use overlapping sub-channels.

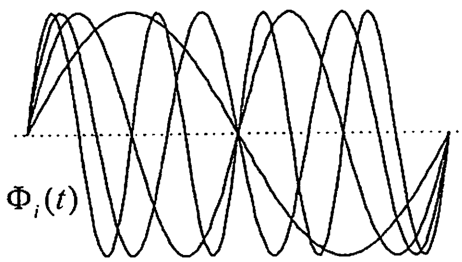


- It is possible to arrange carriers such that there is no interference between them. To do that the carriers must be mathematically orthogonal.





- Note that a necessary and sufficient condition for this requirement is that all carriers must has a same period.
- Time domain waveform:



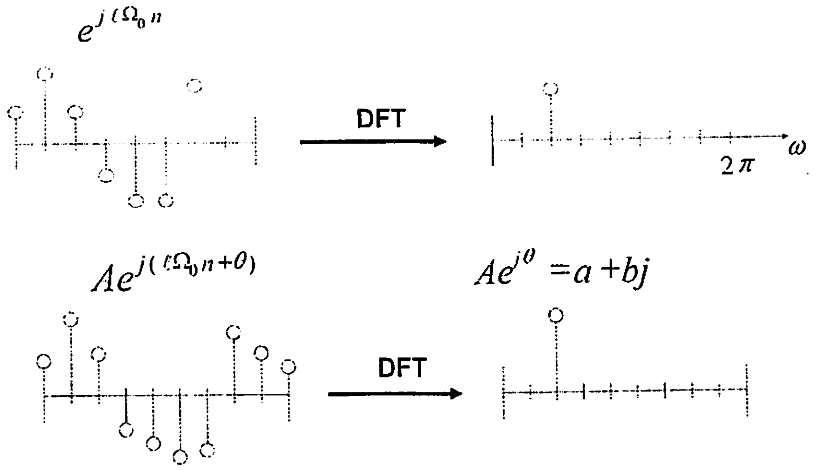
$$\int_{-\infty}^{\infty} \varphi_n(t)\varphi_l^*(t)dt = \begin{cases} 1, & n = l \\ 0, & n \neq l \end{cases}$$

- Consider the sampled $\Phi(t)$.

$$\Phi_k(n) = e^{jk\Omega_0 n}, \qquad \Omega_0 = \frac{2\pi}{N}, \quad k = 0,1,\cdots,N-1$$

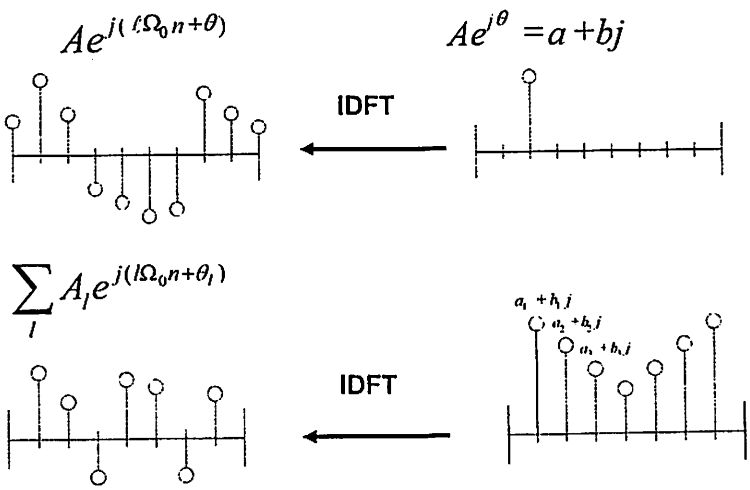
$$\frac{1}{N}\sum_{n=0}^{N-1} e^{j(k-m)\Omega_0 n} = \begin{cases} 1, & k = m \\ 0, & k \neq m \end{cases}$$

- The complex exponential exhibit an impulse in the DFT domain.



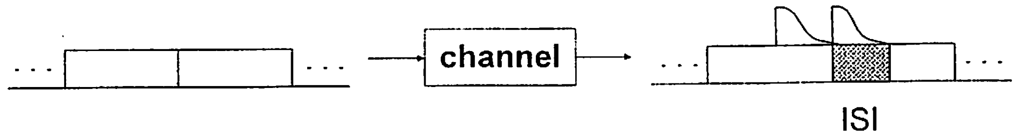
- Thus, we can conduct processing in the frequency domain using DFTs.

- The main idea is to use conduct modulation in the frequency domain.

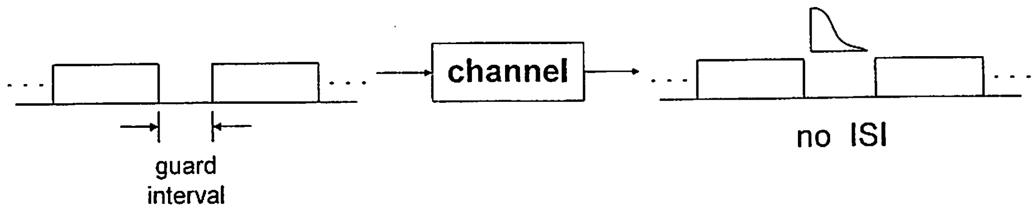


- In other words, we define QAM symbols in the frequency domain

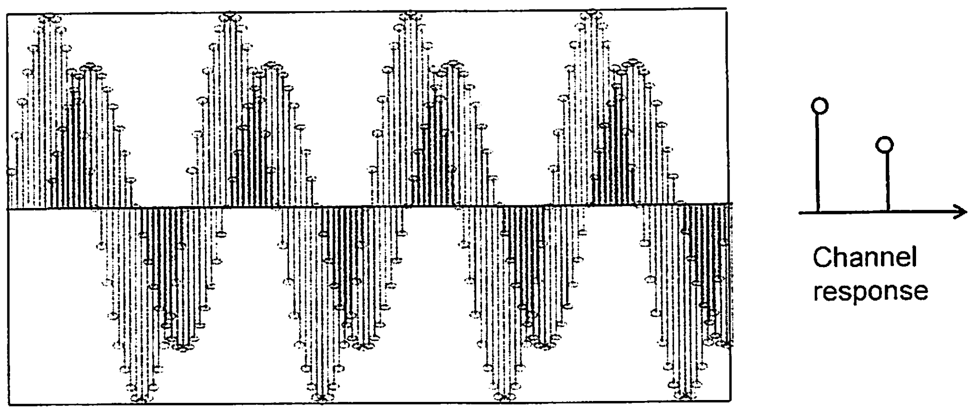
- To eliminate ISI completely, a guard time is introduced for each symbol. Since the guard time has no signal, the problem of intercarrier interference (ICI) arises.
- ISI and guard interval:



* Continuous transmission

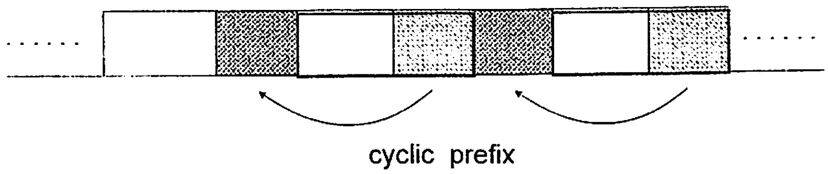


- ICI:



- The selected delayed version in the OFDM symbol is not a sinusoidal signal anymore.
- To solve the problem, cyclic prefix is added in the guard period.

- Cyclic prefix: 截取後面一段放到前面去

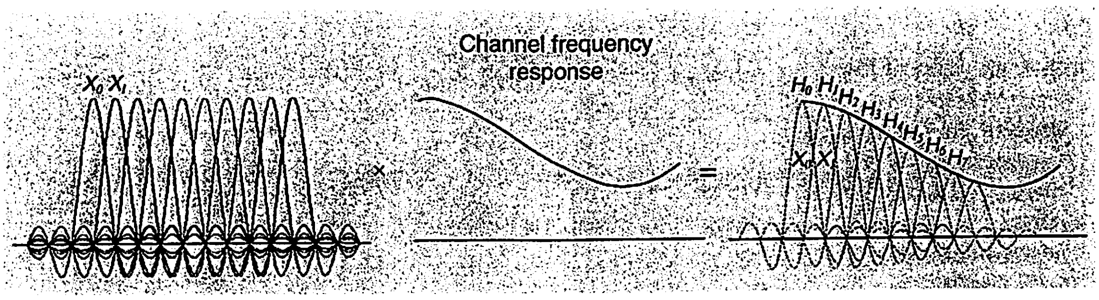


- Since the CP is added, the channel output will be a circular convolution of the channel response and the transmit signal. We then have

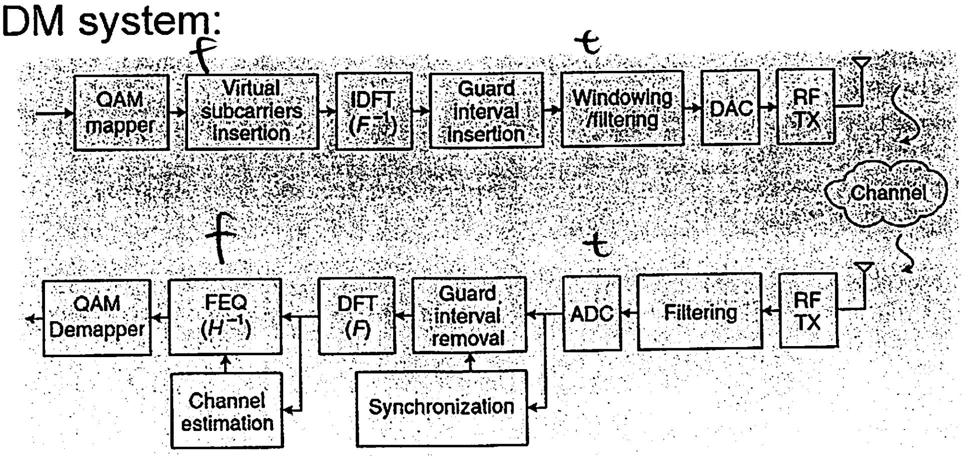
$$y^{m}(n) = x^{m}(n) \otimes h(n) \Rightarrow \tilde{x}^{m}(e^{j\omega_k}) = \frac{\tilde{y}^{m}(e^{j\omega_k})}{\tilde{h}(e^{j\omega_k})}$$ * In the DFT domain

- Thus, data in each channel can be recovered using a single-tap FEQ. (frequency domain equalizer)
- The system using this modulation technique is called orthogonal frequency division multiplexing (OFDM).

- Frequency domain response:



- OFDM system:



- Let the bandwidth for an OFDM system be f_s, the DFT size be N, and the CP size be μN where $0<\mu<1$.
- Let the sampling frequency of an OFDM be f_s. Then, the period will be $T=1/f_s$. Then, the subcarrier spacing (f_{ss}) will be $1/NT = f_b/N$.
- Let the number of subcarriers for data transmission be M. ($M \leq N$). The occupied bandwidth (f_b) is then Mf_s/N.
- The data rate (r) will be $QM/(1+\mu)NT=Qf_sM/(1+\mu)N$ where Q is the number of bits each QAM transmit.
- LTE system:
  - f_s=30.72MHz, N=2048, M=1200, μ=1/8.
  - f_{ss}=30.72MHz/2048=15KHz, f_b=1200x15KHz =18MHz (20MHz).
  - For QPSK, r=2x30.72MHzx1200/(1.125x2048)=32Mbps

- Specifications of LTE:

Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (μs)	5.2 (first symbol) / 4.69 (six following symbols)					
CP Length (Long CP) (μs)	16.67					

- Practice:
  - Build an OFDM system with LTE specifications including
  - Transmitter
  - AWGN channel, and
  - Receiver (perfect synchronization).
  - Plot SER vs. SNR. * Note: SNR in time domain is different from that seen in each subcarrier
  - Assume QPSK symbols
  - FFT size=2048 (number of used subcarriers=1200)

- Homework:
  - Redo the practice with a multipath channel.

QPSK $(\sqrt{2})^2 \times \frac{1}{4} \times 4 = 2$

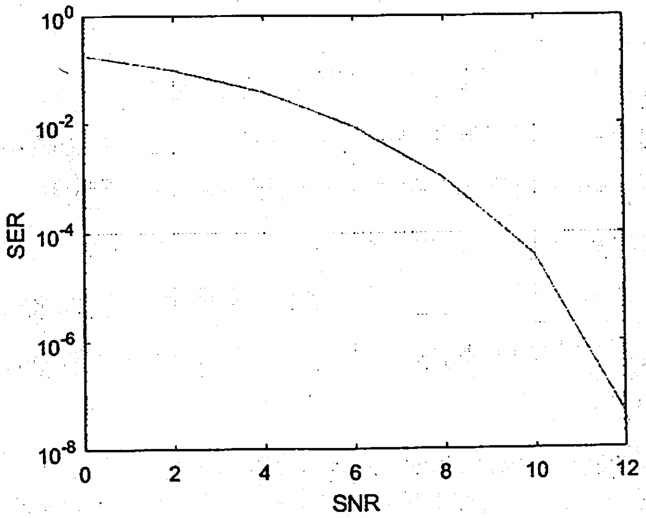
$\sqrt{2}$

$$SNR = 10\log_{10}\frac{E_b}{N_0}$$

$$\Rightarrow 10^{\frac{SNR}{10}} = \frac{E_b}{N_0}$$

$$\Rightarrow N_0 = E_b \div 10^{\left(\frac{SNR}{10}\right)}$$

- Result:



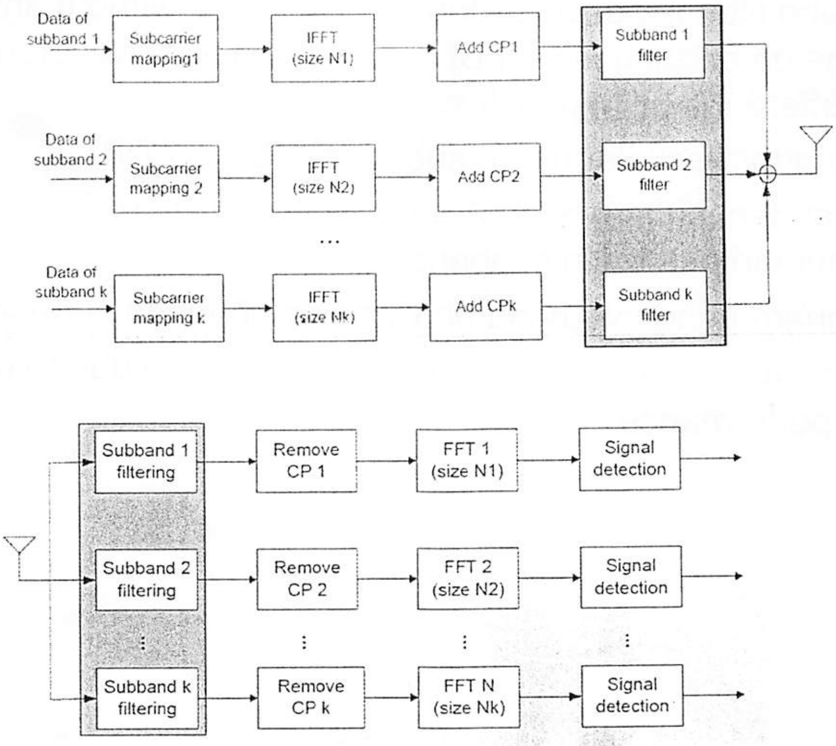
$E = \text{mean}(\text{abs}(\cdot)^2)$

$$SNR = 10\log_{10}\frac{E}{N_0}$$

F-OFDM and W-OFDM

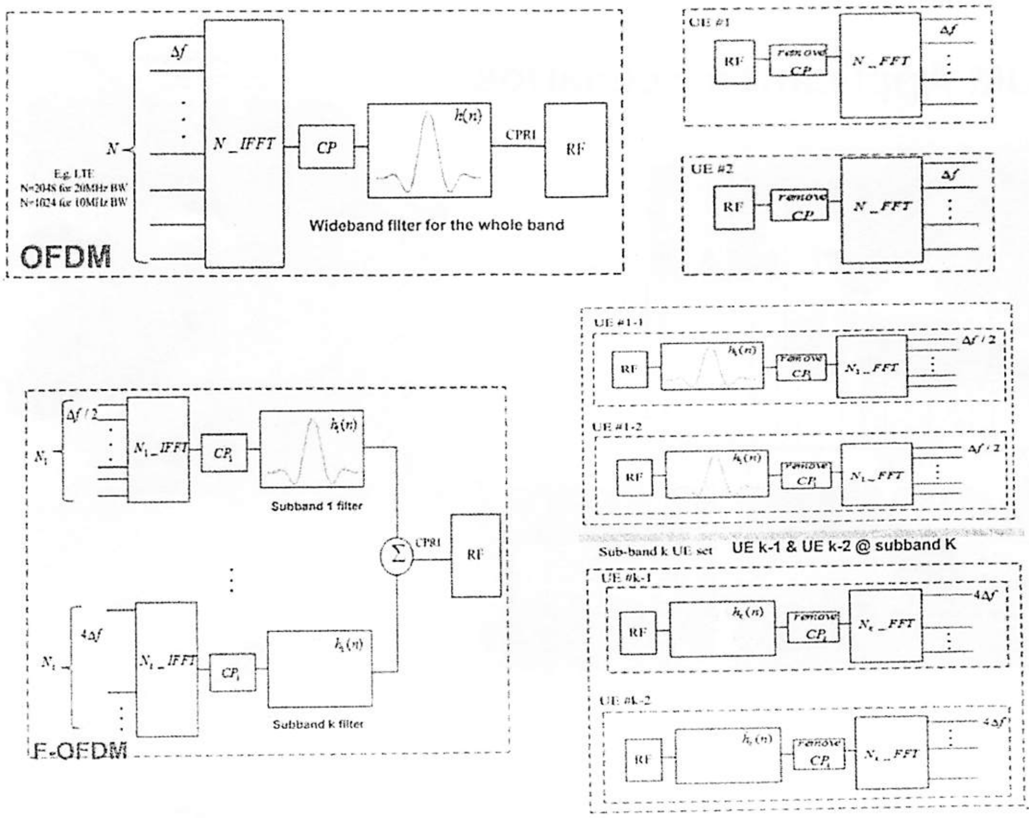
- Problems with CP-OFDM system:
  - Out of band (OOB) power leakage (10% guard band needed)
  - Rigorous requirement of synchronization
  - Same waveform parameters, i.e., the subcarrier spacing, CP length and TTI length for entire bandwidth
- Filtered-OFDM (F-OFDM)
  - Applying subband filtering on traditional CP-OFDM
  - The system bandwidth is divided into sub-bands and filtered independently.
  - Each sub-band can be configured with different waveform parameters set according to the actual traffic scenario.
  - Each subband combined 5G waveforms would supports dynamic soft configurations for traffic types.

- Architecture:



29

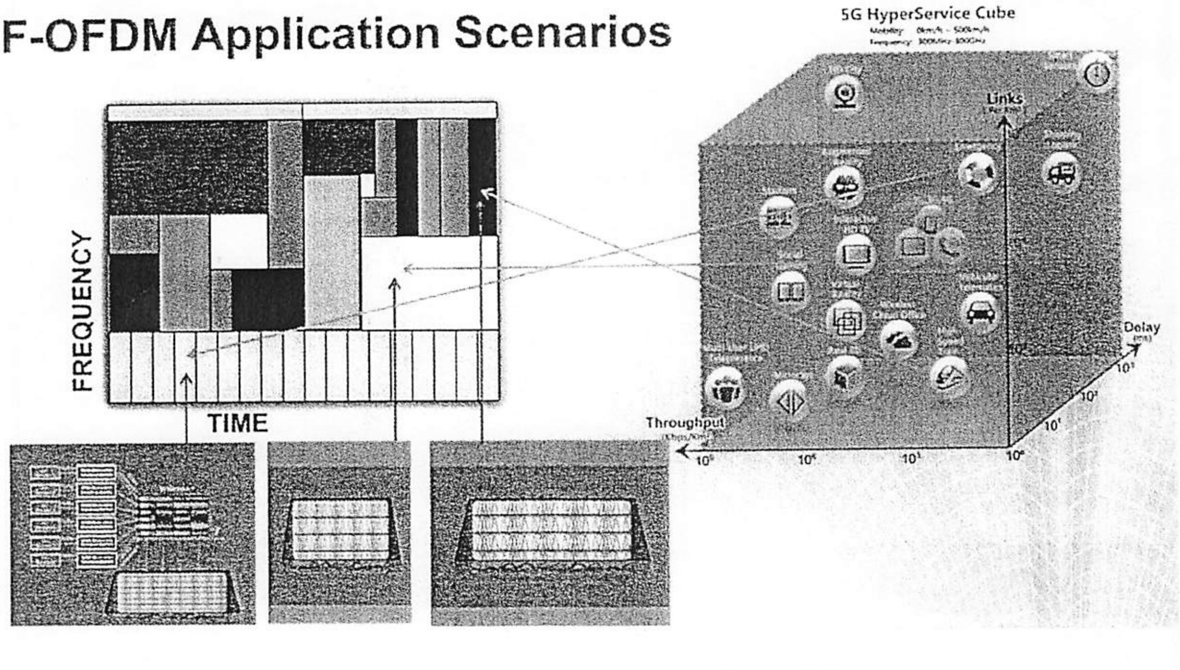
- Comparison:



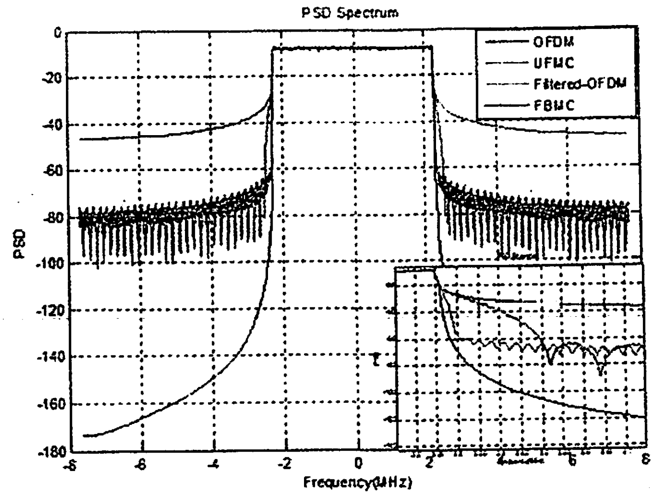
30

- Key features
  - Subband filter is added on top of CP-OFDM, without any change on existing CP-OFDM (co-existence of waveform with different OFDM primitive)
  - Filtering for each subband (subband BW >= 1 RB) resource block
  - Independent subcarrier spacing/ CP length/ TTI configuration for each subband
  - Low guard band overhead between neighboring subband
  - Support asynchronous inter-band transmission due to good OOB performance

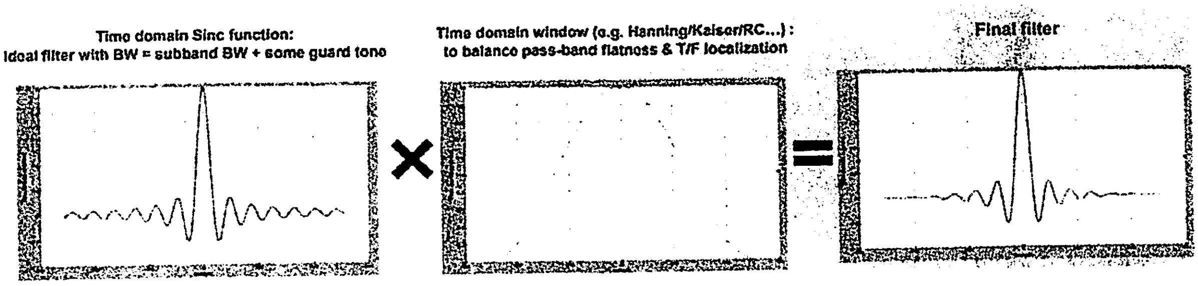
F-OFDM Application Scenarios



- OOB performance:



- Filter design:
  - Soft truncated filter with specific window is recommended.
  - Trade-off between time and frequency localization (that is ISI and ICI)
  - Easy implementation for flexible subband configuration
  - Small round-up error due to frequency domain fixed point implementation



Example of filter

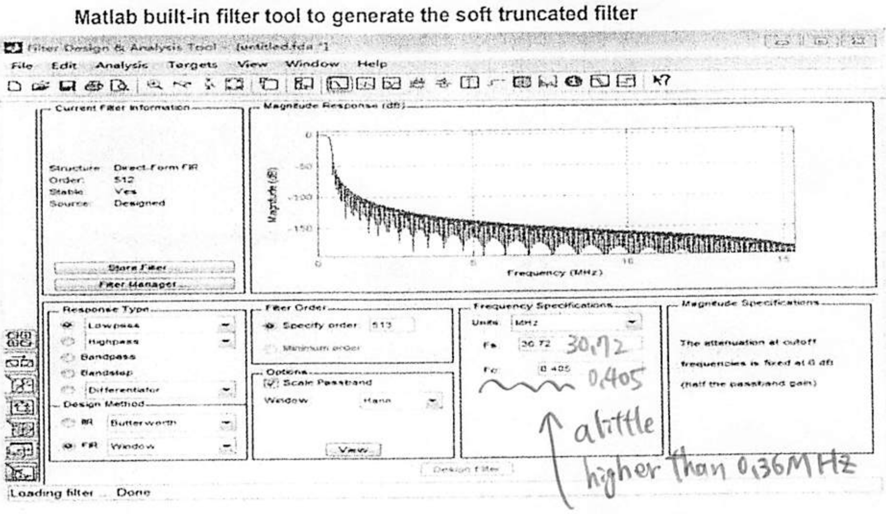
720/15 = 48 subcarriers

- **Example with Hanning window**
  - Subcarrier spacing = 15KHz
  - Subband = 720KHz
  - Fs = 30.72MHz (LTE baseband sampling rate)

$$W_{filter\_time} = W_{Sinc} \cdot W_{Hanning}$$

$$W_{Hanning}(n) = 0.5\left(1-\cos\left(\frac{2\pi n}{N-1}\right)\right)$$

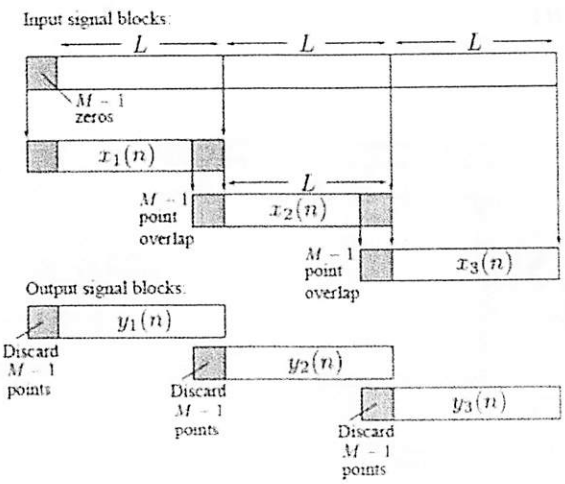
Matlab built-in filter tool to generate the soft truncated filter



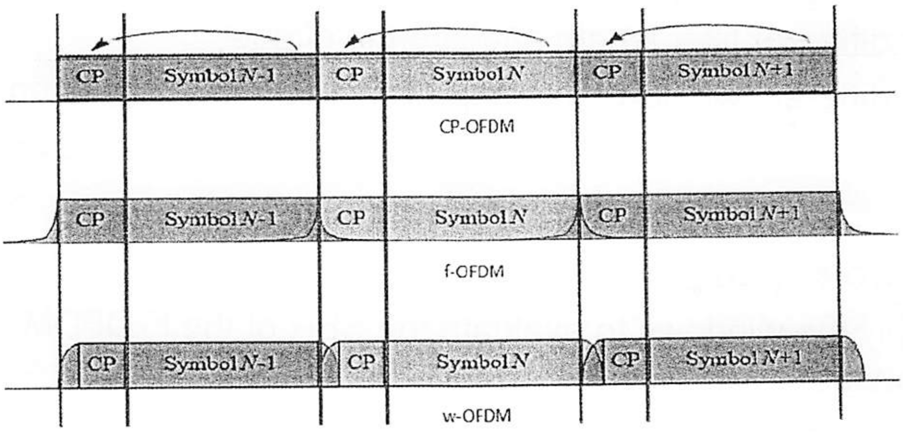
720K / 2 = 0.36 MHz

- Implementation:
  - Filtering is continuously operated in time domain
  - However, frequency domain filtering operation is preferred for implementation.

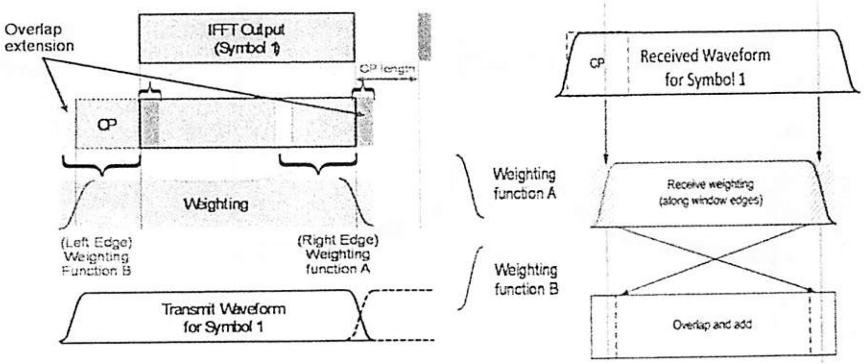
Overlap-Save Method

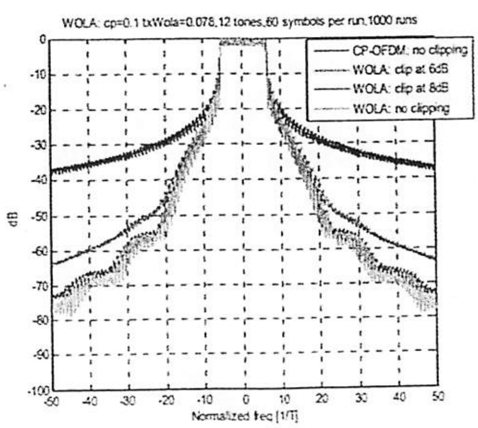


- Another proposal to achieve low OOB interference is weighted OFDM (W-OFDM):
  - Extend prefix and postfix.
  - Weighted extended signal, and
  - Add resultant OFDM symbols.
- Comparison:



- Spectrum property:





- Practice:
  - Use the OFDM system built (LTE), and let the subband occupies 350 subcarriers. (350 x 15K / 2 = 2.625MHz)
  - Let the filter size be 512. (2.7)
  - Design a filter for the F-OFDM system with the Hann, Blackman, or Chebychev windows.
  - Plot the power spectrum of OFDM and F-OFDM systems.
  - Try different filter length and see the effect.
  - Try different window size for power spectrum calculation.

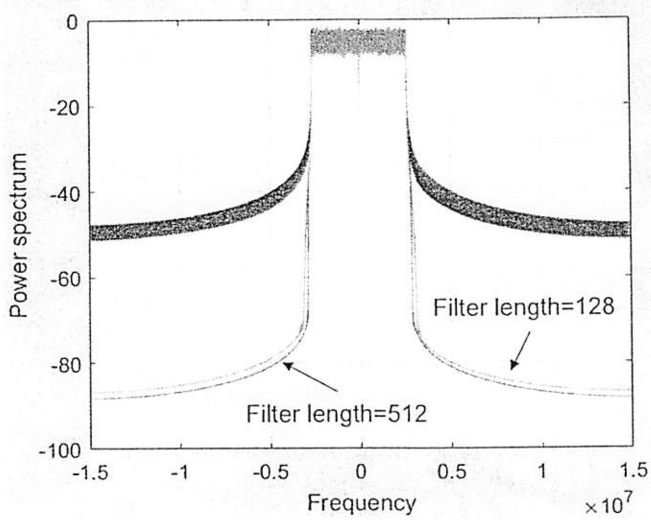
Window size

* psd=pwelch(x,ws)

- Homework: (filter)
  - Apply the windows to evaluate the SER of the F-OFDM systems.

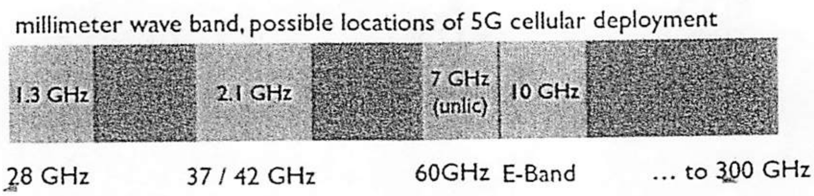
24
120
7.5
7

- Result:



Mini-meter wave communication

- Why mmWave?
  - Crowded spectrum at sub 6 GHz
  - Increasing demand on data rate
  - Huge amount of spectrum possibly available in mmWave bands: 30 GHz ~ 300 GHz

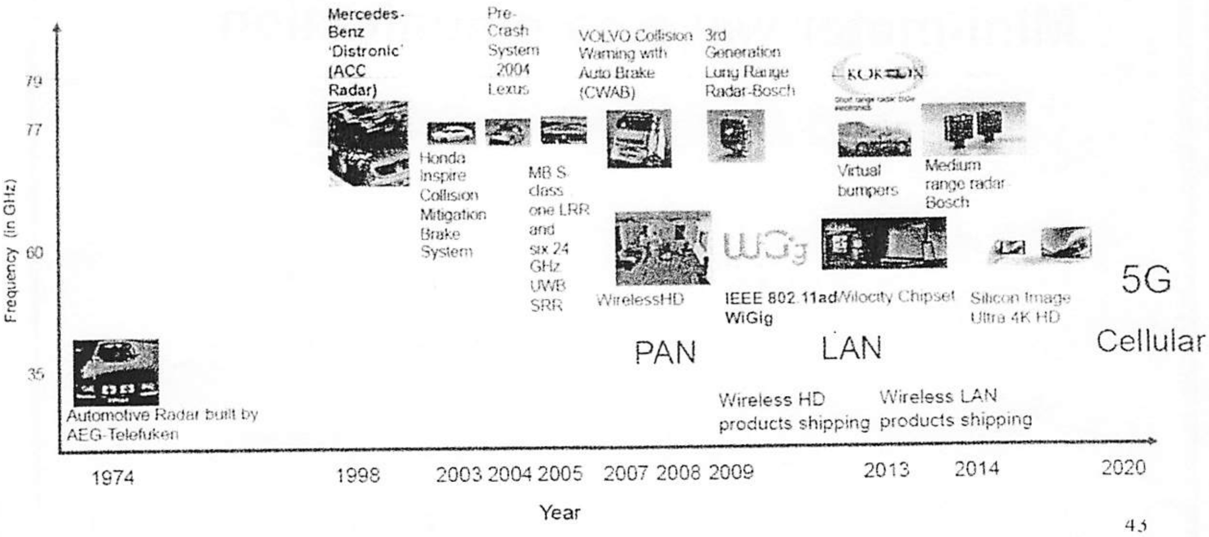


- Communication with mmWave has been used in some applications.

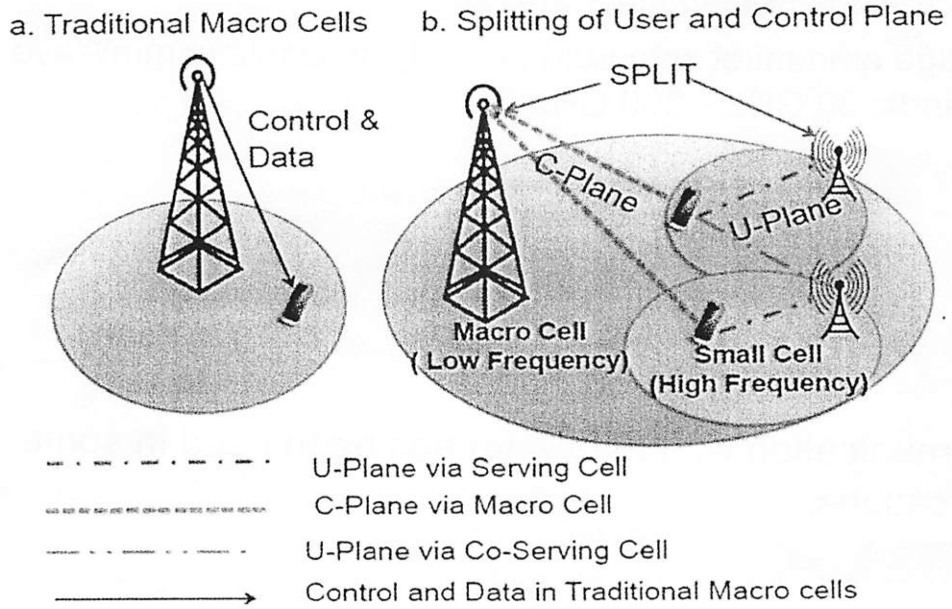
- Personal/local area networks:

Standard	Band	Bandwidth	Rates (Gbps)	Application
WirelessHD	60 GHz	2.16 GHz	3.807	HD Video S.
IEEE 802.11ad		2.16 GHz	6.76	WLAN

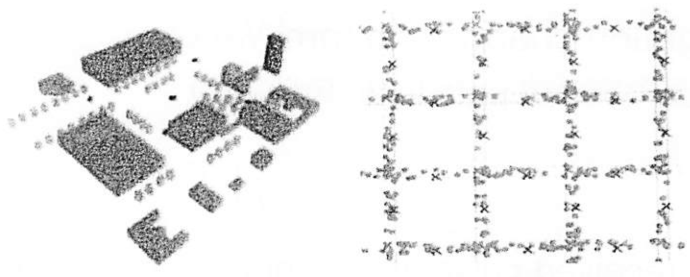
- Collision avoidance:



- In 5G cellular:
  - Network

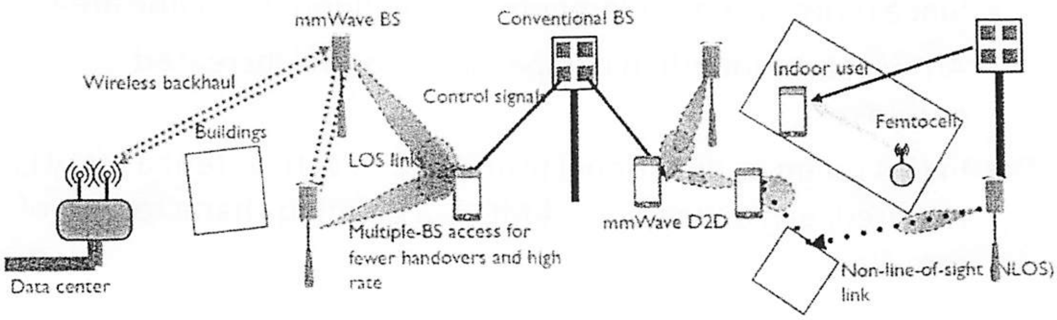


- Usage model:



(a) Campus setting (b) Urban picocell

Fig. 3. *Millimeter-wave cellular use cases. (a) Outdoor coverage in a campus-like environment, as illustrated in [65]. (b) Urban microcells or picocells as illustrated in a figure detail from [66] showing mmW access points (blue and pink crosses) placed on every block on an urban grid to serve mobiles (green circles) on the streets.*



- Micrometer vs. milimeter:

	Sub 6 GHz	mmWave
Bandwidth	<160 MHz	100 MHz – 2 GHz
Role of antennas	multiplexing & diversity	array gain & multiplexing
Exploiting channel	limited feedback	directional beamforming
Antennas @ BS	1 to 8	32 to 256
Antennas @ UE	1 to 2	1 to 32
Scattering	Rich	Sparse
Urban coverage	Via diffraction	Via reflection
Penetration loss	Low	High
Large-scale fading	Distant dependent + shadowing	Distant dependent + blockage

- Propagation channels in mmWave:
  - Distant-based path loss: Friis' law

$$P_r = G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2 P_t$$

  - The received power is proportional to the square of wavelength ☹
  - The gain provided by antenna array is proportional to the inverse of the square of wavelength ☺

$$G_r, G_t \propto \lambda^{-2}$$

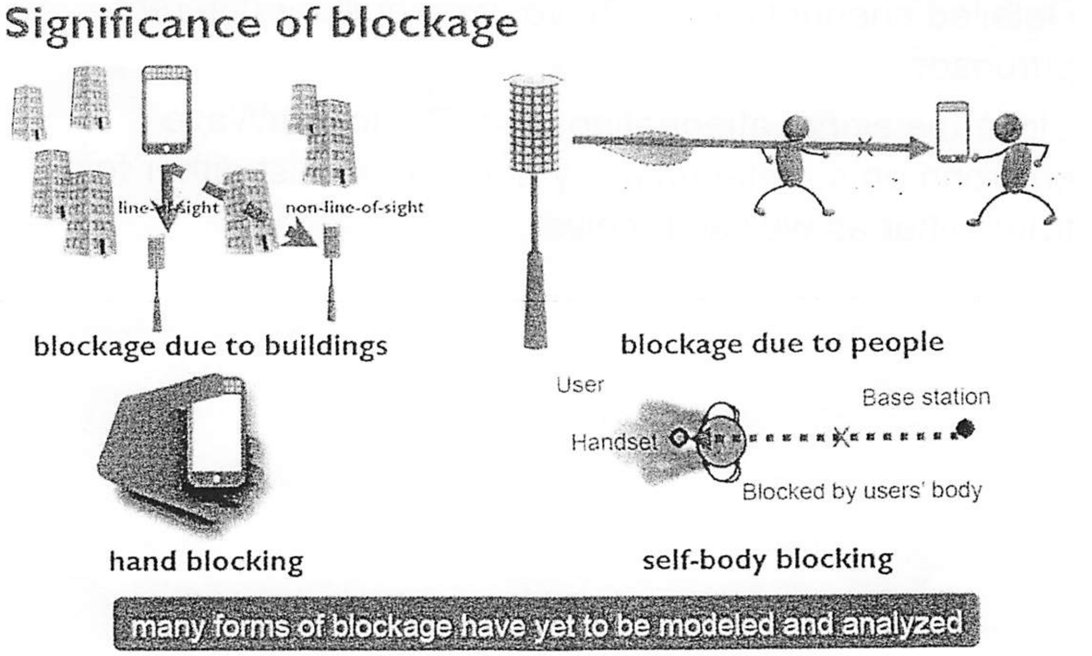
    - Since more antenna elements can be fit into the same area
    - Array gains more than compensates for the increased pathloss
    - In this manner, directional transmission with antenna array is required, explaining how MIMO is a defining characteristic of mmWave

  - In general, the pathloss depends on the particular position of objects that can attenuate, diffract and reflect signals
  - The most common statistical model describes the average path loss (not including small-scale fading):

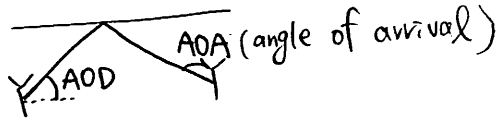
$$PL(d)[dB] = \alpha + 10\beta \log_{10}(d) + \xi$$

$$\xi \sim N(0,\sigma^2): \text{lognormal term for shadowing}$$

- Blockage and outage:



- Loss:
  - Brick: 40~80 dB
  - Foliage loss can also significant
  - Human body (depends on material of the clothing): 20~35 dB
  - Diffraction is not significant → NLOS path is via reflection
  - Three-state model: LOS, NLOS and outage
    - The probability of a link being in each state is a function of distance
    - Similar in form to some LOS-NLOS probabilities used in 3GPP LOS-NLOS for heterogeneous networks
  - Shall characterizing the joint probabilities in outage between links from different cells
  - Path can rapidly appear and disappear, with significant impact on channel tracking



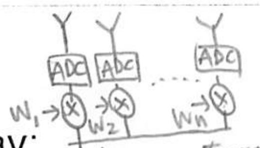
- The paths arrive in "clusters" and each cluster has some distribution on the delay, power, and central (AOA, AOD)
- Detailed channel models have been built for different purposes.
- Since the signal attenuation is severe in mmWave environments, antenna array become a must either for transmitter as well as receiver.

- There are a number of ways to use the multiple transmit/receive antennas.
  - Beamforming
  - Spatial multiplexing
  - Space-time coding
- Beamforming (spatial filtering) is a signal processing technique used in antenna arrays for directional signal transmission or reception.
- This is achieved by combining elements in a array in such a way that signals at particular angles experience constructive while others experience destructive interference.

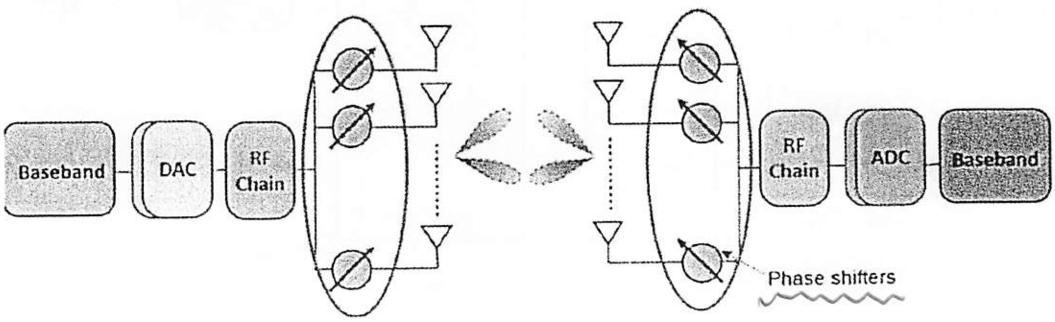
- Hardware constraints: cost and power consumption of mmWave components are high.

Device	Number of devices	Power (mW) (single device)
PA	N_t (N_r)	40-250
LNA	N_t (N_r)	4-86
Phase shifter	N_t (N_r) x L_t (L_r)	15-110
ADC	L_t (L_r)	15-795
VCO	L_t (L_r)	4-25

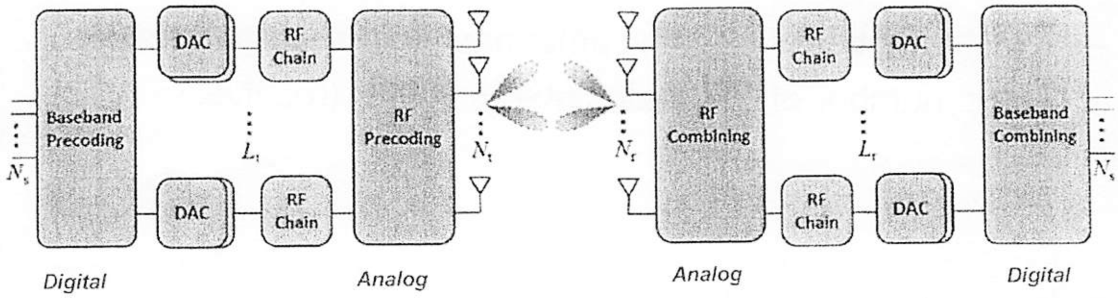
  - N_t (N_r): number of transmit antennas (receive antennas)
  - L_t (L_r): number of RF chains at transmitter (receiver)



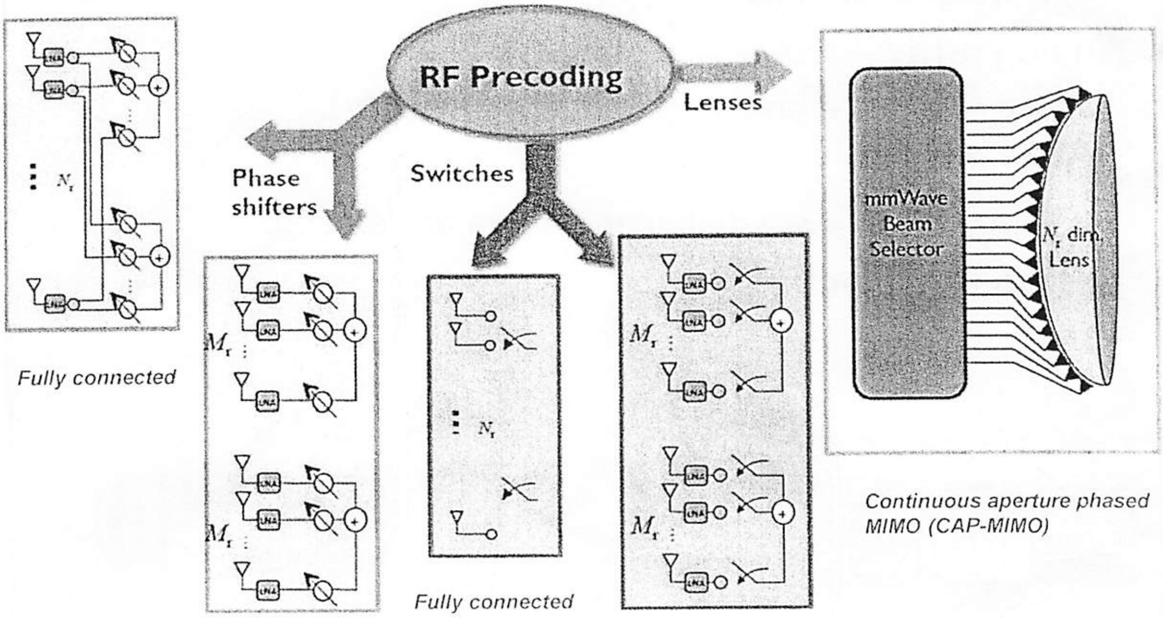
- Digital array: one antenna need one ADC
  - All weights are digital
- Analog array:
  - All weights are analog (may be phase only).
- Hybrid array:
  - Some weights are digital and some are analog.
- Analog beamforming:



- Hybrid beamforming:
  - Combined analog and digital beamforming
  - Make compromise on power consumption and hardware complexity
  - Enables spatial multiplexing and multiuser MIMO
  - Digital can correct for analog limitations
  - Different RF precoding/combining can be implemented using different analog approaches



- Architectures:



Fully connected

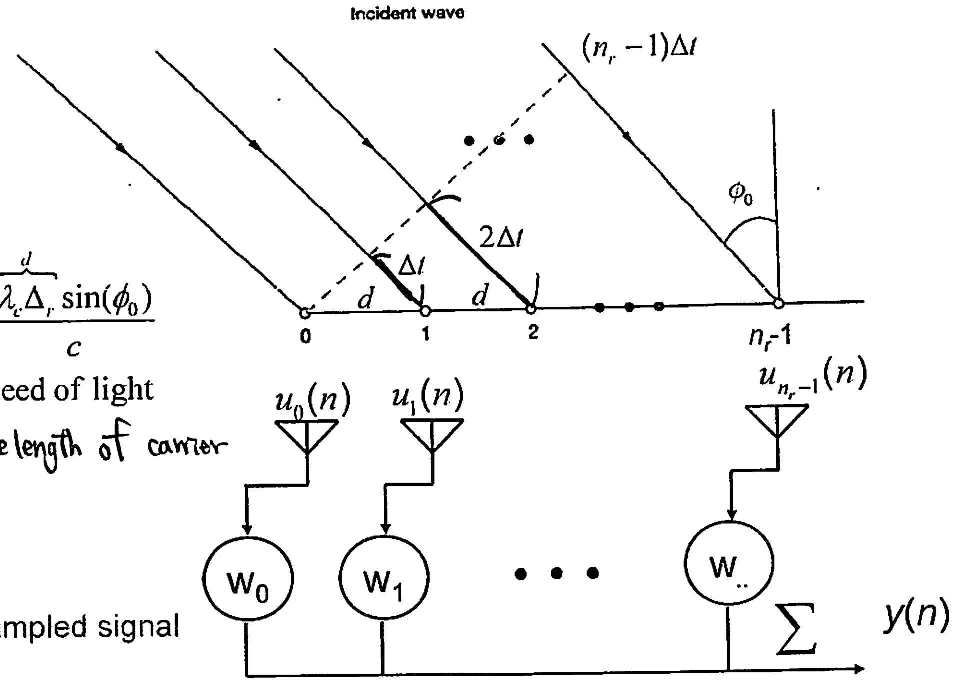
Subarray

Fully connected

Subarray

Continuous aperture phased MIMO (CAP-MIMO)

- Beamformer as spatial filter :
  - Linear array beamformer



$$\Delta t = \frac{\overbrace{\lambda_c \Delta_r}^{d} \sin(\phi_0)}{c}$$

c : speed of light

λ_c = wave length of carrier

* Sampled signal

polar

$$\Delta_r = \frac{L_r}{n_r}$$

- Now, consider a sinusoidal input:

$$u_k(t) = e^{j2\pi f_c(t+\Delta t)} \rightarrow e^{j2\pi f_c \Delta t} = e^{jk\theta_0}$$

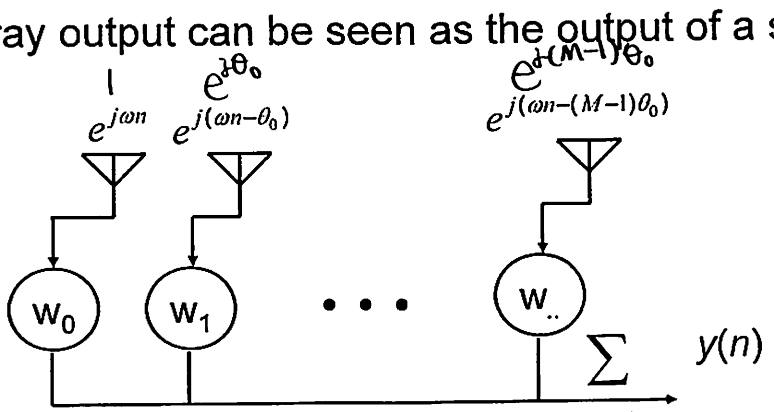
$$\ast\Delta_r = \frac{1}{2} \text{ in general}$$

$$k\theta_0 = 2\pi k f_c \Delta t = \frac{2\pi k f_c \lambda_c \Delta_r \cancel{\cos(\phi_0)} \sin(\phi_0)}{c} = 2\pi k \Delta_r \cancel{\cos(\phi_0)} \sin(\phi_0)$$

$d \sim 2\pi$

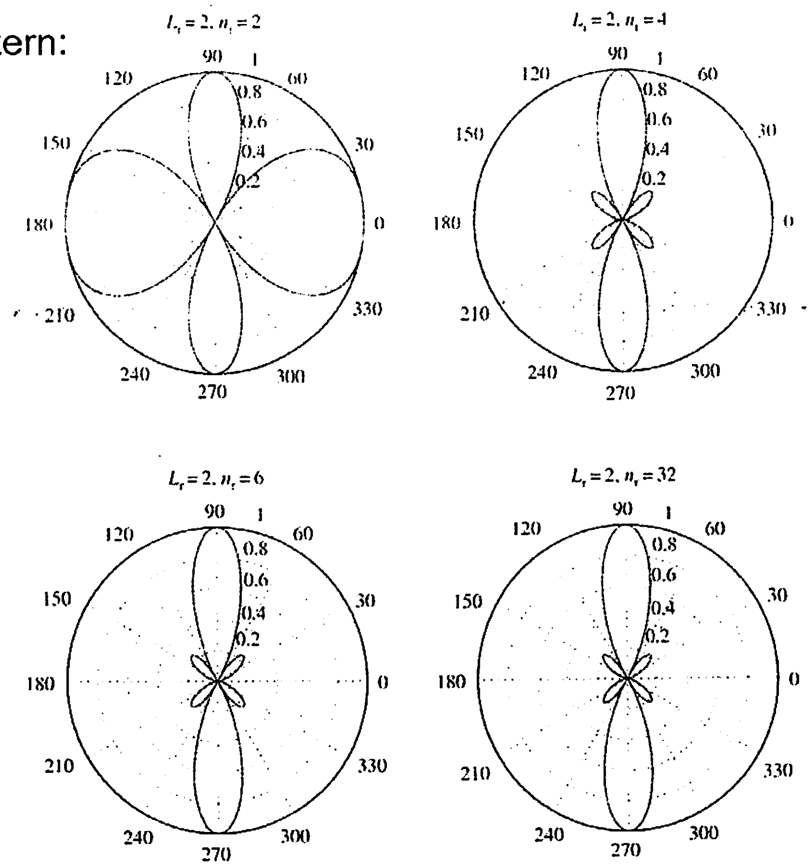
* θ_0 is the phase delay (related to direction of arrival ϕ_0)

- The array output can be seen as the output of a spatial filter.



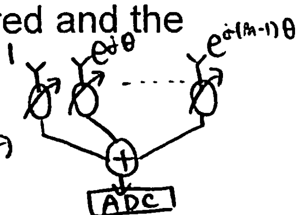
* Definitions of Ω and θ are different from previous ones.

- Beam pattern:



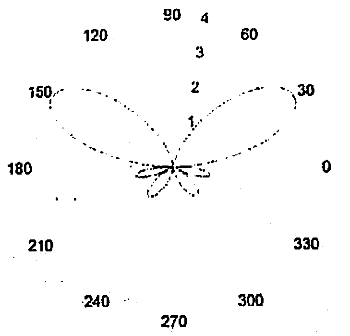
- Practice:
  - Consider digital receive beamforming for a uniform linear array (ULA).
  - Plot its beam pattern.(for a given W corresponding to a specific AOA)
  - Try different antenna spacing and different number of antennas.

- Homework:
  - Consider a system with two users; one is desired and the other is interfering (assume Gaussian signal).
  - Their signals arrive BS with different AOAs.
  - BS is equipped with a hybrid array (one ADC).
  - Design a beamformer to best recover the desired signal (highest SINR).

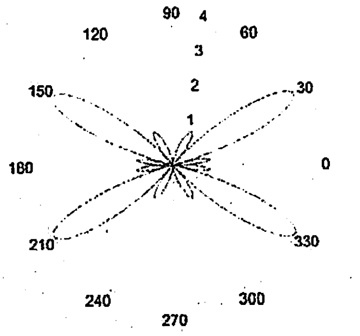


$$10 \log 10 \left(\frac{abs(W^H a_1)}{abs(W^H a_2)} \right)$$

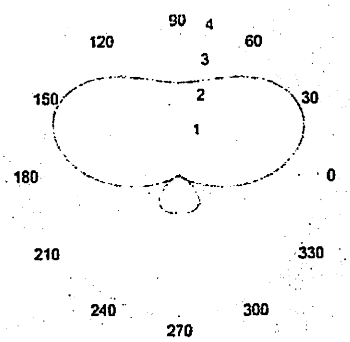
- Result:



$\Delta_r=1/2$



$\Delta_r=1$



$\Delta_r=1/4$

$\frac{\phi}{512} \times \underline{K}$ 0~511

$\frac{\phi}{K}$

1~512

1x4 x4

k: 1~32

4x1 4x512

$2\pi/K$

$$\theta_0 = 2\pi \Delta_r \sin(\underline{\phi_0})$$

AoA

let $a = \begin{bmatrix} 1 \\ e^{j\theta_0} \\ \vdots \\ e^{j(M-1)\theta_0} \end{bmatrix}$, $w = \begin{bmatrix} w_0 \\ w_1 \\ \vdots \\ w_{M-1} \end{bmatrix}$ $\Rightarrow y(n) = (w^H a)\, u(n)$

M

M

$e^{j\frac{\pi}{2}}$

$e^{\frac{2\pi}{K}}$

K

2π

$e^{j\frac{\pi}{2}}$

$\vdots$

$e^{j(M-1)\frac{\pi}{2}}$

M

Given w , if we let $a(k) = [1, e^{jk\alpha}, \ldots\ldots, e^{jk(M-1)\alpha}]^T$ where $k=0,\ldots\ldots,K-1$ and $\alpha = 2\pi/K$, then $z(k) = (w(k)^H a)$ is called the beam pattern of the array.