OFDMA and applications to IoT

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University of Rome "La Sapienza"

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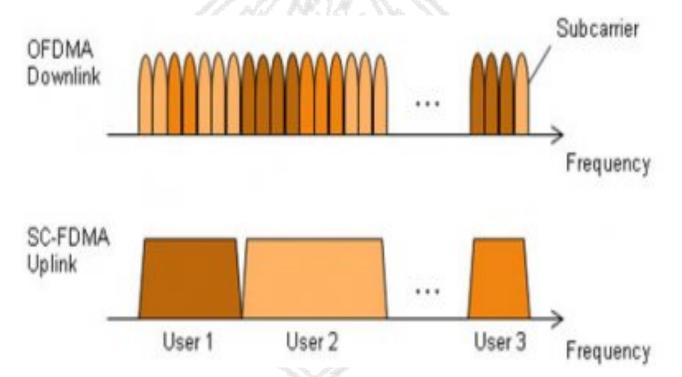[†]*Department of Engineering – University of Palermo – Italy*

Slides partly by Ilenia Tinnirello, Massimo Condoluci, Sami Tabbane, et al.

OFDM by example

- 4G LTE Channel Access
  - OFDMA (Orthogonal Frequency Division Multiple Access)
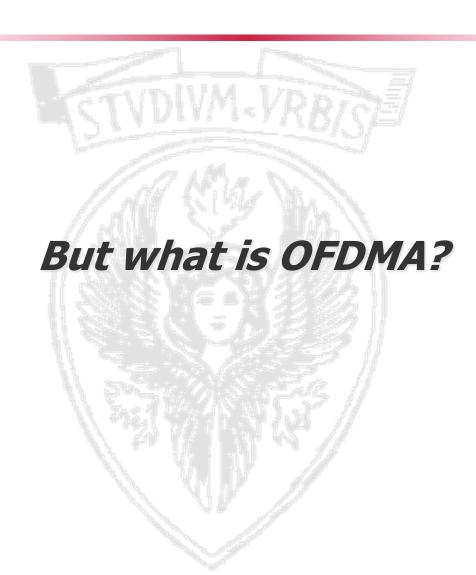 - SC-FDMA (Single Carrier FDMA)

Single Carrier FDMA (SC-FDMA)

- A new multiple access technique which has similar structure and performance to OFDMA
  - Linearly pre-coded OFDMA
  - Single carrier modulation and orthogonal frequency multiplexing using DFT-spreading in the transmitter and frequency domain equalization in the receiver
  - Low PAPR respect to OFDMA
  - Myung et al., "Single Carrier FDMA for Uplink wireless transmission", IEEE Vehicular Technology Magazine, 2006
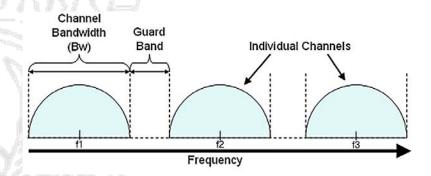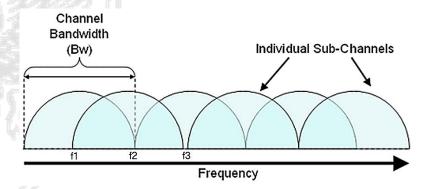
But what is OFDMA?

OFDM Basic Concept

- OFDM is a special case of *Frequency Division Multiplexing* (FDM)

- For FDM
  - No special relationship between the carrier frequencies
  - Guard bands must be inserted to avoid *Adjacent Channel Interference* (ACI)

- For OFDM
  - Strict relation between carriers:
    $f_k = k \cdot \Delta f$ where $\Delta f = 1/T_U$
    (T_U is the symbol period)
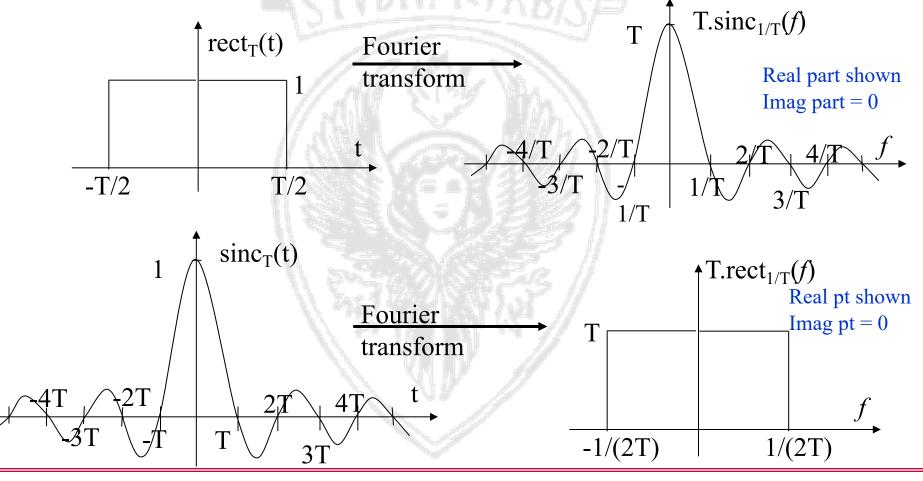 - Carriers are orthogonal to each other and can be packed tight

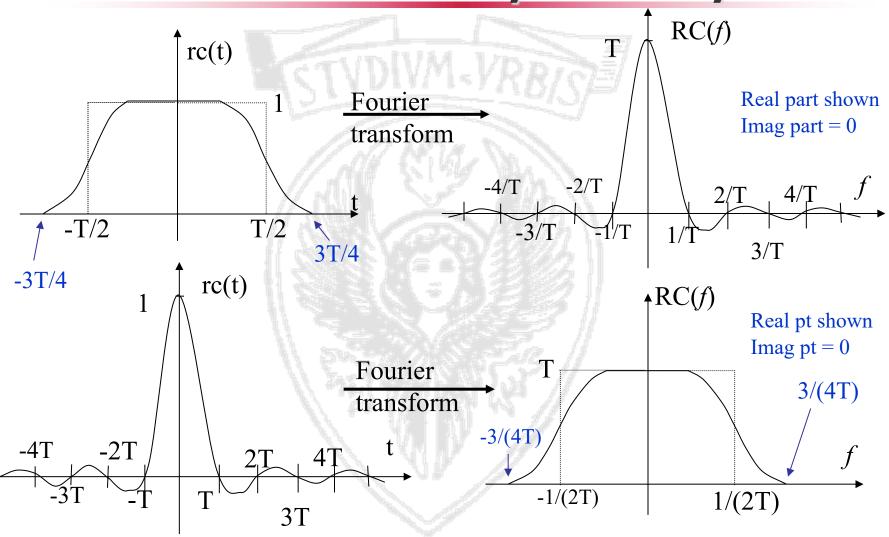# Spectra of rect & sinc pulses

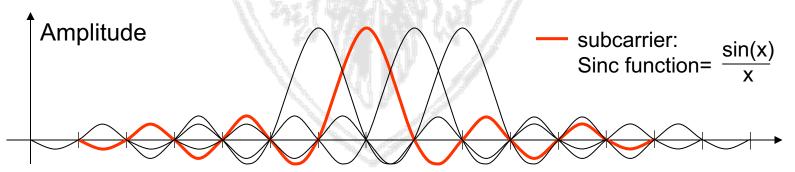- Spectrum occupation is never limited (requires inf. time!)

$rect_T(t)$

Fourier transform

$T.sinc_{1/T}(f)$

Real part shown
Imag part = 0

$sinc_T(t)$

Fourier transform

$T.rect_{1/T}(f)$

Real pt shown
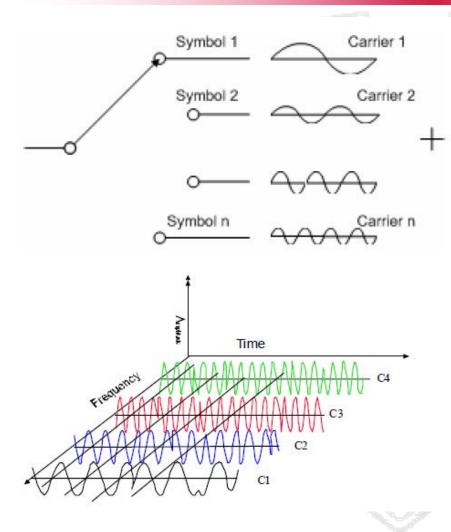Imag pt = 0

Sub-band spectral interference (ICI)

- With single carrier, smoothed pulses are used at expense of decreasing band-width efficiency.

- With multi-carrier, pulse shapes close to rectangular may be used.
  - Their spectra are 'sinc-like' & of very wide bandwidth.

- With 64 adjacent sub-bands (e.g. WiFi), there is clearly a danger of inter spectrum interference, or inter-carrier interference (ICI).

- Also danger of spectrum leaking outside the OFDM band.

Amplitude

subcarrier:
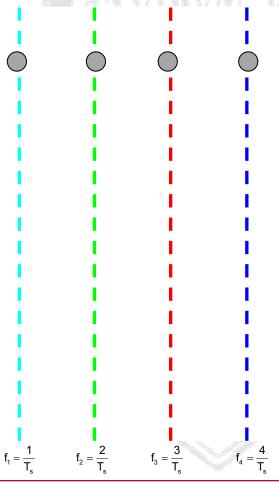Sinc function= $\dfrac{\sin(x)}{x}$

How does OFDM work?

- In principle, similar to CDMA with orthogonal codes!
- Each modulated sub-carrier is 'orthogonal', which means that they do not interfere with each other
- Highly efficient because sub-carriers are as close as they can possibly be

OFDM signal example

- OFDM Signal of 4 sub-carriers (separated by $1/T_U$)

The separation between carriers guarantee that samples from individual sub-carriers correspond to samples from the composite spectrum
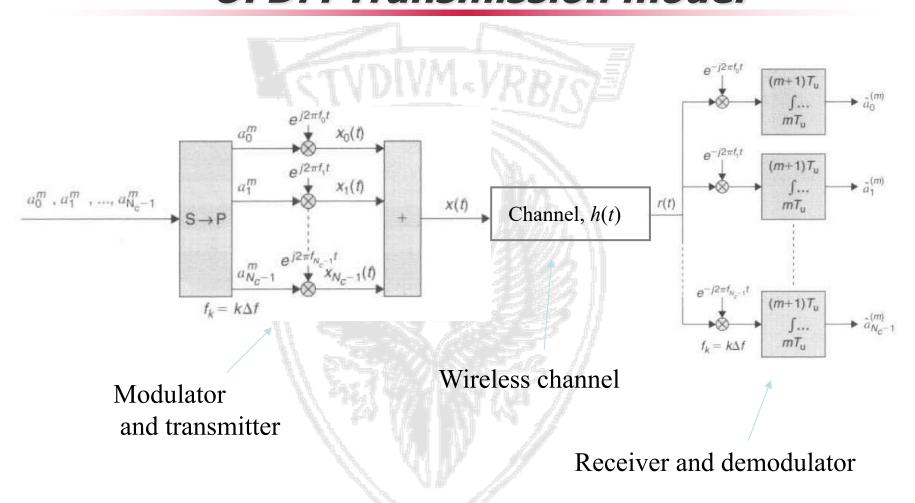
$$f_1 = \frac{1}{T_s} \qquad f_2 = \frac{2}{T_s} \qquad f_3 = \frac{3}{T_s} \qquad f_4 = \frac{4}{T_s}$$

Use of sub-carriers

- Bit-rate using N sub-channels is 1/N of total bit-rate
- Zero-crossings of sinc spectra (at $\pm 1/T$ $\pm 2/T$, ..) much closer together.
- So the sinc spectra 'die away' must faster.
- Ones in centre of band die away almost completely at edges.
- Ones near edges not modulated (avoid spectrum out of band leakage)
  - E.g. out of 64 sub-carriers, do not modulate first six, last five & no. 32 (center frequency becomes 0 at base-band).
- Some other sub-carriers reserved as 'pilots'
  - Used to estimate channel (more later)

Modulator
and transmitter

Wireless channel

Receiver and demodulator

Orthogonality – the essential property

- Example: Receiver branch *k*
  - Ideal channel: No noise and no multipath

$$\frac{1}{T_U} \int_0^{T_U} \underbrace{\left(\sum_{q=0}^{N_c-1} a_q \cdot e^{j2\pi q \Delta ft} \right)}_{\text{Received signal, } r(t)} \cdot e^{-j2\pi k \Delta ft} dt = \sum_{q=0}^{N_c-1} \frac{a_q}{T_U} \int_0^{T_U} e^{j2\pi(q-k)\frac{1}{T_U}\cdot t} dt = \begin{cases} a_k, & k = q \\ 0, & k \neq q \end{cases}$$

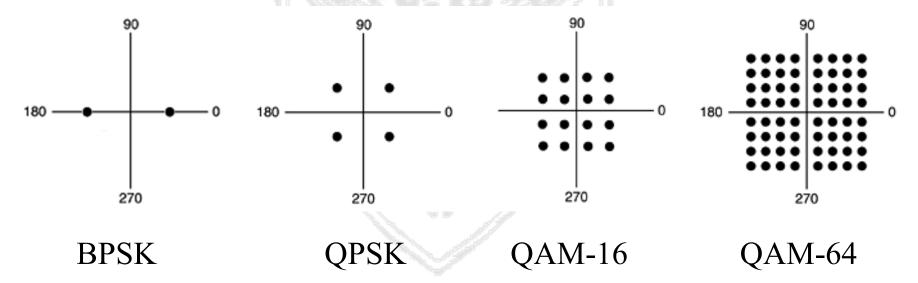$T_u = 1/\Delta f$ gives subcarrier orthogonality over one T_u
=> possible to separate subcarriers in receiver

Modulation of sub-carriers

- Choice of or combination of amplitude or phase modulations, e.g.:
  - BPSK (Binary Phase Shift Keying) = 2 phase shifts, 1 amplitude level, 1 bit/symbol
  - QPSK (Quadrature Phase Shift Keying) = 4 phase shifts, 1 amplitude level, 2 bits/symbol
  - QAM-16 = 4 phase shifts, 4 amplitude levels, 4 bits/symbol
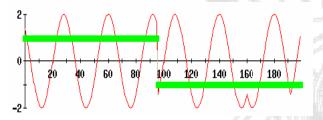 - QAM-64 = 4 phase shifts, 16 amplitude levels, 6 bits/symbol

BPSK   QPSK   QAM-16   QAM-64

Example of OFDM

- Lets we have following information bits

  1, 1, -1, -1, 1, 1, 1, -1, 1, -1, -1, -1, -1, 1, -1, -1, ...

- Just converts the serials bits to parallel bits

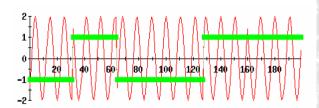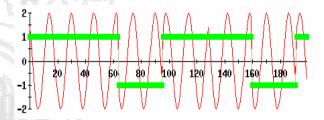| C1	C2	C3	C4
1	1	-1	-1
1	1	1	-1
1	-1	-1	-1
-1	1	-1	-1
-1	1	1	-1
-1	-1	1	1

Modulate each column with corresponding sub-carrier using BPSK
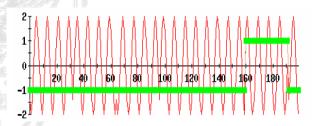
Modulated signal for C1
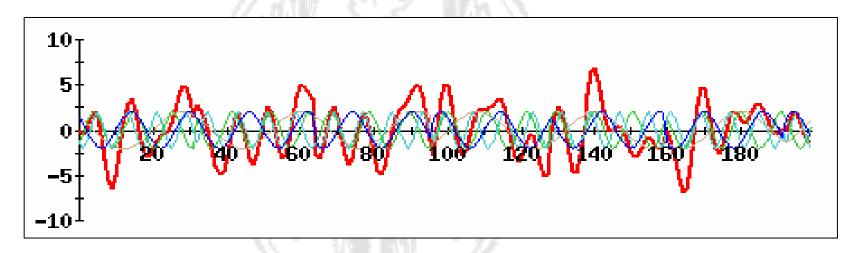

Modulated signal for C2

Modulated signal for C3

Modulated signal for C4

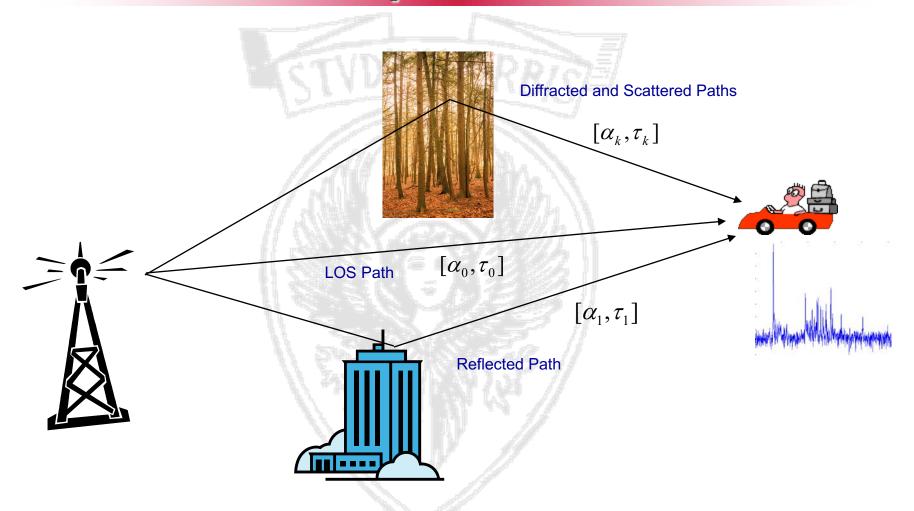# *Example of OFDM cont..*

- Final OFDM Signal = Sum of all signal   V(t) ———

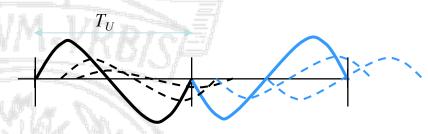$$V(t) = \sum_{n=0}^{N-1} I_n(t) \sin(2\pi nt)$$

Generated OFDM signal, V(t)

Multipath channel

Diffracted and Scattered Paths

$$[\alpha_k, \tau_k]$$

LOS Path $\quad [\alpha_0, \tau_0]$

$$[\alpha_1, \tau_1]$$

Reflected Path
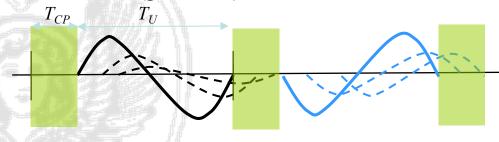
Multipath channel (cyclic prefix)
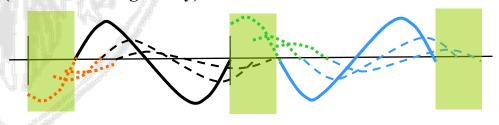
Multipath introduces *inter-symbol-interference* (ISI)

T_U

Example multipath profile

Amplitude [α]

τ_0 τ_1 τ_2

Time [τ]
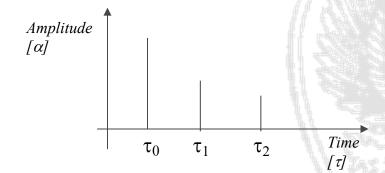
Prefix (guard time) is added to avoid ISI

T_{CP} T_U

The prefix is made cyclic to avoid *inter-carrier-interference* (ICI) (maintain orthogonality)
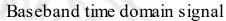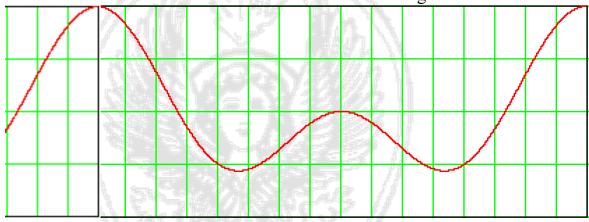
OFDM Cyclic Prefix

Starting discontinuity

Tail end always aligns with the starting discontinuity

Baseband time domain signal

v_p

$\dfrac{p}{samples}$

DAC output sample #

Starting discontinuity
has been masked by copying
tail end and inserting it
as a cyclic prefix
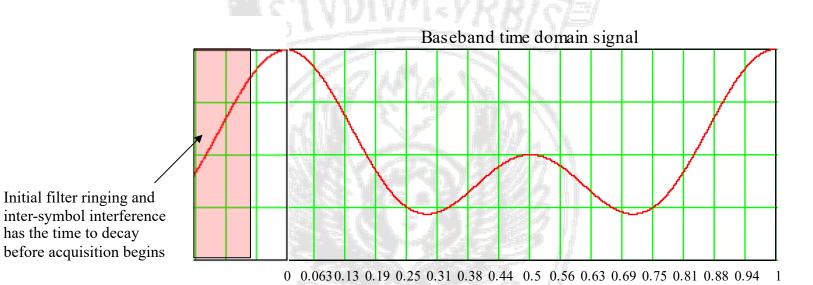
Baseband time domain signal

0   0.063 0.13 0.19 0.25 0.31 0.38 0.44   0.5   0.56 0.63 0.69 0.75 0.81 0.88 0.94   1

$$\frac{p}{samples}$$

DAC output sample #

OFDM Cyclic Prefix

Baseband time domain signal

Initial filter ringing and
inter-symbol interference
has the time to decay
before acquisition begins

0   0.063 0.13 0.19 0.25 0.31 0.38 0.44   0.5   0.56 0.63 0.69 0.75 0.81 0.88 0.94   1

$$\frac{p}{samples}$$

DAC output sample #

OFDM Cyclic Prefix

Baseband time domain signal

τ_1

0   0.063 0.13 0.19 0.25 0.31 0.38 0.44   0.5   0.56 0.63 0.69 0.75 0.81 0.88 0.94   1

$$\frac{p}{samples}$$

DAC output sample #
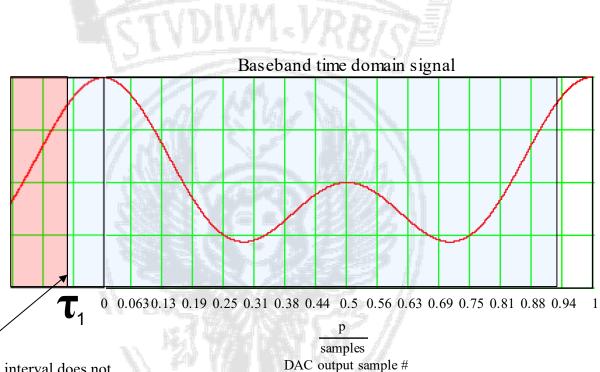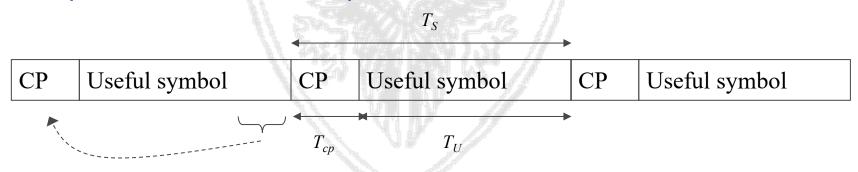
Signal acquisition interval does not
have to be precisely aligned to get
a valid orthogonal signal set

Cyclic Prefix length
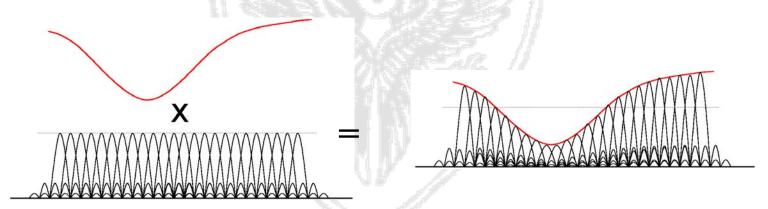
- T_{cp} should cover the maximum length of the time dispersion
- For example, assume T_{cp} =0.8μs. Since speed of radio waves ≈ 300×10^6 m/s, this allows for a path-length difference of 0.8 × 300 = 250 m.
- Increasing T_{cp} implies increased overhead in power and bandwidth (T_{cp}/T_S)
- For large transmission distances there is a trade-off between power loss and time dispersion

CP	Useful symbol	CP	Useful symbol	CP	Useful symbol

T_S

T_{cp} T_U

Multipath channel (frequency diversity)

- The OFDM symbol can be exposed to a frequency selective channel
- The attenuation for each subcarrier can be viewed as "flat"
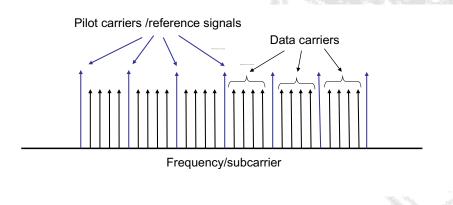 - Due to the cyclic prefix there is no need for a complex equalizer
- Possible transmission techniques
  - *Forward error correction* (FEC) over the frequency band
  - Adaptive coding and modulation per carrier
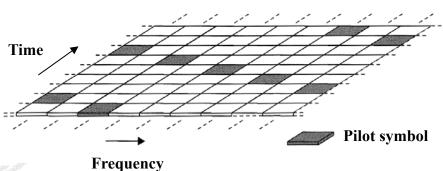
Multipath channel (pilot symbols)
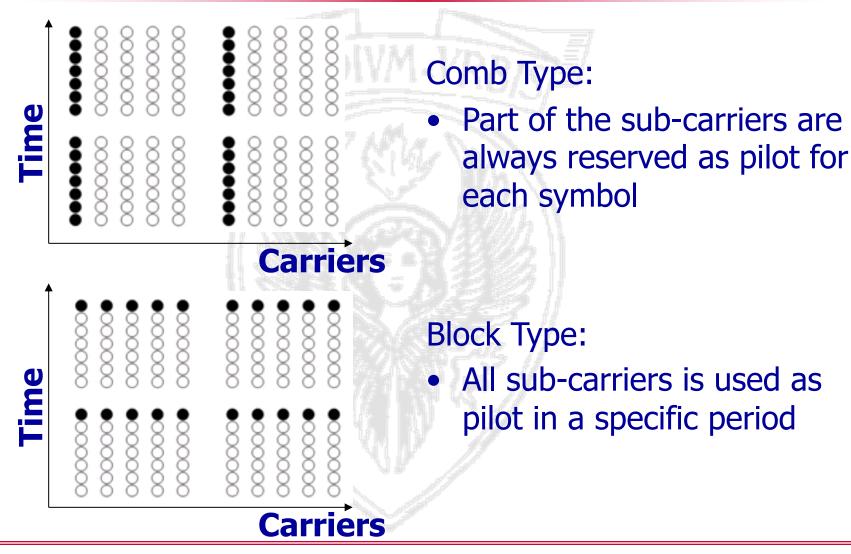
- The channel parameters can be estimated based on known symbols (pilot symbols)
- The pilot symbols should have sufficient density to provide estimates with good quality (tradeoff with efficiency)
- Different estimation methods exist
  - Averaging combined with interpolation
  - *Minimum-mean square error* (MMSE)

Pilot carriers /reference signals

Data carriers

Frequency/subcarrier

Time

Frequency

Pilot symbol

Pilots for Channel Estimation

Comb Type:

- Part of the sub-carriers are always reserved as pilot for each symbol

Block Type:

- All sub-carriers is used as pilot in a specific period

Received and Recovered Signals

- Recovering signal phases distorted by multi-path fading

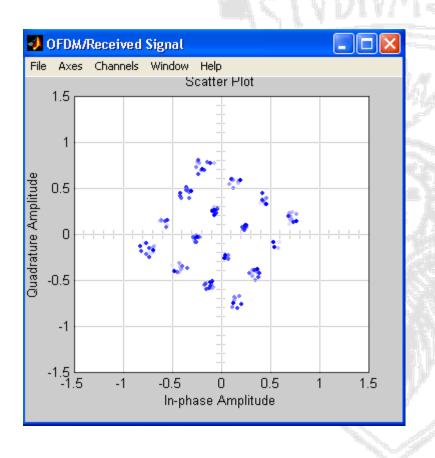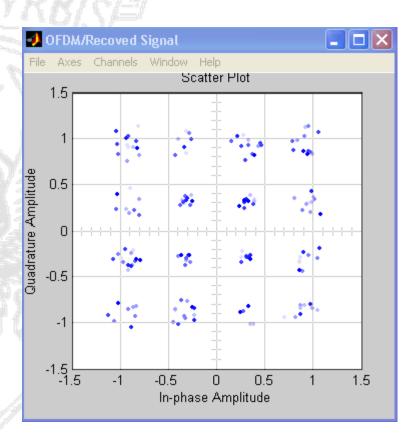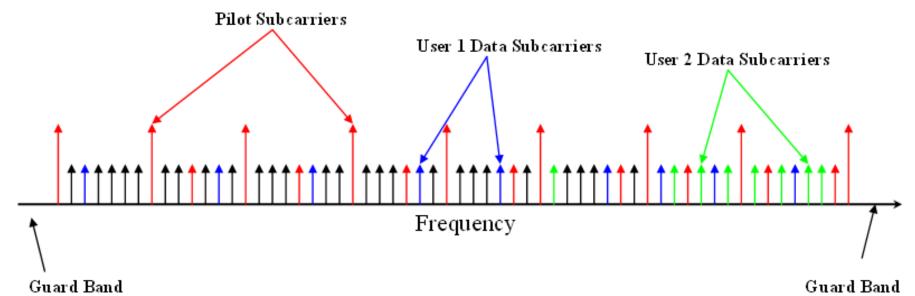# Multi-user OFDM: OFDMA

- OFDM can be used to transmit simultaneously to multiple destinations
- Sub-carriers assigned to different users
  - Possibly spread out using 'interleaving' so that FEC can more easily correct any bit-errors.
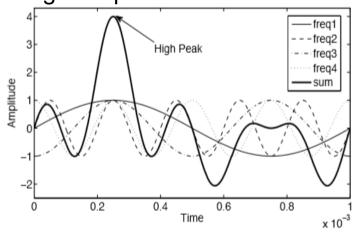
Problems of OFDMA

1) *peak-to-average-power ratio* (PAPR)

When sub-carriers are added coherently, the instantaneous power will be more than the average power.

High peaks in OFDM signal generated by summing multiple sinusoids

2) *Carrier frequency offset*

Necessity of accurate frequency synchronization between the receiver and the transmitter. With frequency deviation, the sub-carriers will no longer be orthogonal causing ICI.
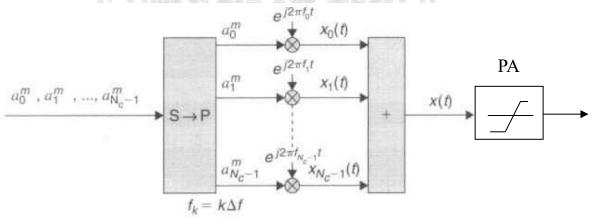
The Peak to Average Power Problem

- The sum of independently modulated subcarriers can have large amplitude variations

$$x(t) = \sum_{k=0}^{N_c-1} a_k \cdot e^{j2\pi k\Delta f\, t}$$

- Signal goes into nonlinear region of operation of the power amplifier (PA) at the transmitter (nonlinear distortions and spectral spreading)
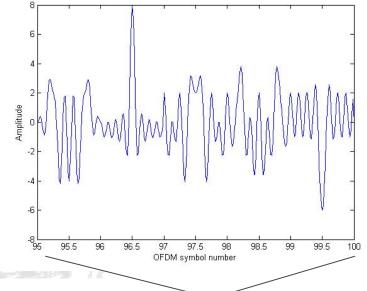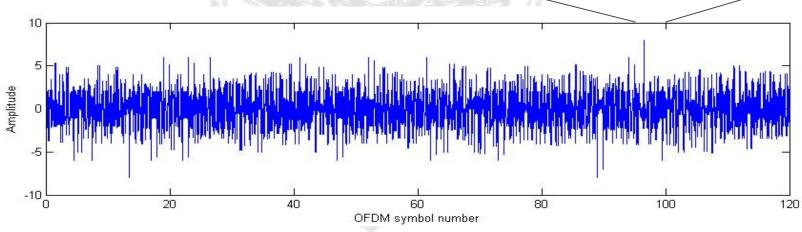
- High peak-to-average-power ratio (PAPR), requires linear transmitter circuitry, which suffers from poor power efficiency.

The Peak to Average Power Problem

- Example with 8 carriers and BPSK modulation
  - x(t) plotted
- It can be shown that the PAPR becomes equal to number of sub-carriers N
- N can be in the other of thousands!

The Peak to Average Power Problem
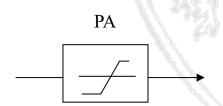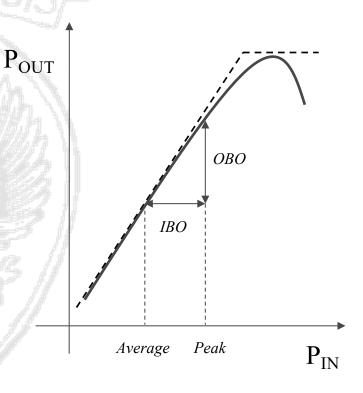
- High efficiency power amplifiers are desirable
  - For the handset, long battery life
  - For the base station, reduced operating costs
- A large PAPR is negative for the power amplifier efficiency
- Non-linearity results in inter-modulation
  - Degrades BER performance
  - Out-of-band radiation

AM/AM characteristic

P_{OUT}

OBO

IBO

Average   *Peak* P_{IN}

PA

The Peak to Average Power Problem
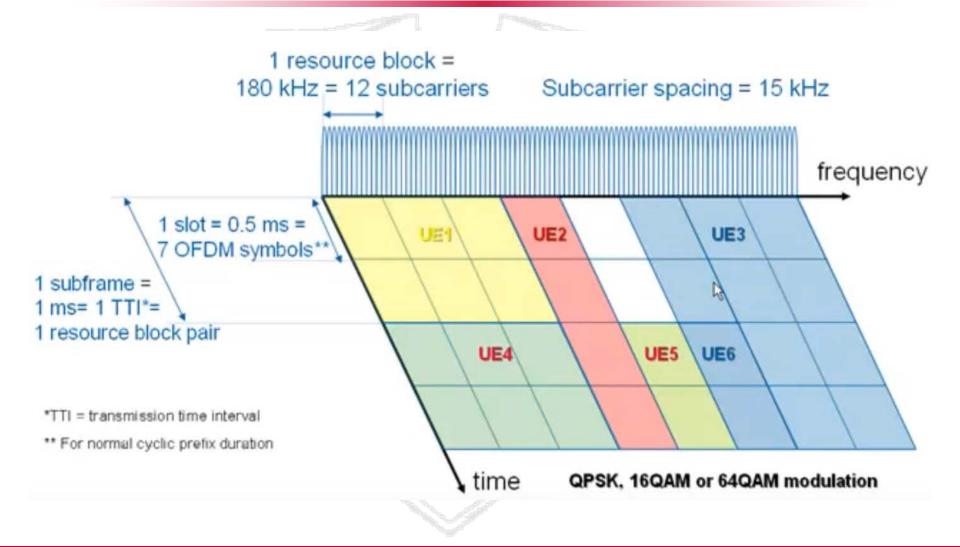
- Different tools to deal with large PAPR
  - Signal distortion techniques
    Clipping and windowing introduces distortion and out-of-band radiation, tradeoff with respect to reduced backoff
  - Coding techniques
    FEC codes excludes OFDM symbols with a large PAPR (decreasing the PAPR decreases code space). Tone reservation, and pre-coding are other examples of coding techniques.
  - Scrambling techniques
    Different scrambling sequences are applied, and the one resulting in the smallest PAPR is chosen

OFDMA in LTE
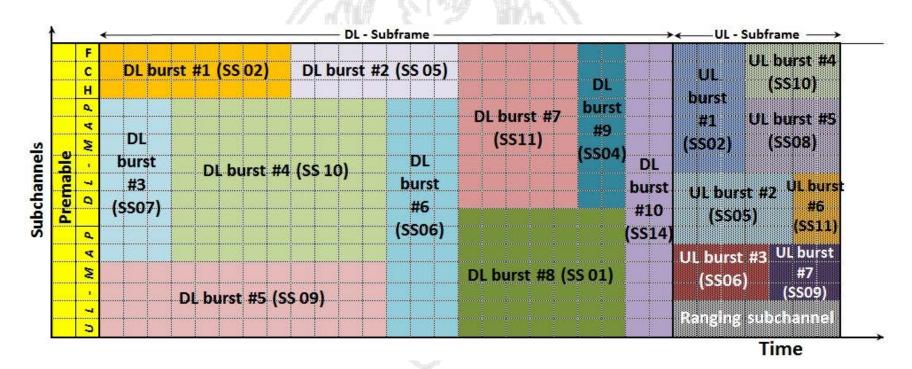
OFDMA/TDD structure

- OFDMA for downlink and SC-FDMA for uplink
- Flexible bandwidth from 1.4 to 20 MHz (i.e., from 6 to 100 resource blocks - RBs)
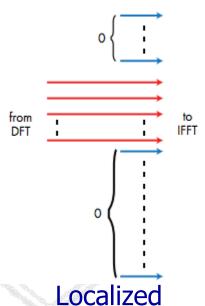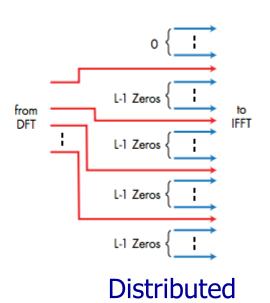
What about the uplink?

- **Single-carrier FDMA (SC-FDMA)**
  - Very similar to OFDMA
  - Also called linearly precoded OFDMA (LP-OFDMA)
- **Transmitter inserts null sub-carriers at positions assigned to other users**
- **Subcarrier mapping:**
  - localized mapping
  - distributed mapping

Localized

Distributed

OFDM Summary
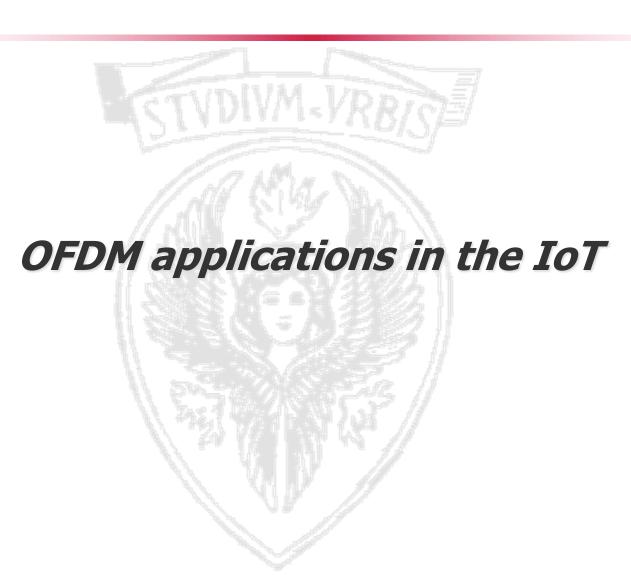
- ## Advantages
  - Splitting the channel into narrowband channels enables significant simplification of equalizer design
  - Effective implementation possible by applying FFT
  - Flexible bandwidths enabled through scalable number of sub-channels
  - Possible to exploit both time and frequency domain variations (time domain adaptation/coding + freq. domain adaptation/coding)

- ## Challenges
  - Large peak to average power ratio (PAPR)
  - Carrier frequency offset

- ## Today is used in TVB, DSL, WLANs, 4/5G, …

OFDM applications in the IoT

The rise of IoT

World Population	6.3 Billion	6.8 Billion	7.2 Billion	7.6 Billion
Connected Devices	500 Million	12.5 Billion	25 Billion	50 Billion
Connected Devices Per Person	0.08	1.84	3.47	6.58
	2003	2010	2015	2020

More connected devices than people
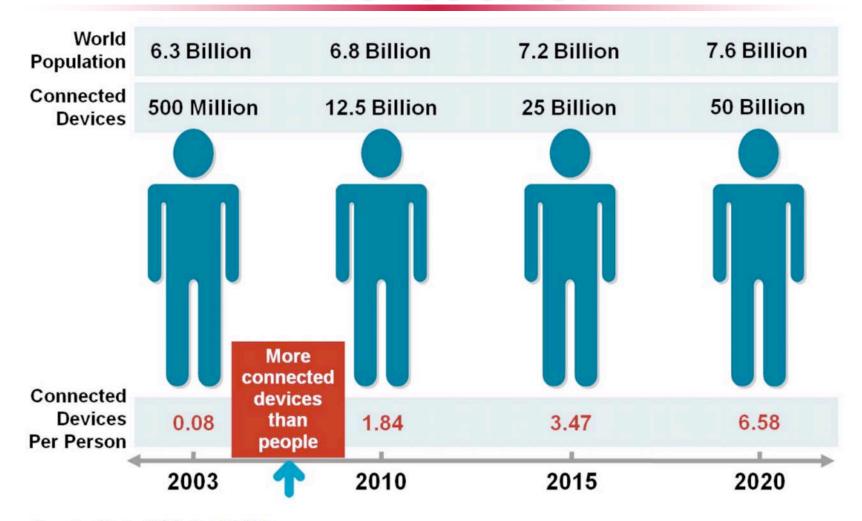
Source: Cisco IBSG, April 2011

Machine-type communications

	Human-type traffic	Machine-type traffic
Traffic direction	Bi-directional	Mainly uplink
Message size	Large/Very Large	Small
Traffic duration	From 10s of seconds to minutes	Very short (one transmission)
Delay	Variable	Usually delay-tolerant
Transmission periodicity	No period, frequent sessions	From 10s of minutes to hours
Mobility	From static to high-mobility	Static, very low
Information priority	Usually low	From low to high
Amount of devices	100s per cell	1000s per cell (target ~35000)
Battery lifetime	Re-charge whenever a socket is available!	In the order of years

Some use cases

. © 2013 Vivante Corporation
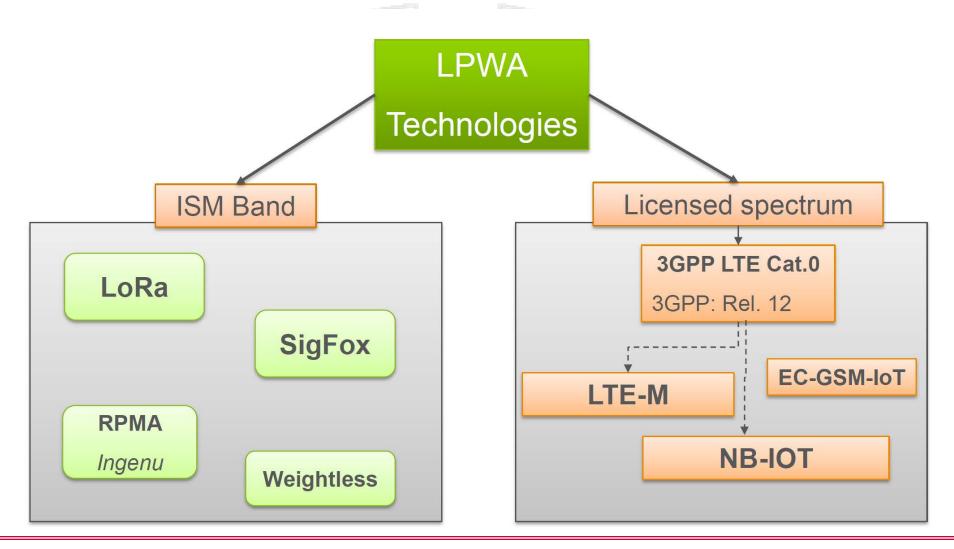
Low Power Wide Area (LPWA) networks

- Battery duration ~10 years
- Optimized for the transmission of brief messages
- Low module cost (<5$)
- Coverage in the order of 10s of km for a cell
- Outdoor, indoor, deep-indoor, underground coverage
- High link budget with narrowband modulation
- "Short" time-to-market
- Support very huge number of devices (massive MTC - mMTC)
- End-to-end secure connectivity (application authentication)

Licensed or ISM?

LPWA Technologies

ISM Band
- LoRa
- SigFox
- RPMA *Ingenu*
- Weightless

Licensed spectrum
- 3GPP LTE Cat.0 — 3GPP: Rel. 12
- LTE-M
- EC-GSM-IoT
- NB-IOT

Comparison of LPWA technologies

Feature	LORAWAN	SIGFOX	LTE Cat 1	LTE M	NB - LTE
Modulation	SS chip	UNB / GFSK / BPSK	OFDMA	OFDMA	OFDMA
Rx Bandwith	500 – 125 KHz	100 Hz	20 MHz	20 – 1.4 MHz	200 KHz
Data Rate	290bps – 50Kbps	100 bit / sec 12 / 8 bytes Max	10 Mbit /sec	200 kbps – 1 Mbps	Average 20K bit / sec
Max. # Msgs/day	Unlimited	UL: 140 msgs / day	Unlimited	Unlimited	Unlimited
Max Outpu Power	20 dBm	20 dBm	23 – 46 dBm	23/30 dBm	20 dBm
Link Budget	154 dB	151 dB	130 dB+	146 dB	150 dB
Battery lifetime – 2000 mAh	105 months	90 months		18 months	
Power Efficiency	Very High	Very High	Low	Medium	Med high
Interference immunity	Very High	Low	Medium	Medium	Low
Coexistence	Yes	No	Yes	Yes	No
Security	Yes	No	Yes Oui	Yes	Yes
Mobility / localization	Yes	Limited mobility, No localization	Mobility	Mobility	Limited mobility, No localization

Source: LoRAWAN Alliance, 2015

www.vertical-m2m.com

Cellular IoT

- The idea is to provide connectivity to IoT devices via cellular networks

- Ad-hoc radio interfaces tailored for IoT requirements

- Exploitation of the _same physical layer_ technique as current cellular technologies, to guarantee a deployment via software update of _currently deployed_ base stations

- Re-utilization of the core network and already available cellular coverage

- **EC-GSM-IoT** (Enhancement of EGPRS)

- **LTE-M** (Enhancement of LTE with extended power saving modes)

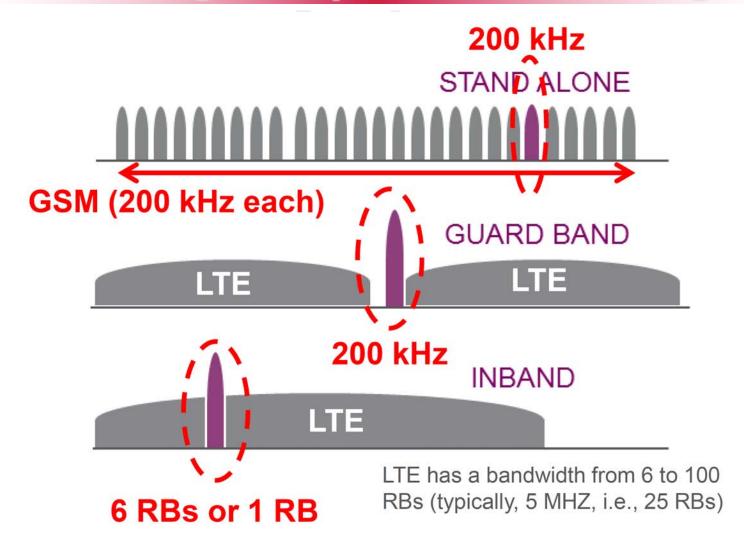- **NB-IoT** (New radio added tailored for low-end market)

From LTE to 'cellular' IoT

- Lower cost of modules and installation
  - Re-using available spectrum and "technologies"
  - Simplified transmission/reception hardware
  - "Reducing" UE capabilities (e.g., no need for 16/64-QAM)

- Extended coverage: IoT devices can be deployed outdoor, indoor, deep indoor, underground
  - Reducing sub-carrier spacing (smaller bandwidth increases robustness of the signal), Repetitions

- Lower energy consumption
  - Difficulties (i.e., high-cost) in replacing the battery of 1000s of devices, especially for those in challenging location
  - Introducing new classes of UEs with lower transmission power
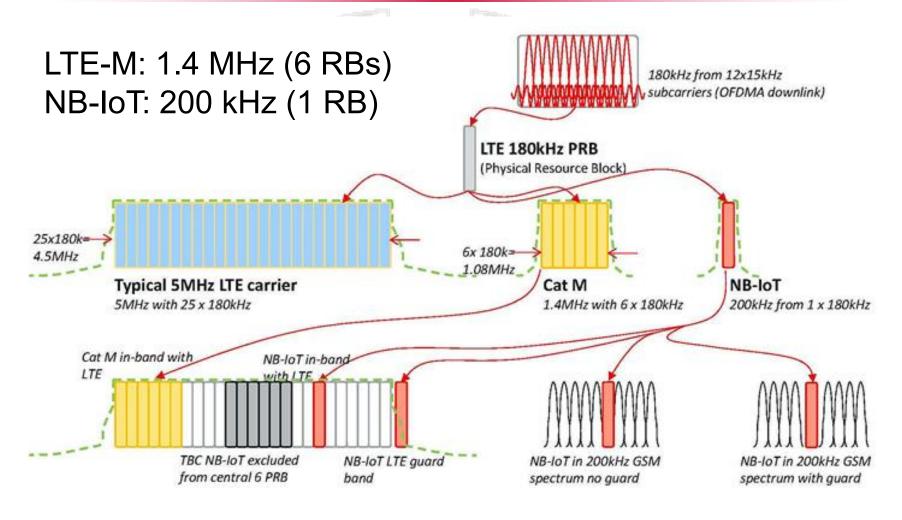 - Allowing devices to sleep by idle/connected management

200 kHz
STAND ALONE

GSM (200 kHz each)
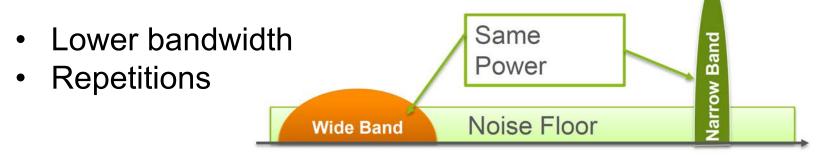
GUARD BAND

LTE   LTE

200 kHz
INBAND

LTE

6 RBs or 1 RB

LTE has a bandwidth from 6 to 100 RBs (typically, 5 MHZ, i.e., 25 RBs)

Deployment of LTE-M and NB-IoT
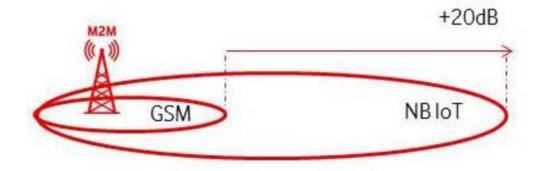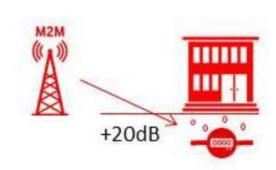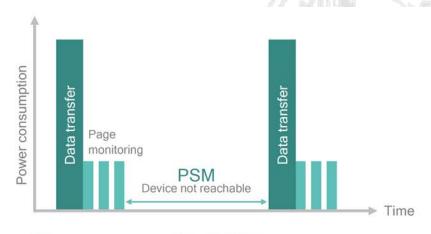
LTE-M: 1.4 MHz (6 RBs)
NB-IoT: 200 kHz (1 RB)

Extended coverage

- Lower bandwidth
- Repetitions

Lower energy consumption

- Devices wake up on a per-need basis
  - stay asleep for minutes, hours, even days
- Reduced complexity and less channel measurements

Power save mode (PSM)
Eliminates page monitoring between data transmissions

Extended discontinuous receive (eDRx)
Extends time between monitoring for network messages

LTE-M vs NB-IoT

	eMTC (LTE Cat M1)	NB-IOT
Deployment	In-band LTE	In-band & Guard-band LTE, standalone
Coverage*	155.7 dB	164 dB for standalone, FFS others
Downlink	OFDMA, 15 KHz tone spacing, Turbo Code, 16 QAM, 1 Rx	OFDMA, 15 KHz tone spacing, TBCC, 1 Rx
Uplink	SC-FDMA, 15 KHz tone spacing Turbo code, 16 QAM	Single tone, 15 KHz and 3.75 KHz spacing SC-FDMA, 15 KHz tone spacing, Turbo code
Bandwidth	1.08 MHz	180 KHz
Peak rate (DL/UL)	1 Mbps for DL and UL	DL: ~250 kbps UL: ~250 for multi-tone, ~20 kbps for single tone
Duplexing	FD & HD (type B), FDD & TDD	HD (type B), FDD
Power saving	PSM, ext. I-DRX, C-DRX	PSM, ext. I-DRX, C-DRX
Power class	23 dBm, 20 dBm	23 dBm, others TBD

Coverage measure as Maximum Coupling Loss

Dino Flore, "3GPP standards for Internet of Things," Feb. 2016
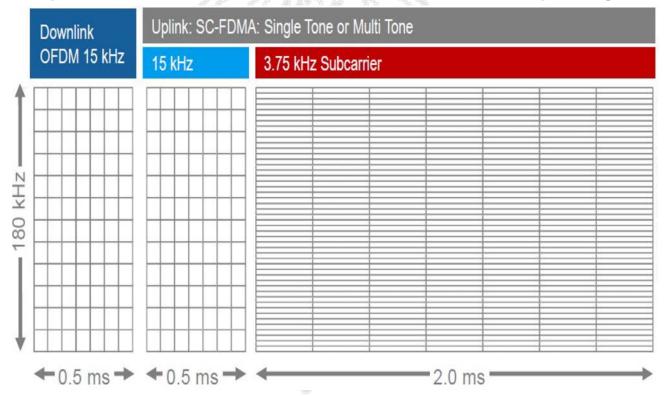
Main characteristics of NB-IoT

- Very narrowband: 180 kHz
  - In-band, guard-band, stand-alone
- Extended coverage: 164 dB link budget to be compared to 144dB of GPRS and 142.7 dB of LTE
- Long battery life: 10 years (depending on traffic)
- Massive number of devices: at least 50.000 per cell
- Reuses the LTE design extensively:
  - numerologies, DL OFDMA, UL SC-FDMA,
  - channel coding, rate matching, interleaving,
  - etc.
- NB-IoT products for existing LTE equipment and software vendors

NB-IoT transmission modes

- Supports two modes for uplink
  - Single tone with 15 kHz and/or 3.75 kHz tone spacing
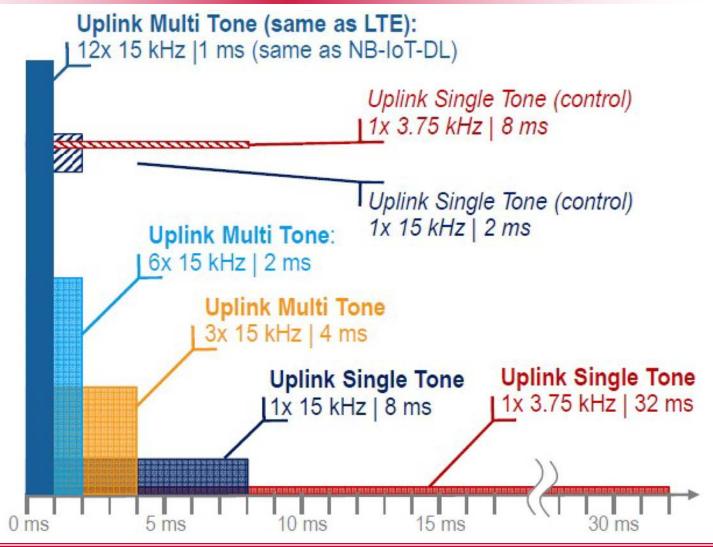 - Multiple tone transmissions with 15 kHz tone spacing

Transmission band and delays
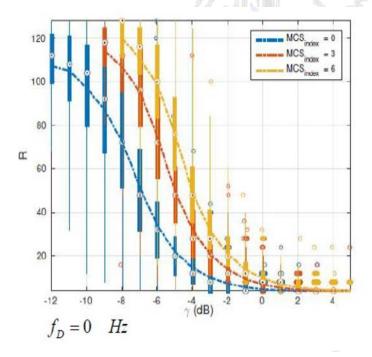
Repetitions and tx parameters

- Repetitions in NB-IoTare introduced to have different coverage classes
  - Variable number of repetitions: 1, 2, 4, 8, ….
  - Up to 128 (UL) and 2048 (DL)

- NB-IoT defines three coverage classes
  - **Normal** (outdoor, MCL 144db), **Robust** (outdoor, MCL 154db), **Extreme** (deep indoor/underground, MCL 164db)
  - Each channel is repeated a number of times equal to the number of repetitions of the coverage class the channel is associated to

- Transmission parameters
  - MTU Size: 1500B
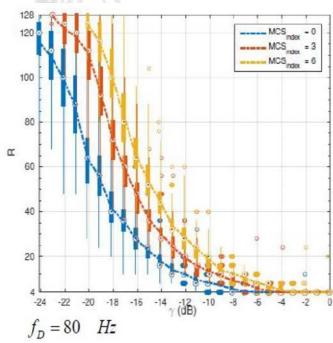 - Maximum Transport Block Size: 680 DL, 1000 UL (Rel. 13)
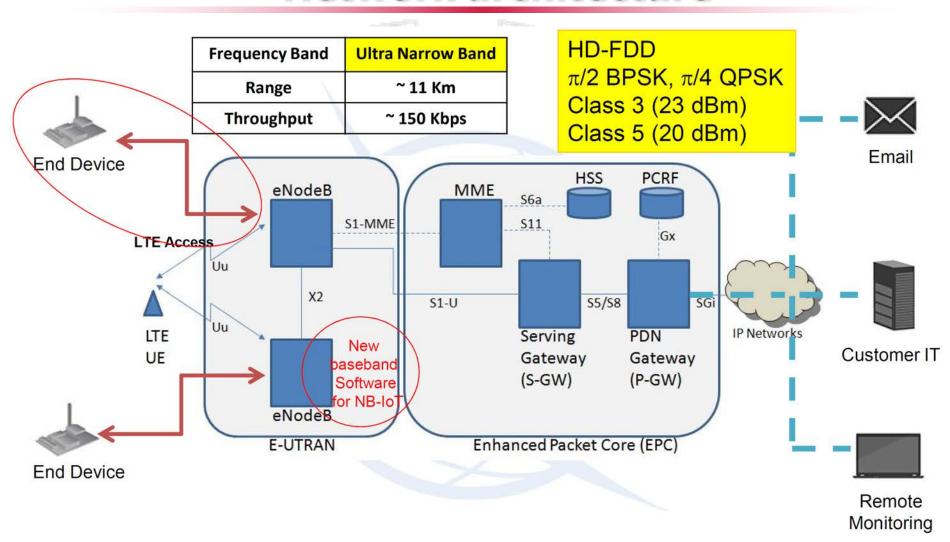
Performance

- **Repetitions achieve extra coverage (up to 20 dB compared to GPRS)**
  - Each repetition is self-decodable
  - SC is changed for each transmission to help combination
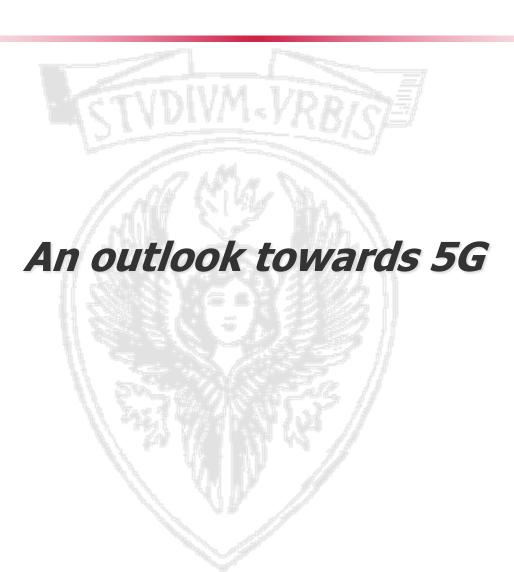
Network architecture

Frequency Band	Ultra Narrow Band
Range	~ 11 Km
Throughput	~ 150 Kbps

HD-FDD
$\pi/2$ BPSK, $\pi/4$ QPSK
Class 3 (23 dBm)
Class 5 (20 dBm)

End Device

LTE Access

LTE UE

eNodeB

Uu

X2

Uu

New baseband Software for NB-IoT

eNodeB

E-UTRAN

End Device

S1-MME

S1-U

MME

S6a

S11

HSS

PCRF

Gx

S5/S8

Serving Gateway (S-GW)

PDN Gateway (P-GW)

SGi

Enhanced Packet Core (EPC)

IP Networks

Email

Customer IT

Remote Monitoring

An outlook towards 5G

4G Networks
- Access Site — LTE RAN
- Edge Site
- Central Site — EPC Core — Apps/Contents

- Centralized Architectures
- VNF/SDN/MANO Adoption
- NW Slices emerge(IoT)

5G Networks
- Multi Access
- Apps/Contents Distribution/Local
- NW Slices — Apps/Contents
- 5G Core
- RAN Functions Centralization
- Core User Plane Distribution

- Functional Decomposition
- RAN/Core/Apps move to Edge
- VNF/SDN/MANO as a foundation
- NW Slicing enabling new use cases
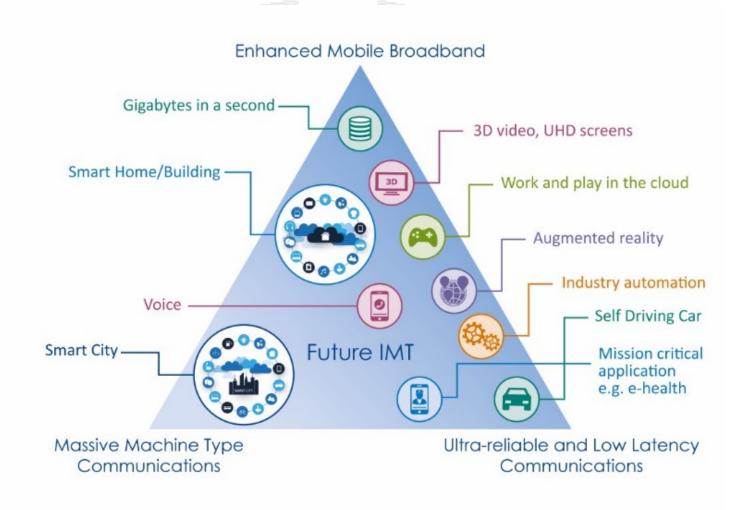- Multi Access(NR/eLTE, Non 3GPP, Unlicenced, Fixed)

5G Architecture

The 5G triangle

5G Performances

- Peak data rate ≥ 10Gbps,
- Minimum guaranteed user data rate ≥ 100Mbps,
- Connection density ≥ 1M connections/ km^2,
- Traffic density ≥ 10 Tbps/ km^2 ,
- Radio latency ≤ 1 ms,
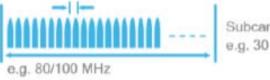- E2E latency ≤ 10 ms,
- Mobility up to 500km/h.

Scalable OFDM

- 5G requires scalable OFDM subcarrier spacing to support diverse spectrum bands and deployment models

Outdoor and macro coverage FDD/TDD <3 GHz		Subcarrier spacing e.g. 15 kHz
	e.g. 1, 5, 10 and 20 MHz	
Outdoor and small cell TDD > 3 GHz		Subcarrier spacing e.g. 30 kHz
	e.g. 80/100 MHz	
Indoor wideband TDD e.g. 5 GHz (Unlicensed)		Subcarrier spacing e.g. 60 kHz
	e.g. 160MHz	
mmWave TDD e.g. 28 GHz	Subcarrier spacing, e.g. 120 kHz	
	e.g. 500MHz	
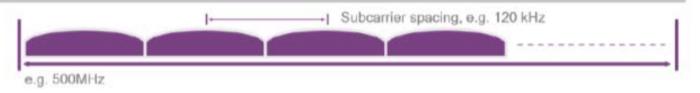
Conclusions

- 3GPP has been actively working to meet the requirements of the IoT over mobile networks

- New features to improve energy efficiency and coverage

- Performance achieved by NB-IoT strongly depends on the deployment scenario and configuration parameters
  - The higher the number of repetitions, the more reliable the communication but the lower the spectral efficiency
  - Optimization between thresholds for the different coverage classes, number of repetitions, number of sub-carriers needed

- Several countries have already NB-IoT available!
  - 90 of those operators in 51 countries (March 2019)

- SigFox, LoRa, NB-IoT, LTE-M, etc. are complementary

- *Costs??*

Thank you!
Questions?