5G and Beyond

Waveforms

Outline

- What is 5G and beyond?
- 5G and Beyond – requirements from waveform design perspectives
- Evolution of wireless (waveform perspectives)
- Why waveform is important?
- Trends in waveform designs – old rules vs. new rules
- 5G waveform approaches
- Waveform and RF Impairments.

Evolution of wireless

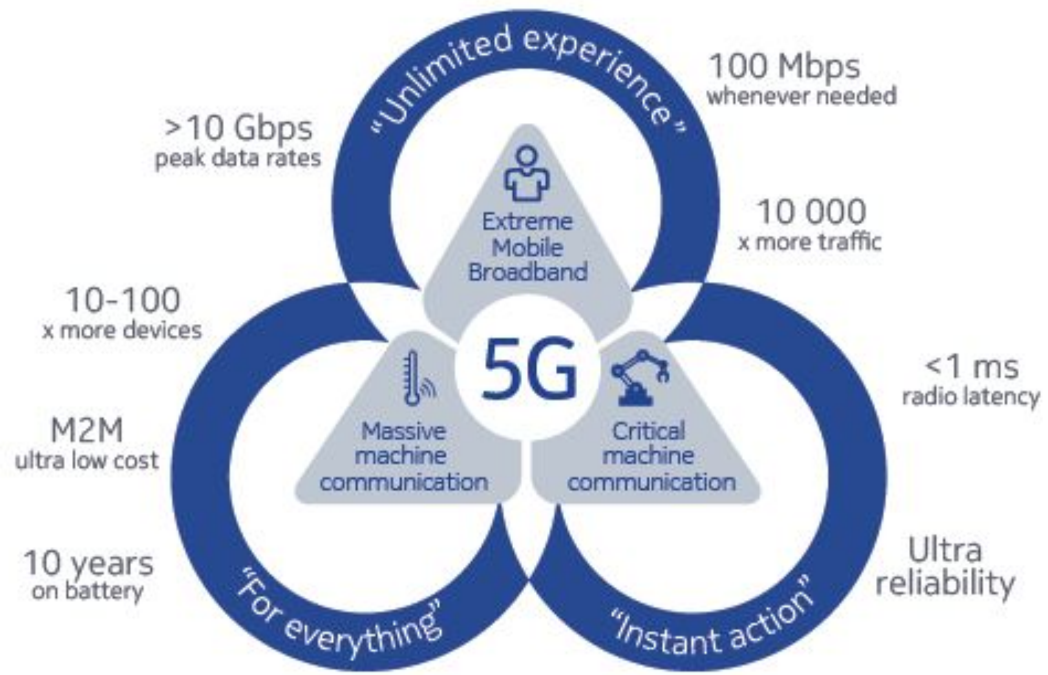
- BW
  - Increasing (from 30kHz, 200kHz, 1.25MHz, 5MHz, 20MHz, 100MHz, …)
  - Getting flexible (fixed earlier, flexible now, aggregation is now real, dynamic spectrum access (DSA) further along the line). Fractional BW
- Spectrum Efficiency
  - Increased number of bits per Hertz
  - Re-use is increasing (cell size is getting smaller, re-use factor is getting smaller)
  - HetNets and Co-existence
- Data rates
  - 1G:2kbps 2G:64kbps 3G:2Mbps 4G:1 Gbps
- Services
  - 1G: Mobile telephony (voice)
  - 2G: Digital voice, SMS 2.5: Higher capacity packetized
  - 3G: Integrated high quality audio, video and data
  - 4G: Wireless internet, video, gaming, …; better, faster,
- Devices

Evolution of wireless

- Cell sizes
- Adaptation capabilities
- Awareness capabilities
- Spectrum (started below 1 GHz, later included above 1GHz, now mm-wave frequencies, possibly terahertz and visible light communication in the future)

5G and Beyond

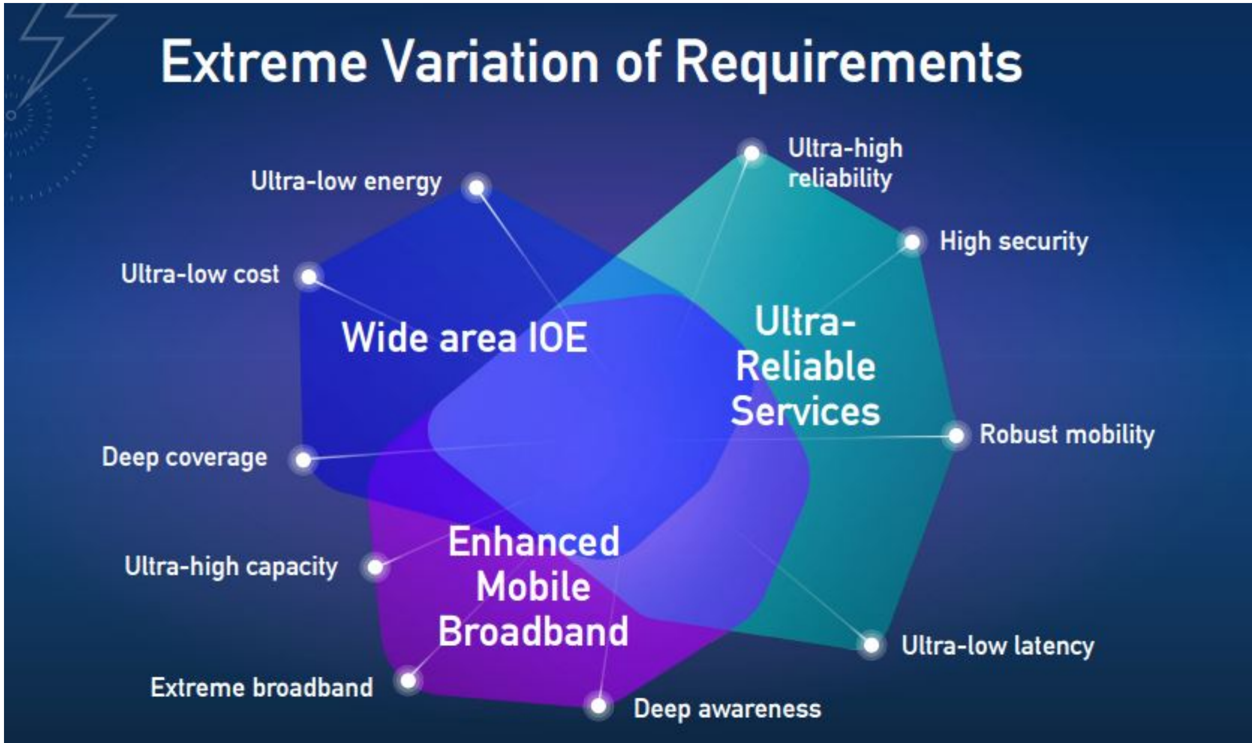
5G use cases



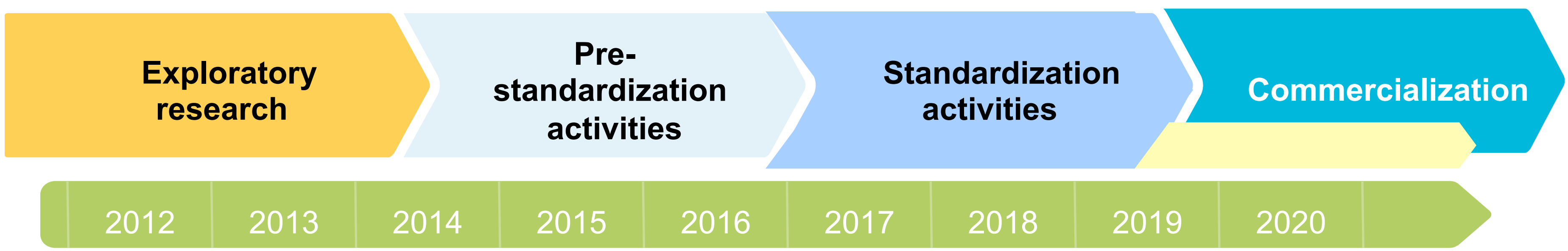
	eMBB	mMTC	URLLC
Critical Requirements	High Spectral Efficiency	Massive Asynchronous Transmission	High Reliability Security
	Ultra High Capacity Extreme Broadband	High Energy Efficiency	Low Latency Guaranteed Availability
		Low Device Complexity	

NOKIA

QUALCOMM



5G Status


Exploratory research
Pre-standardization activities
Standardization activities
Commercialization
2012
2013
2014
2015
2016
2017
2018
2019
2020

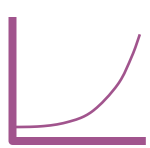
5G and beyond challenges

1) Extreme high traffic
2) Extreme variable traffic

Avalanche of
Traffic Volume

Further expansion of mobile broadband

Additional traffic due to communicating machines



“1000x in ten years”

Massive growth in
Connected Devices
“Communicating machines”

“50 billion devices in 2020”

Large diversity of
Use cases & Requirements

Device-to-Device Communications

Car-to-Car Comm.

New requirements and characteristics due to communicating machines

Everything Connected by Wireless

Monitor/collect information & control devices

Multiple personal devices

Interaction across multiple devices

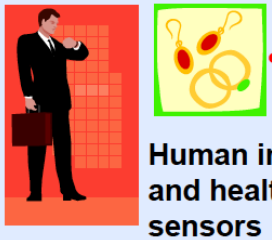
Transportation (Car/Bus/Train)

Entertainment, Navigation
Traffic information

Consumer electronics

Remote operation using personal terminal

Watch/jewelry/cloth



Human interface and healtchcare sensors

House

Remote control of facilities
House security

Sensors

Smart power grid
Agriculture and farming
Factory automation
Weather/Environment

Cloud computing

All kinds of services supported by the mobile personal cloud

Extension/enrichment of wireless services

Deliver rich contents in real-time & ensure safety

Video streaming

4K/8K video resolutions
Video on newspapers
Background video

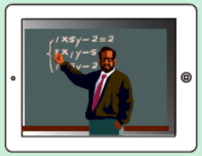
New types of terminal/HI

Glasses/Touch internet

Healthcare

Remote health check & counseling

Education



Distance (remote) learning
Any lesson anywhere/anytime

Safety and lifeline system

Prevention of accidents
Robustness to disasters

DoCoMo

Technical Expectations from future
Waveform perspectives

- Higher capacity and data rates: 100 Mbps to 10Gbps (Better spectral efficiency, more BW, better reuse)

- Interoperability & co-existence (multiple networks)
- Dynamic spectrum access (Flexible spectrum use)
- Support of variety of services (flexibility, scalability)
- Exploiting spatial domain (Massive MIMO, Beam forming, spatial multiplexing, spatial modulation)
- Lower latency
- Security (Communication security in PHY, MAC, NET)
- Improved QoS and better coverage
- Energy efficiency (PAPR, CCDF)
- Cost

Capacity and data rates

- Need more capacity from the spectrum
  - Historically major capacity gains obtained through frequency reuse
  - This trend will continue
    - Smaller cells and better reuse
  - Remove the guards in multiple domains
  - Exploiting other dimensions of electrospace (MIMO and beyond)
  - Better channel awareness, better channel assignments
  - Better interference awareness, more interference allowance (partial overlapping)
  - DSA and new spectrum usage policies
- Need wider bands for higher data rates
  - Carrier and resource aggregation (adjacent or scattered)
- Need more spectrum
  - Higher frequencies (60GHz, visible light, etc.)- propagation issues

Major enabling technologies

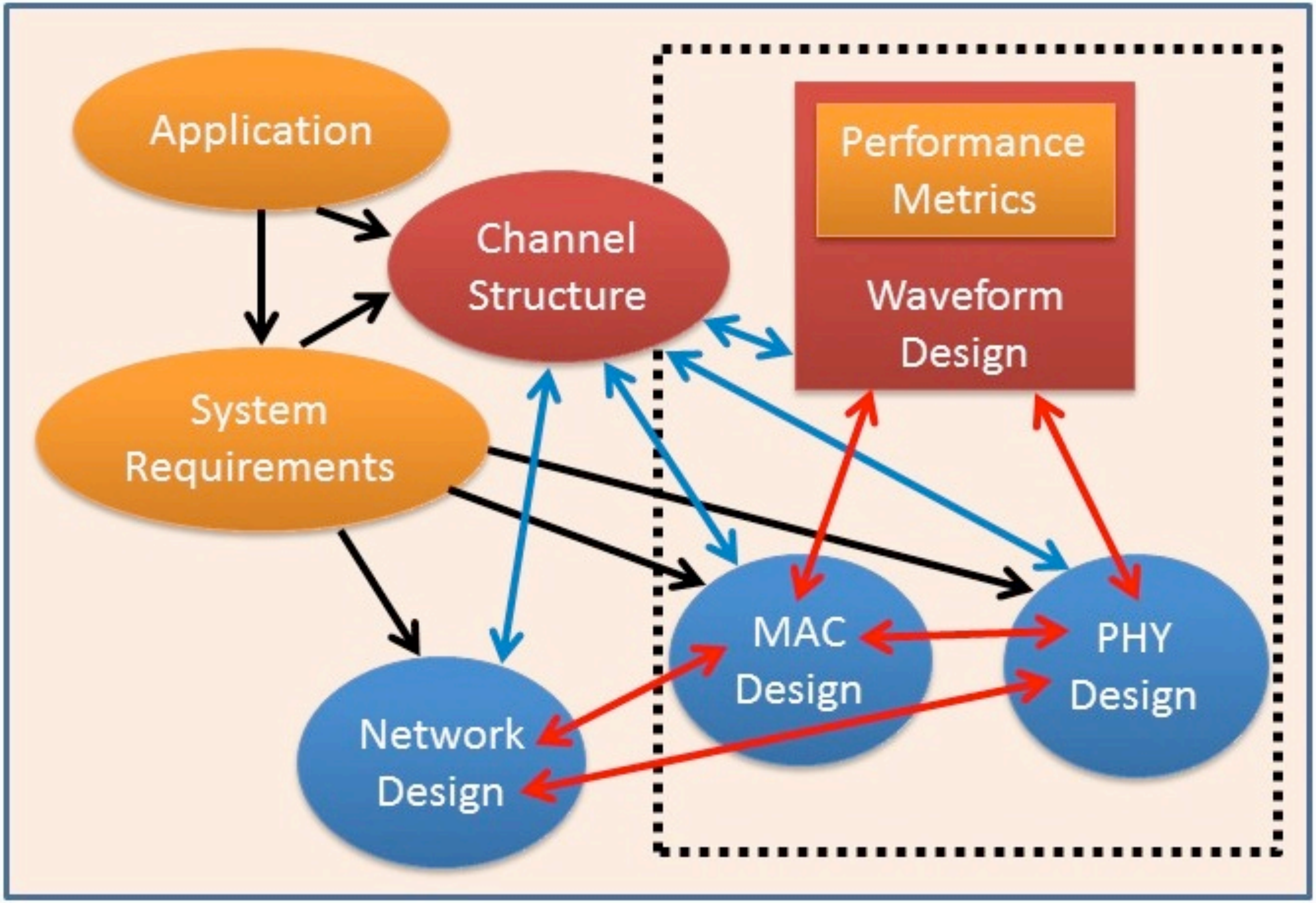
- Massive MIMO and beamforming
- Millimeter wave (spectrum extension)
- Small cell (network densification)
- Dynamic spectrum usage
- Spectrum aggregation
- SON
- Interference cancellation and coordination
- Multiuser detection and NOMA
- Flexible and hybrid waveform
- Flexible multiple accessing and advanced scheduling
- Multi-site transmission, relays, and multi-layer connectivity (coverage layer, capacity layer, ⋯)
- Full duplex – flexiple duplex

Back to 5G and beyond Waveform

Why waveform design is so important?

- Everything is connected to the waveform design
- It is in the core of the communication system design
- Related to the application through system requirements
- Related to the channel environment
- Related to all the communication layers (Network, MAC, PHY, ⋯)
- Can not be independently designed

Cross-layer interaction



Some major relations

- Channel (Doppler spread, delay spread, angular spread, ⋯)
- Application and system requirements for a specific application (latency, power efficiency, complexity, spectrum efficiency, bandwidth and desired data rates, reliability and QoS, security, ⋯)
- MAC (frame structure, multiple accessing, duplexing, scheduling, resource allocation, coding, ARQ and retransmission, DSA, interference, ⋯)
- Network (synchronous/asynchronous, homegeneous/ HetNets, centralized/distributed, coordinated/ uncoordinated, ⋯)
- PHY (modulation, RF impairments, PA, carrier frequency, bandwidth, computational complexity, processing power, hardware complexity and ability, ...)
- Politics-Business (backward and forward compatibility, patents, spectrum policy and availability, ⋯)

Waveform history

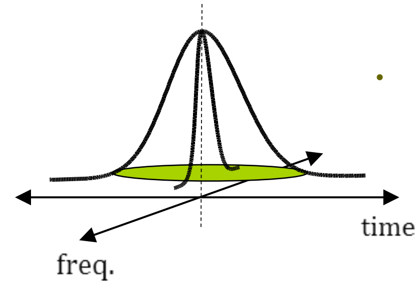
- 2G (IS-136 and GSM) both TDMA
  - IS-136 (30 KHz) with RRC – no equalizer needed (pulse is orthogonal, and BW is less than coherence BW of the channel) – channel tracking
  - GSM (200 KHz) with Gaussian filtering – equalizer needed for two reasons 1) pulse is not orthogonal 2) channel is frequency selective. No tracking
- 2G (IS-95) CDMA. Spreading, RRC pulses, rake receiver.
- 3G (IS-2000, WCDMA)
- 4G- broadband – Time domain equalization is complex. Freq. domain equalization is used. OFDMA and SCFDMA for multiple accessing.

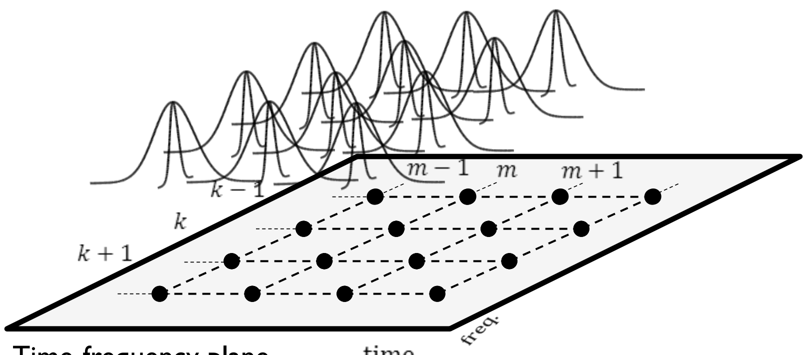
What is Waveform?

Waveform defines:
- what to transmit
- where to transmit
- how to transmit

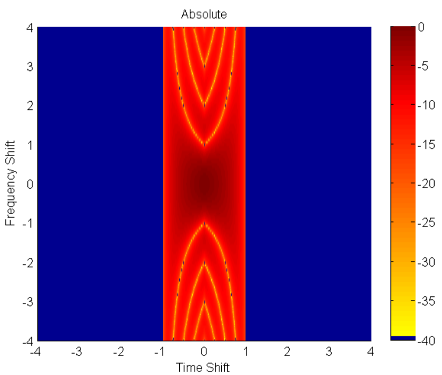
- Lattice
- Pulse (filter)
- Packaging (formation) of multiple user information in hyper-spectrally efficient manner (related to multiple accessing & scheduling)
- Not only the data carrying symbols, but also anything added (noise, redundancy, precoding process, etc) are also part of the waveform

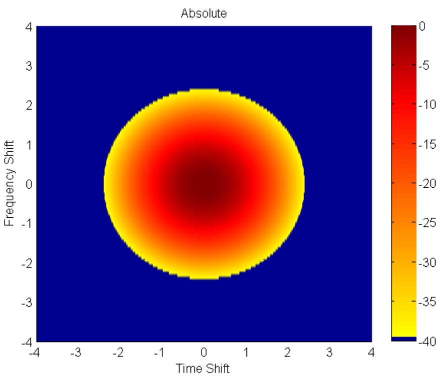
A pulse:
- Carries information symbol
- Has a well defined shape in time/ frequency





Time-frequency plane





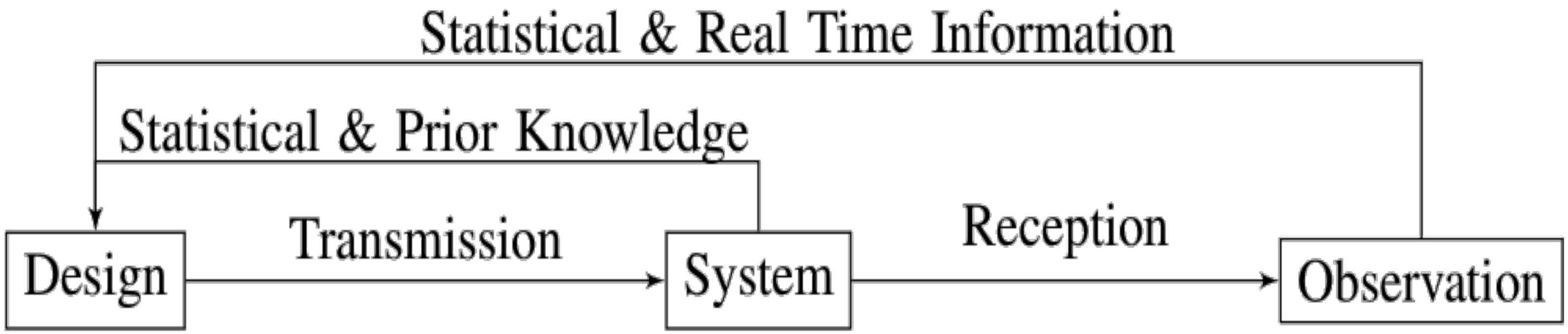
Transmitter → System → Receiver

Waveform Shaping

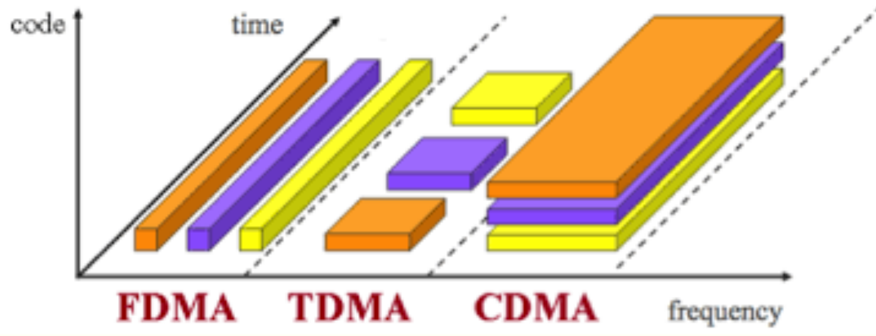
Wireless Channel, Tx/Rx Hardware, Interference, etc..

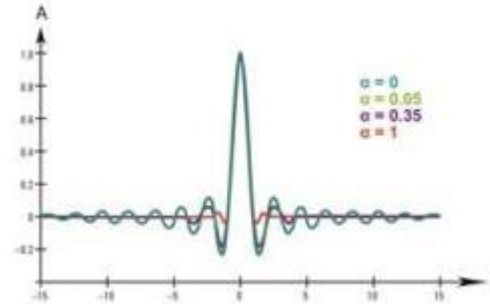
Equalization, Demodulation, etc..

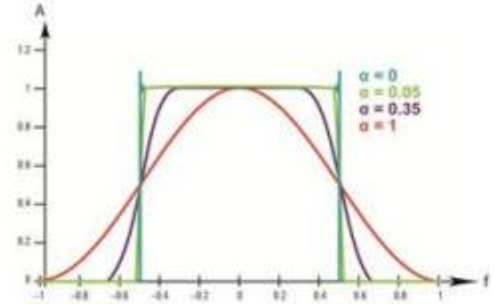
Dynamic system
- Random
- Time varying
- Wide variety of scenarios

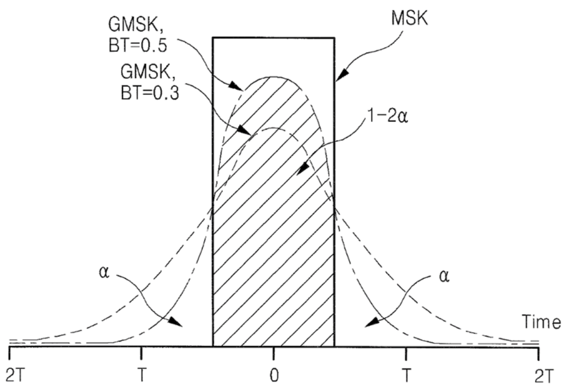


Transmitter	Environment	Receiver
• Lattice design • Pulse/filter design • Pre/post processing • Multiplexing • Scheduling	• Doubly-dispersive channel • Tx & Rx nonlinear hardware effects • Self-interference • Other-user interfer-ence	• Synchronization • Filtering & interference suppression • Equalization • Demodulation









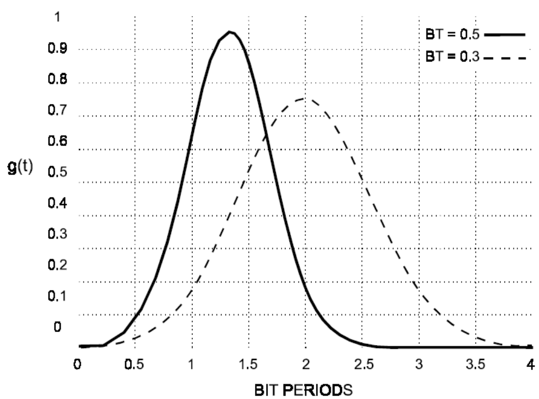
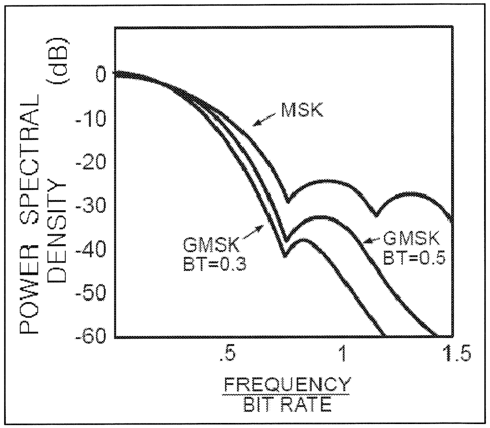
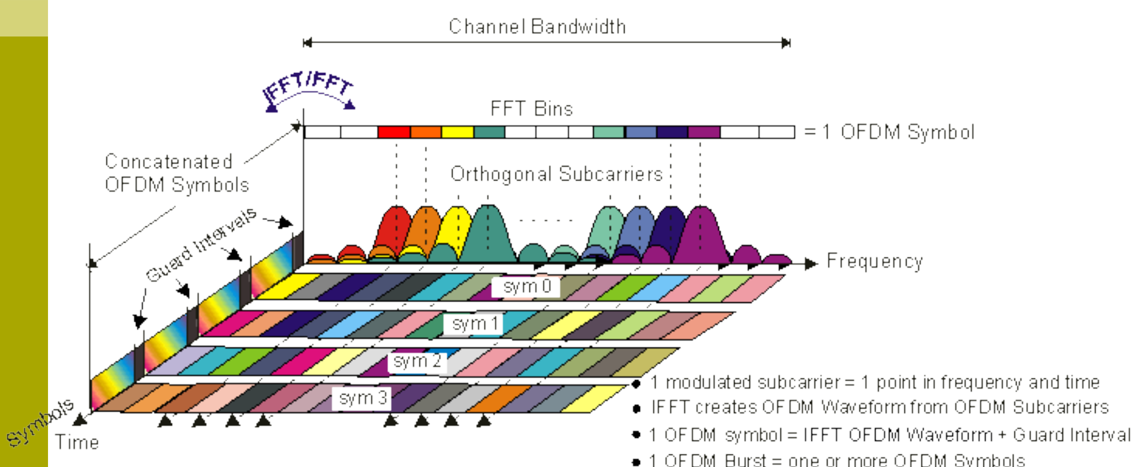
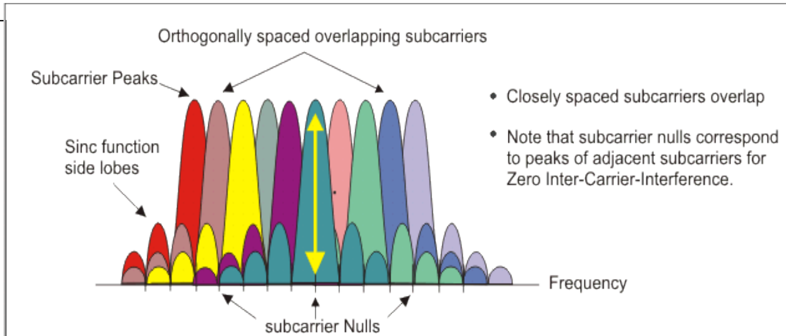


Figure 3: Gausssian filter impluse response for BT = 0.3 and BT = 0.5





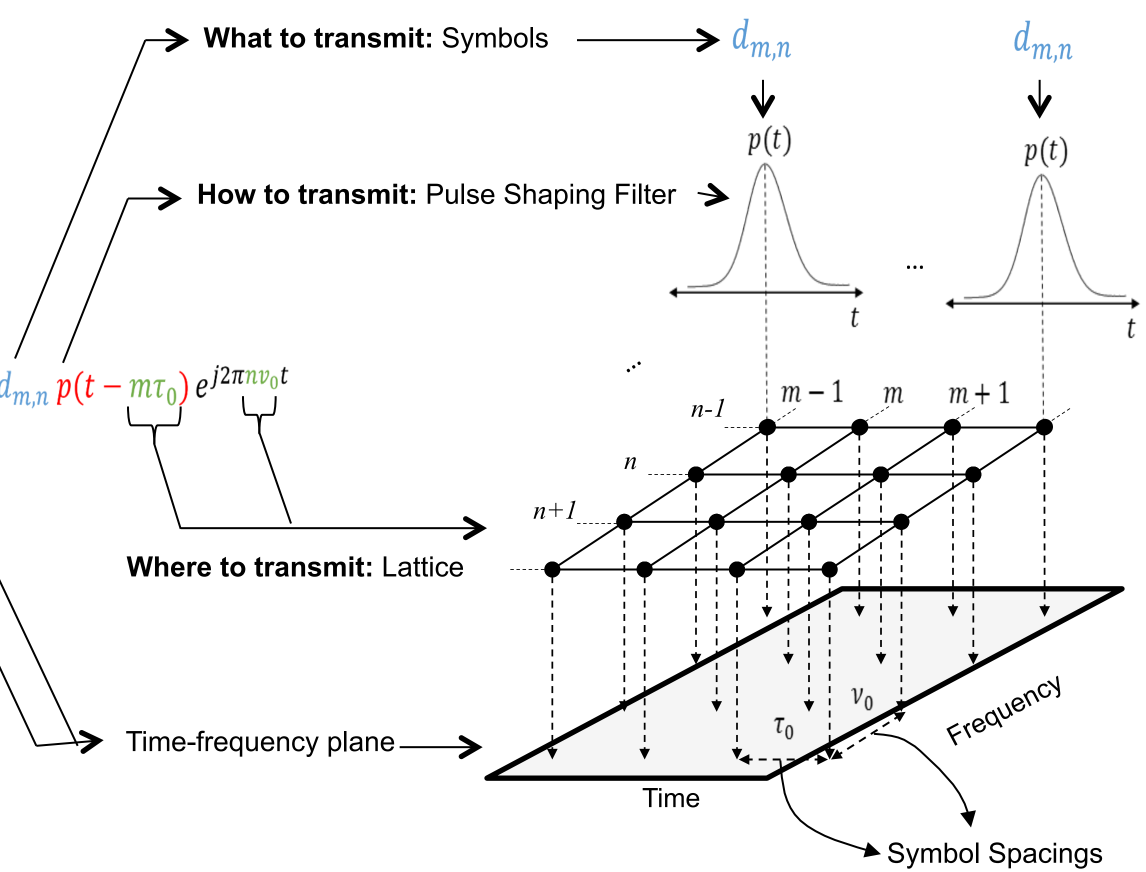
Frequency-Time Representative of an OFDM signal



OFDM Signal Frequency Spectra

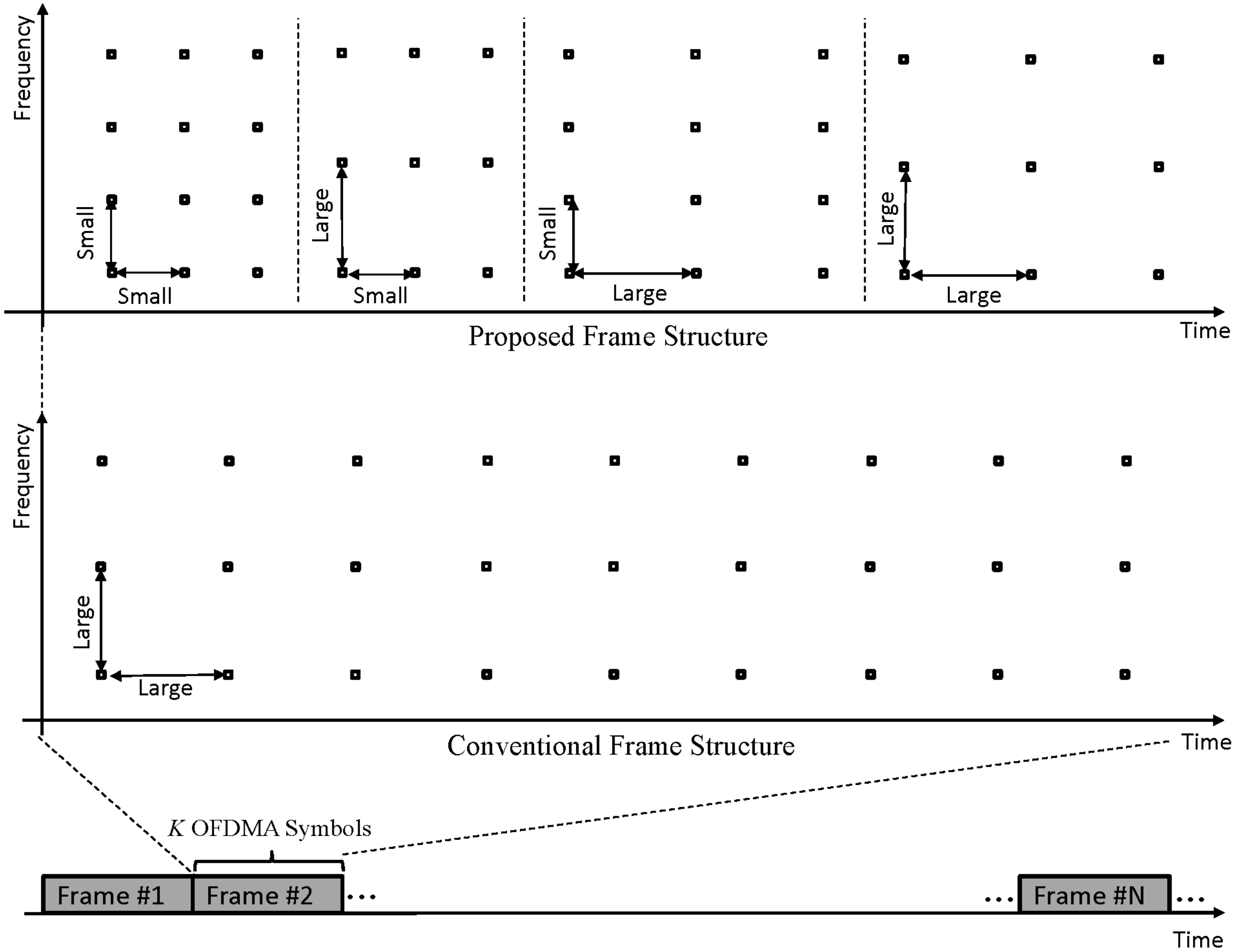
Waveform Definition

$$s(t) = \sum_{m=-\infty}^{+\infty} \sum_{n=0}^{N-1} d_{m,n}\, p(t - m\tau_0)\, e^{j2\pi n \nu_0 t}$$



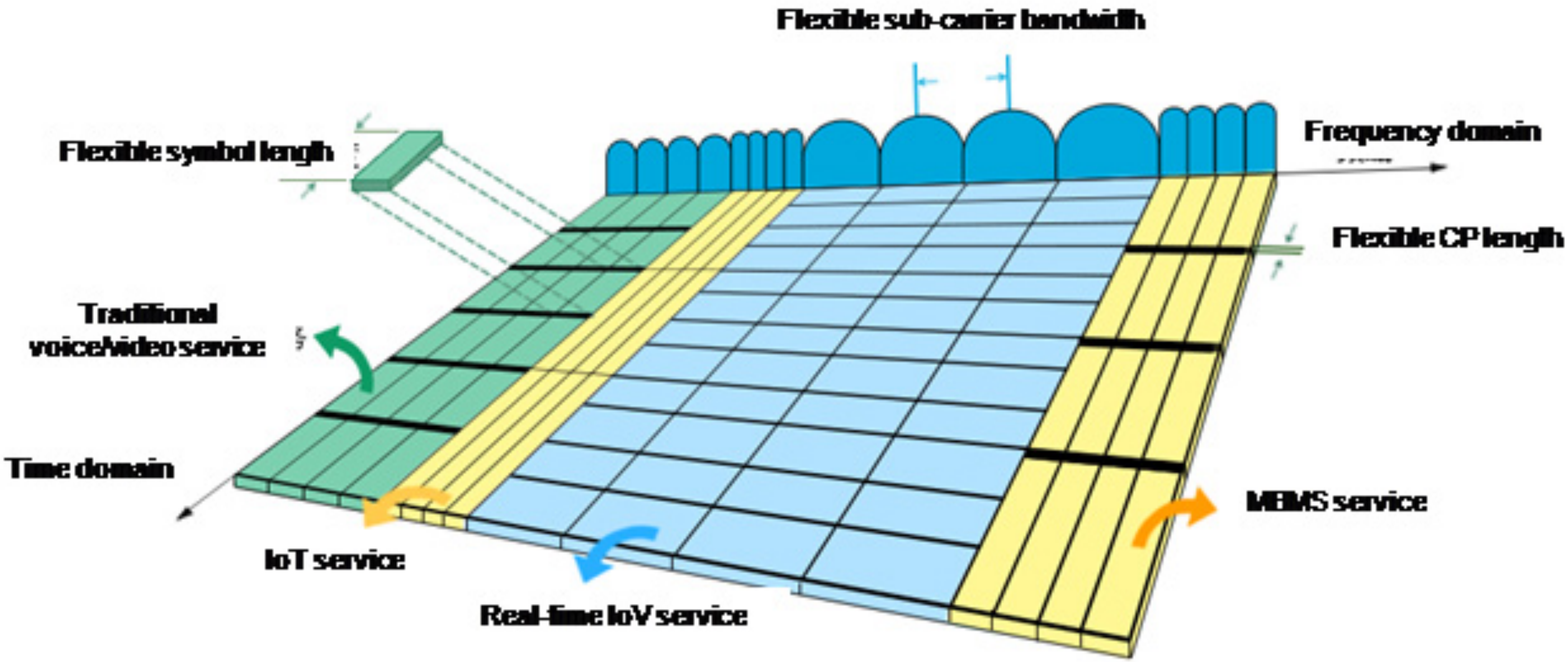
Lattice

Can be uniform, or non-uniform
Can be fixed or dynamic

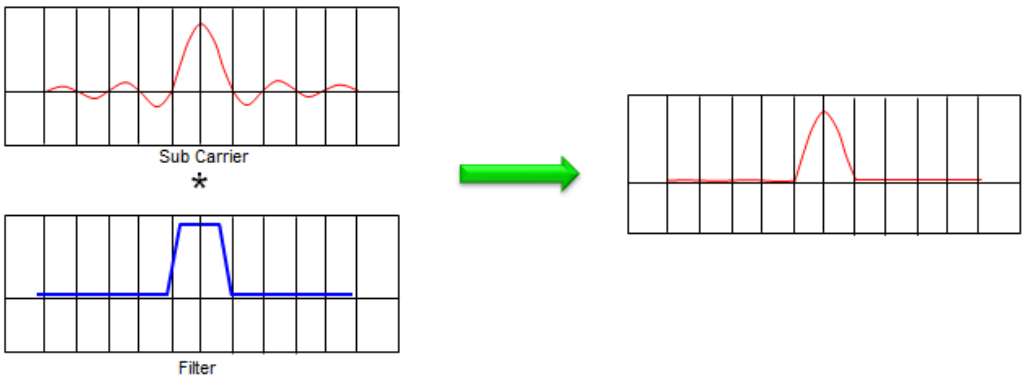

Frequency
Small
Small
Large
Small
Small
Large
Large
Large
Time
Proposed Frame Structure
Frequency
Large
Large
Time
Conventional Frame Structure
K OFDMA Symbols
Frame #1
Frame #2
...
...
Frame #N
...
Time

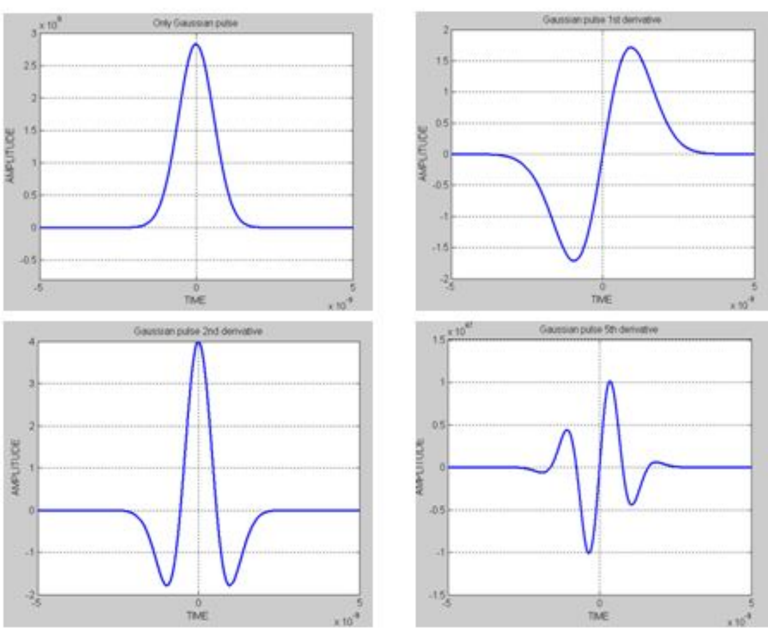
On the time-frequency granularity of waveforms

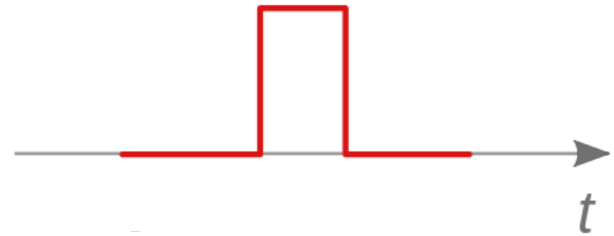
- Need to manage/control/adapt time and frequency
- Better multiple accessing, optimal scheduling, multi-user diversity
  - Control of multiuser channel, adapt the time/frequency variation
- Better control on interference (narrowband, impulsive)
- Adaptive modulation, power control, etc.

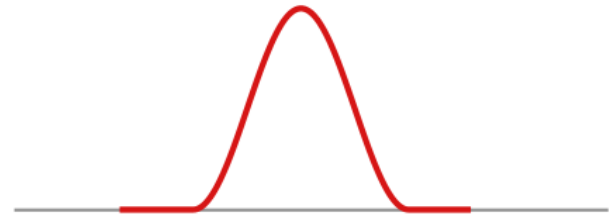


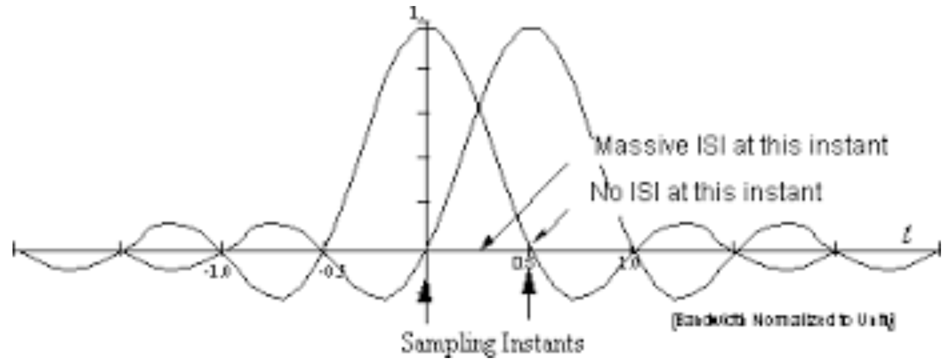
Pulse and Filter

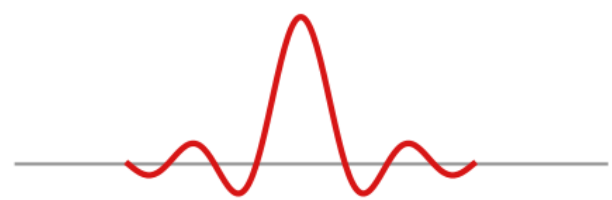


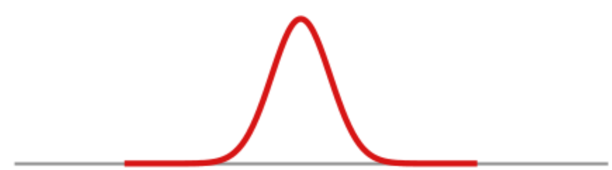










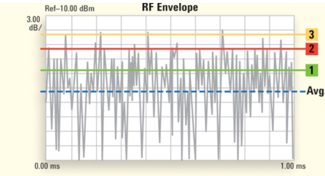


Why need new waveforms?

- mm-wave will need rethinking of waveforms (wider bands, significantly different channel characteristics, polarization effects, beam forming effects, etc…)
- New applications (especially heterogeneous applications) will require more robust and flexible waveforms
- New networks (especially asynchronous and HetNets) will need new waveforms
- Flexible/Scalable waveforms (more applications and user cases)
- Introduction of angular and spatial domains will need rethinking of waveforms
- New requirements: complexity, latency, power, asynchronism, wider bands, more bands, security, etc.

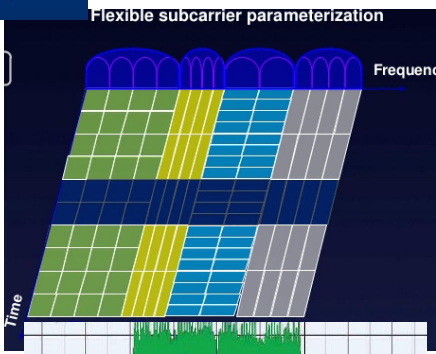
PerfectWaveform ?

- Power efficient (Low PAPR)
- Spectral Efficient (well packed in time/freq., less overhead)
- Computationally less complex (easy generation, synchronization, channel estimation, equalization, detection, …)

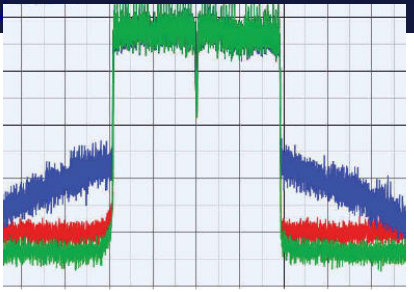


- Easy to implement
- Scalable, flexible (BW) for wide variety of applications
- MIMO and multiple antenna support

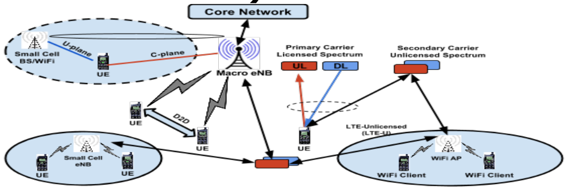
- Adaptable for channel and user conditions
- Reliable (QoS) and Robust (to channel)



- Low latency
- Minimum signaling and control overhead
- Multiple access capable
  - Minimal interference
  - Time-frequency-space slicing and multi-user diversity



- Allow asynchronous multiplexing
- Low out-of-band emissions (side lobes)
- Support for co-existence



- High order modulation support
  - The new waveform should be optimized to support high order modulations such as 64QAM and 256QAM
- Frequency localization
  - Good frequency localization is essential in providing the following flexibilities to the air interface with minimal loss in spectral efficiency
  - Flexible and scalable bandwidth support by concatenation of the several sub-bands
  - Efficient co-existence with other systems and also efficient usage of fragmented spectrum
  - Efficient asynchronous communication
- Time localization
  - A well time-localized waveform is essential for 5G to support low-latency communication with very short TTIs
- Robustness to hardware impairments such as carrier frequency offset

Critical waveform parameters

- Power parameters
  - PAPR (peak, mean powers), CCDF (power statistics)
- Localization parameters
  - Energy distribution in time-frequency. Relative energy distribution in these domains. Ambiguity function (or better ways of quantifying this characteristics)
- Orthogonality versus non-orthogonality properties and measures. Need ways of measuring the level or orthogonality, and effective orthogonality. Signal seperability measure…
- Redundancy and guard allocations (in time and frequency), not just at the edges but also inside the blocks
- External correction and manipulation requirements and deployment strategies of these (like noise addition in the null space, etc)
- Synchronization, equalization, and detection mechanisms and the related configurations
- Security parameters, security measures
- Time-frequency granularity and the ability to exploit (manipulate, take advantage, adjust, and control) these domains
- Computation and implementation complexity measures
- BER performance – EVM
- Sensitivity (robustness) to impairements (RF and channel)
- Flexibility and ability to adapt (adaptable parameters and domains)
- Ability to co-exist and ability to collocate

Case study: Latency

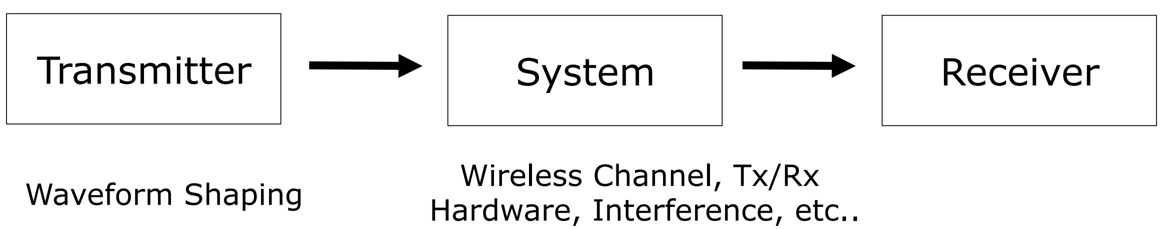
- Application: tactical, mission critical
- System requirement: Low latency
- Design-1: MAC Frame (shorter frames)
  - Impact on Waveform: time localized waveform
- Design-2: MAC - No retransmission (no ARQ)
  - Impact on waveform: low EVM and better FER performance to maintain reliable communication

Conclusion: Even though latency is directly controlled by MAC design, the indirect effect on waveform design is critical

OLD & NEW RULES

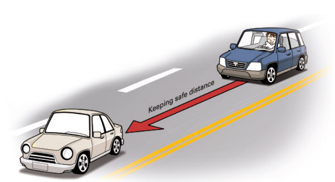
Waveform Perspectives

Old Rule	New Rule
Heavily depend on statistics; average, worst case (offline info. about channel)	User specific, real-time adaptive

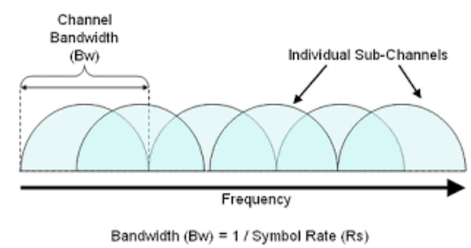


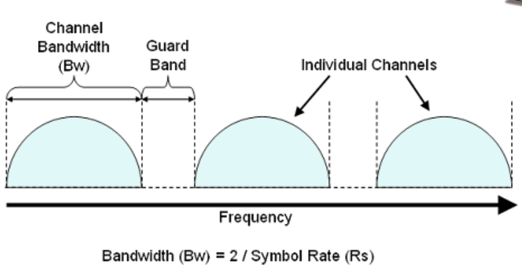
Old rules	New rules
-Orthogonal transmission -Additional guards to maintain orthogonality -Guards for the worst case channel	-Partial overlapping -Removing guards -More coordination -More awareness -More signal processing

GSM is an exception



■ Keeping safe distance adequately based on vehicle speed can help prevent collision, reduce driver fatigue and provide more time to respond to unexpected situations.





Old rule	New Rule
Waveform is a time-frequency phenomenon	Waveform is a multidimensional phenomenon (includes space, angle, etc.)

Old rule	New Rule
Waveform design is link layer issue	Waveform design is tightly coupled with MAC scheduling - Resource units, resource allocation - Multiuser diversity - Time-frequency scheduling Highly related to network - Asynchronous, homogeneous - Asynchronous, heterogeneous - Primary, secondary Dependent on application

Paradigm shift in waveform design

- Optimize the waveform design at Tx or Rx, or both?
- Zero ISI/ICI/IBI/MAI or allow some, if so which one(s)?
- One waveform for all, or multiple waveforms with more coordination and awareness

If Multiple waveform:

- What is the appropriate rule?
  - Change the parameters of a fixed shape or completely different shape?
  - How to change (every carrier and symbol, blocks of carriers, block of symbols, every user, group of similar users, …
- What is the goal function?

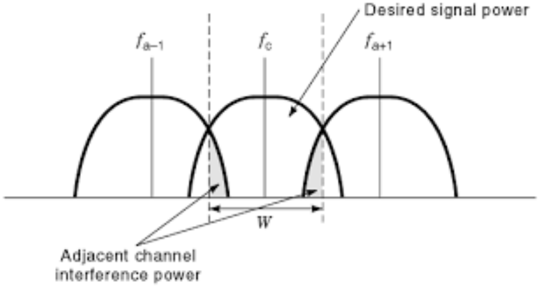
- Minimizing the number of taps in time-frequency plane (design of optimum lattice, pulses, filter/ window to minimize the effective number of channel taps)
- Minimizing ISI/ICI (zero forcing)
- Tradeoff between self interference and multiuser interference
- Minimizing the mean error (mmse)
- Maximizing SINR
- Maximizing secrecy capacity
- Minimizing out of band radiation
- Minimizing PAPR
- Minimizing latency
- Maximizing capacity (spectral efficiency)

5G waveform approaches

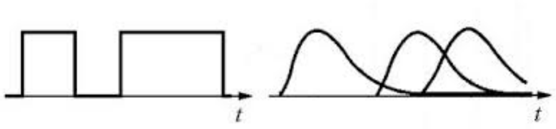
- Modification of OFDM (fixing the issues)
- Something new, something different, something amazingly better ???
- Hybrid utilization of various known waveforms
- More flexible and adaptive waveform, more degree of freedom, more parameters
- Non-orthogonal ???

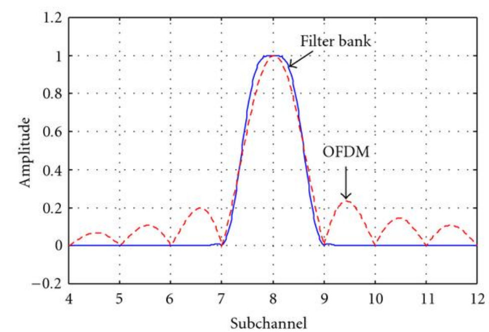
More on self interference versus multiuser interference

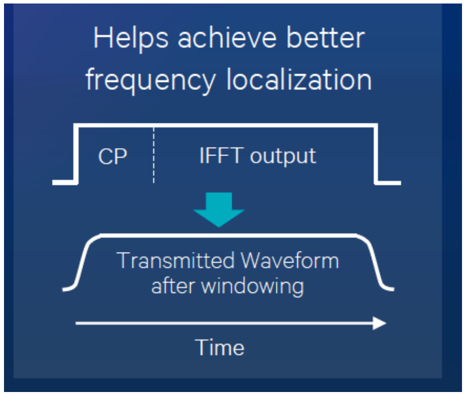
- ISI/ICI: self interference
- ACI/CCI: multiuser interference

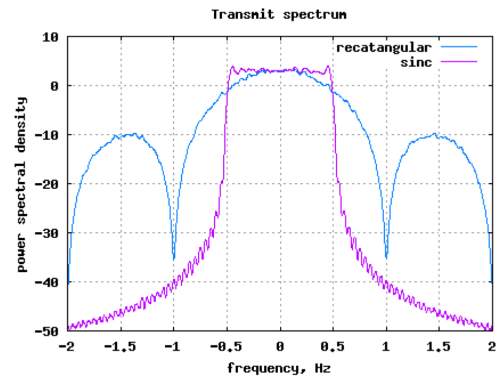


- Waveform and scheduling design can consider trading off one interference with another.
- For example, utilizing filters in OFDM (or in general multicarrier systems) can minimize ICI and multiuser interference with more ISI



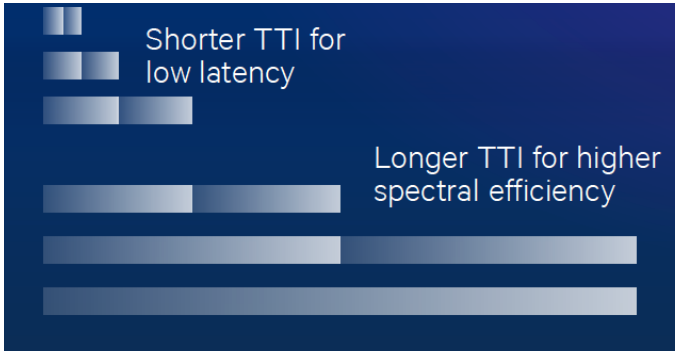


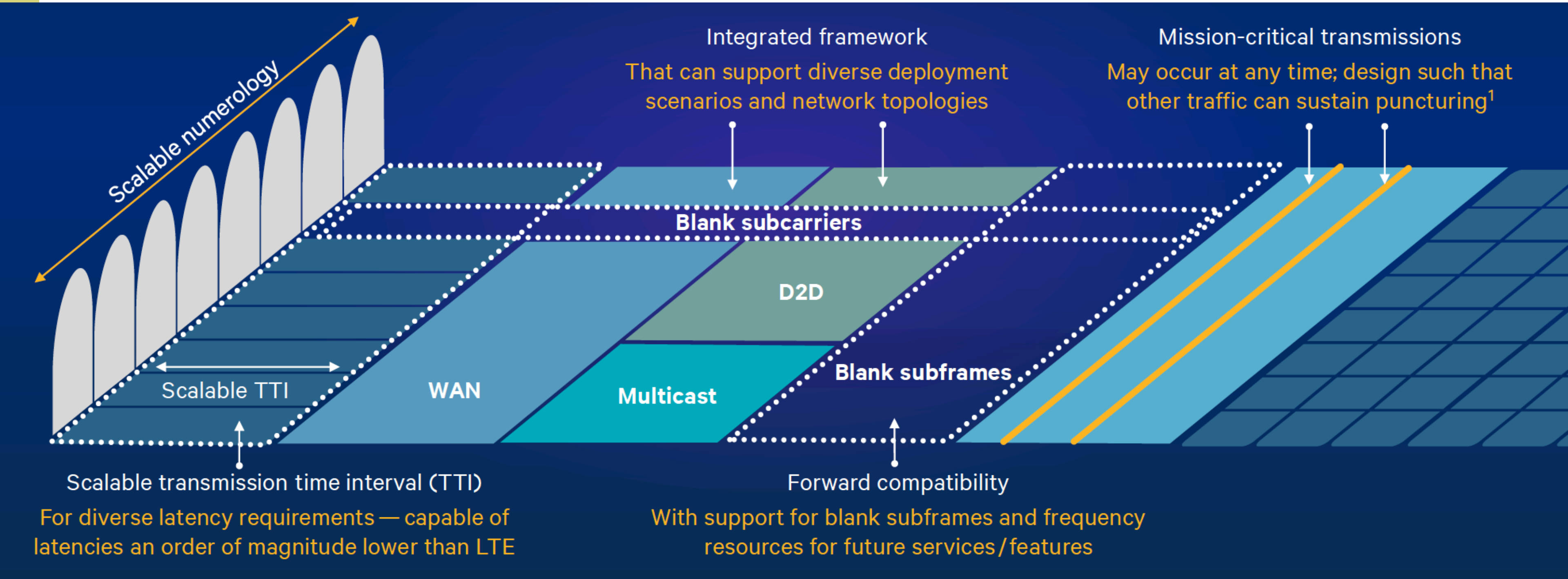




More on Latency

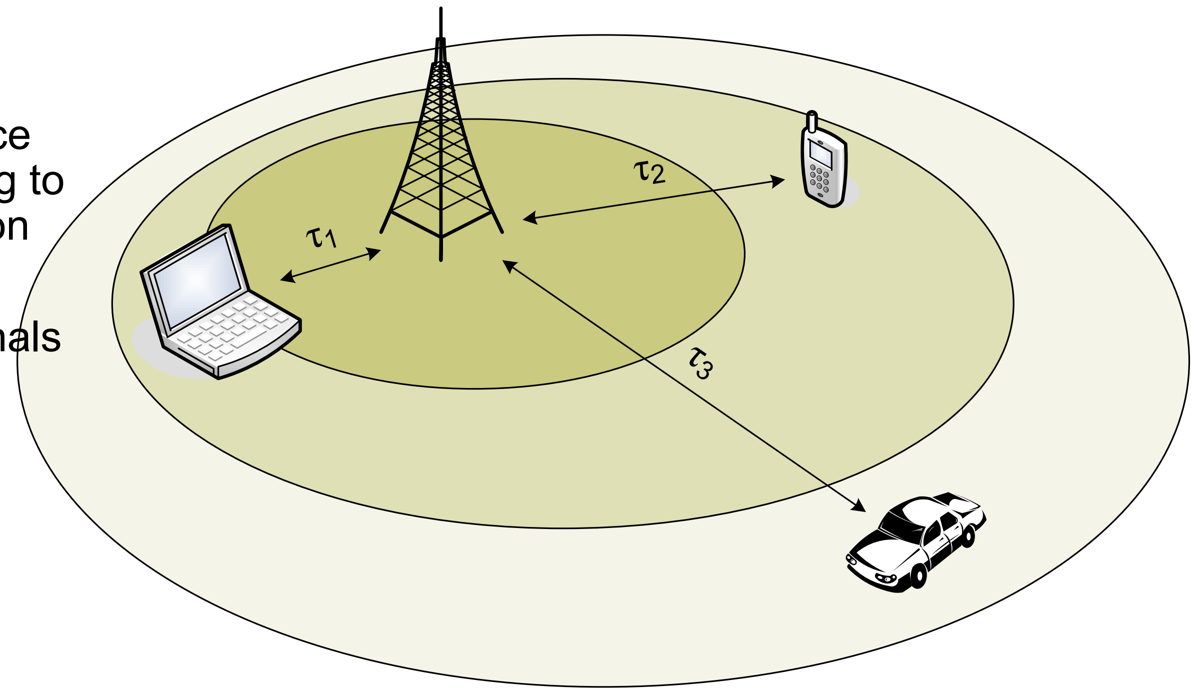
- Future applications like tactical radio will require less delays (less than milliseconds)
- Packets can`t be long
- Waveforms that form the packets should be time limited (no long tails)

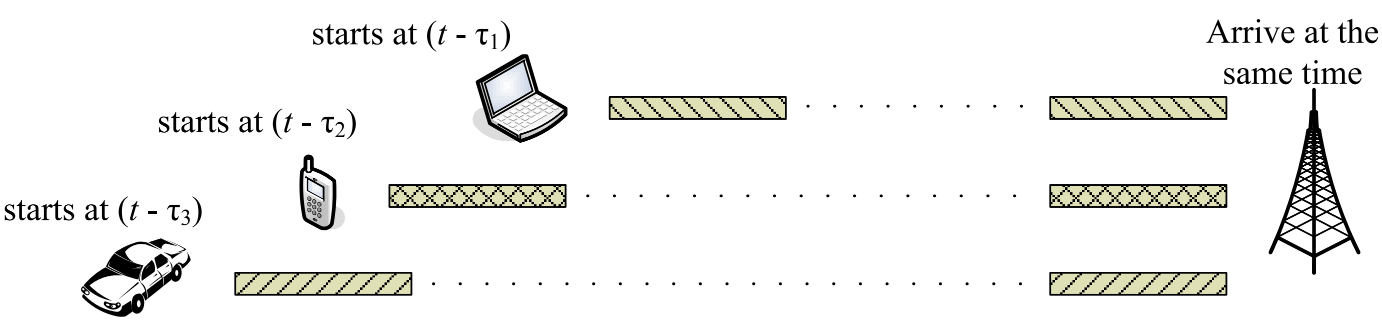




More on coordination: ex. Uplink Ranging

- Users' signals experience different delays according to distance from base station
- In Multi-user OFDM, signals should be received synchronously

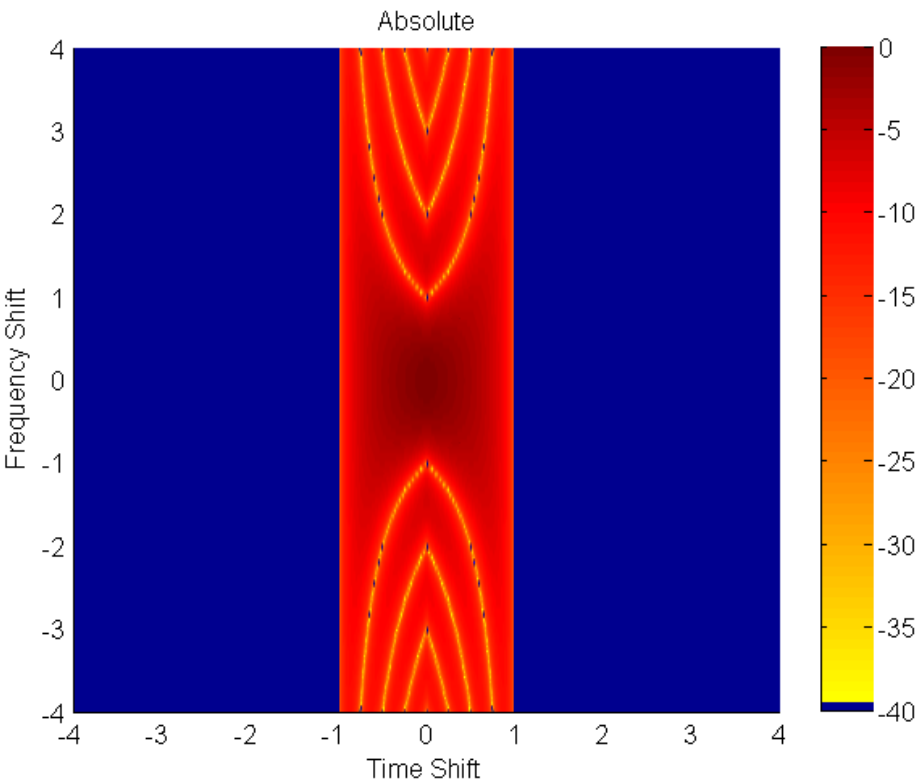




- By estimating users' delay, BS can adjust transmit time such that signals arrive at the same time

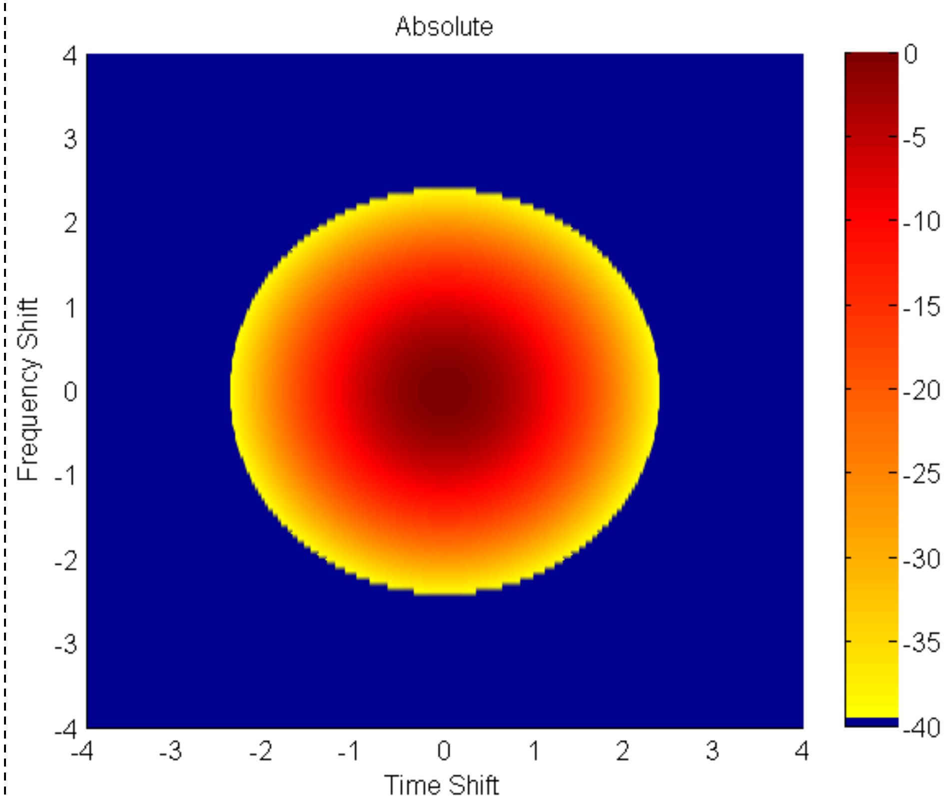
More on localization

Asynchronous Net.+ Orthogonal Schemes
➔ It is complex to deal with the interference



TX: Rectangular, RX: Rectangular

Asynchronous Ne. + Non-Orthogonal Schemes
➔It is practical to deal with the interference



TX: Gaussian, RX: Gaussian