

OFDMA and applications to IoT

a.a. 2019/2020

University of Rome "La Sapienza"

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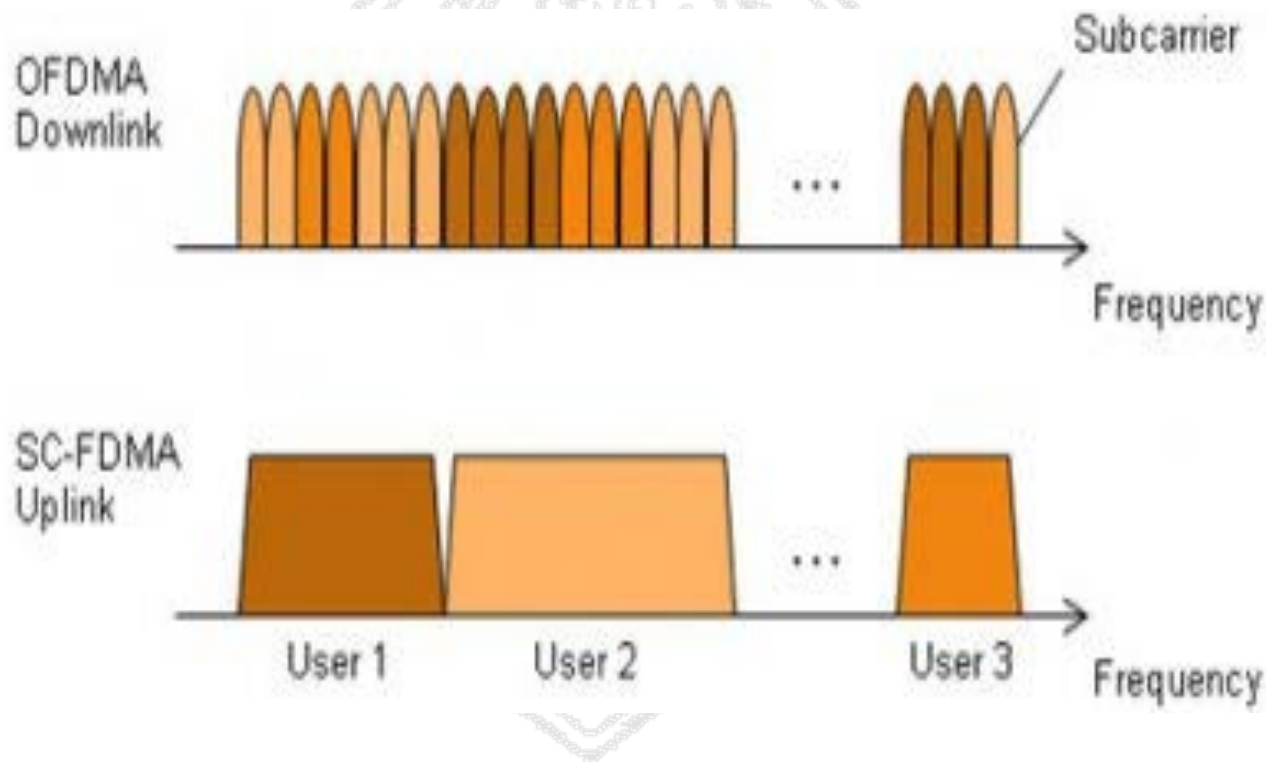
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Slides partly by Ilenia Tinnirello, Massimo Condoluci, Sami Tabbane, et al.



OFDM by example

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



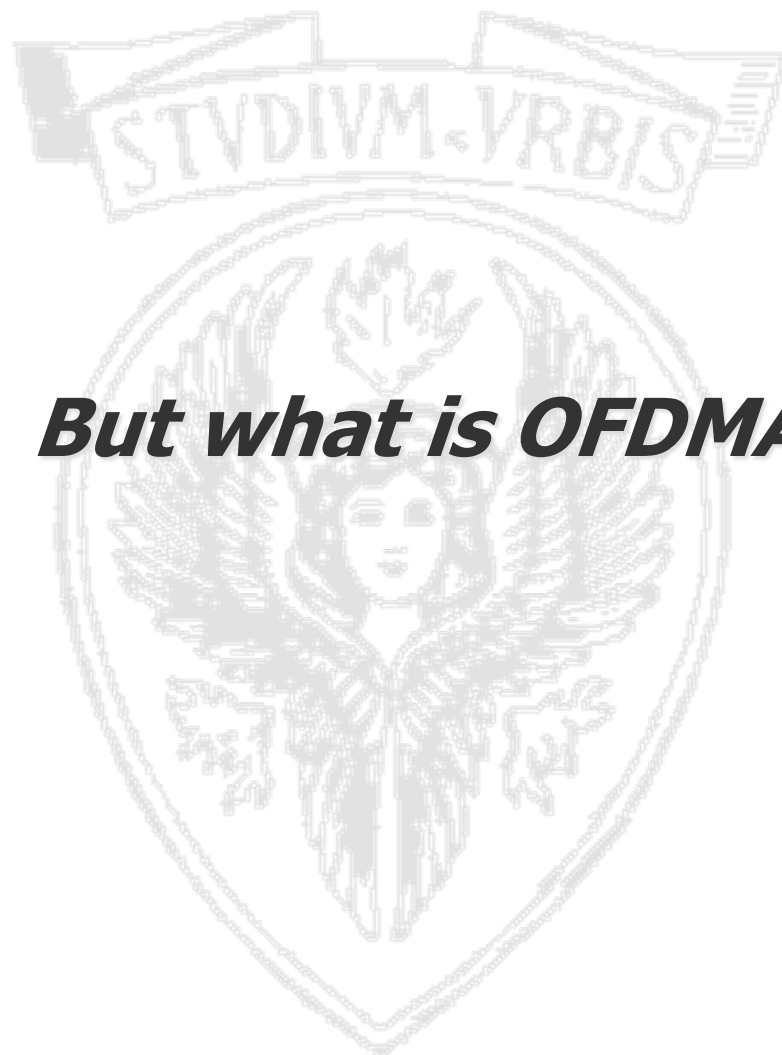


Single Carrier FDMA (SC-FDMA)

- 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



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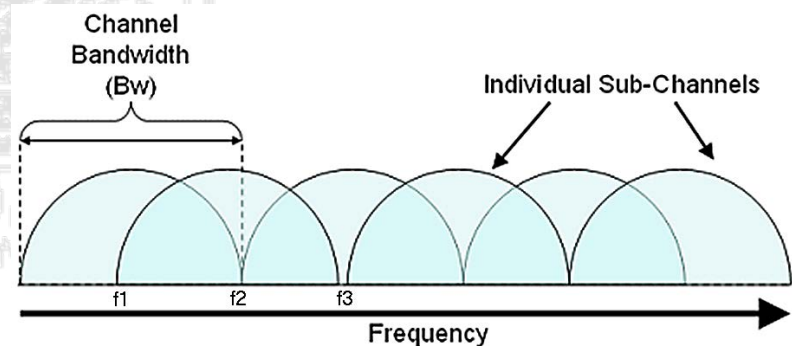
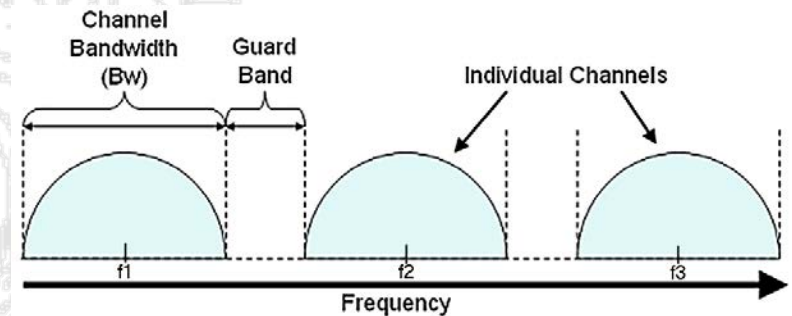
But what is OFDMA?



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:

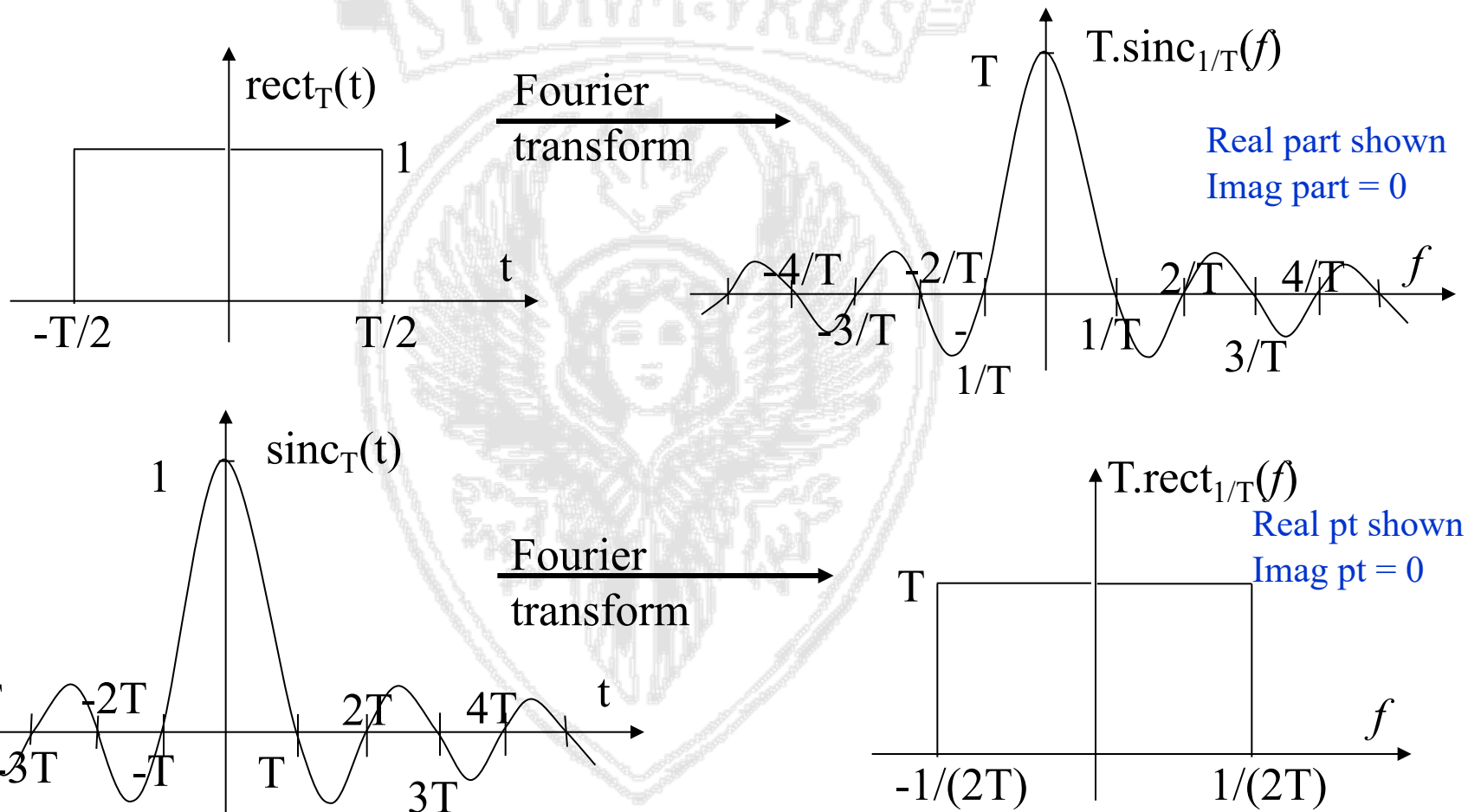
$$f_k = k \cdot \Delta f \text{ where } \Delta f = 1/T_U$$
(T_U is the symbol period)
 - Carriers are orthogonal to each other and can be packed tight





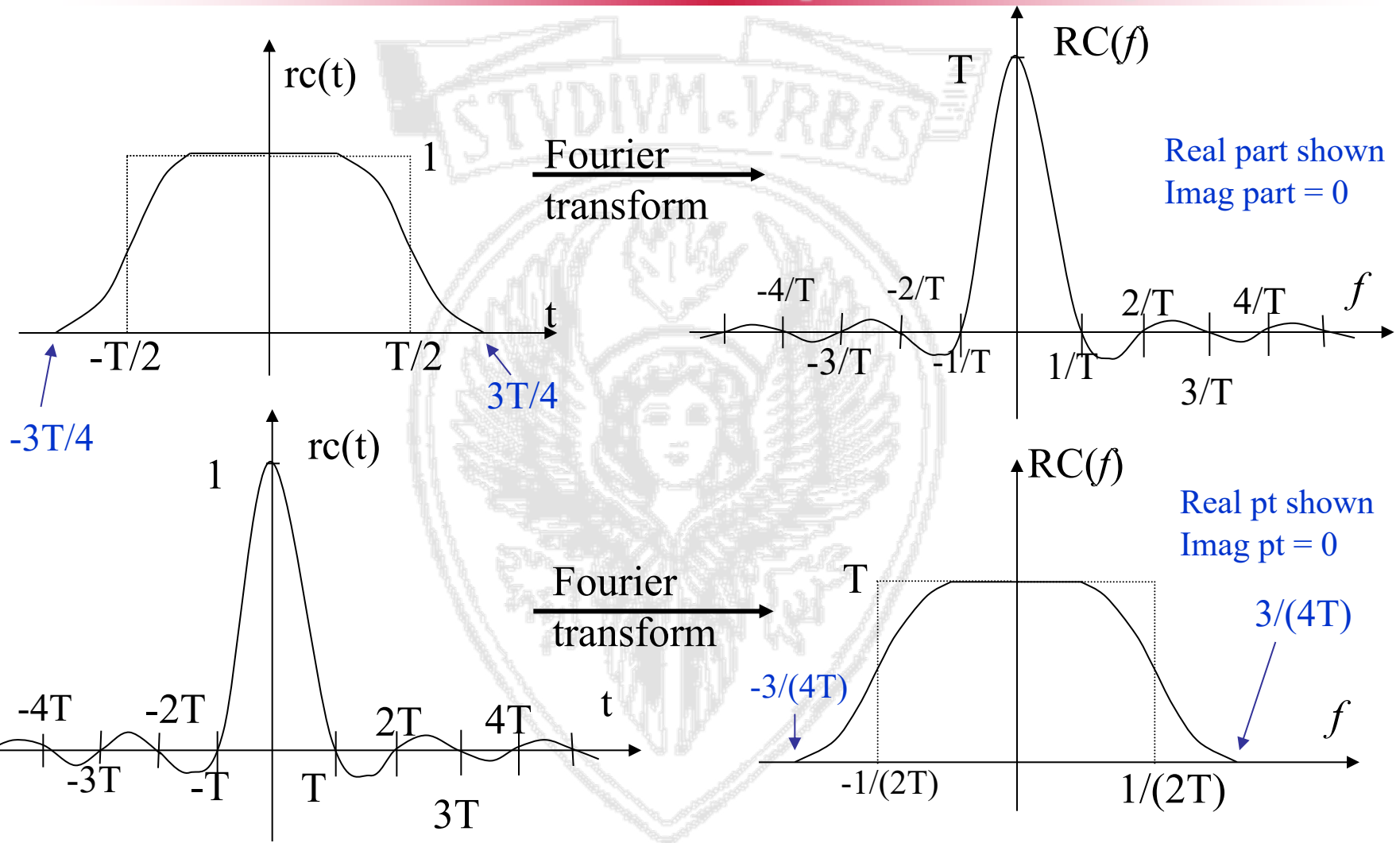
Spectra of rect & sinc pulses

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





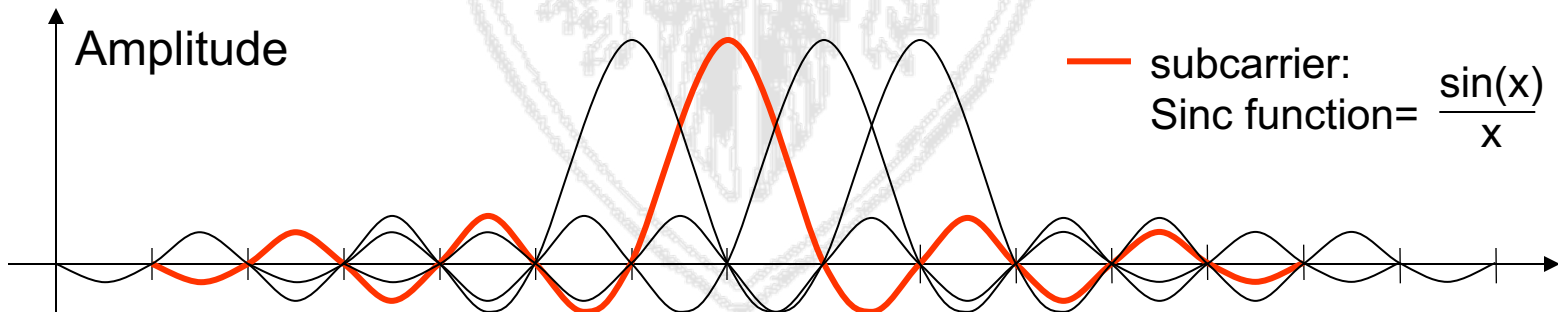
50% Raised Cosine pulses & spectra





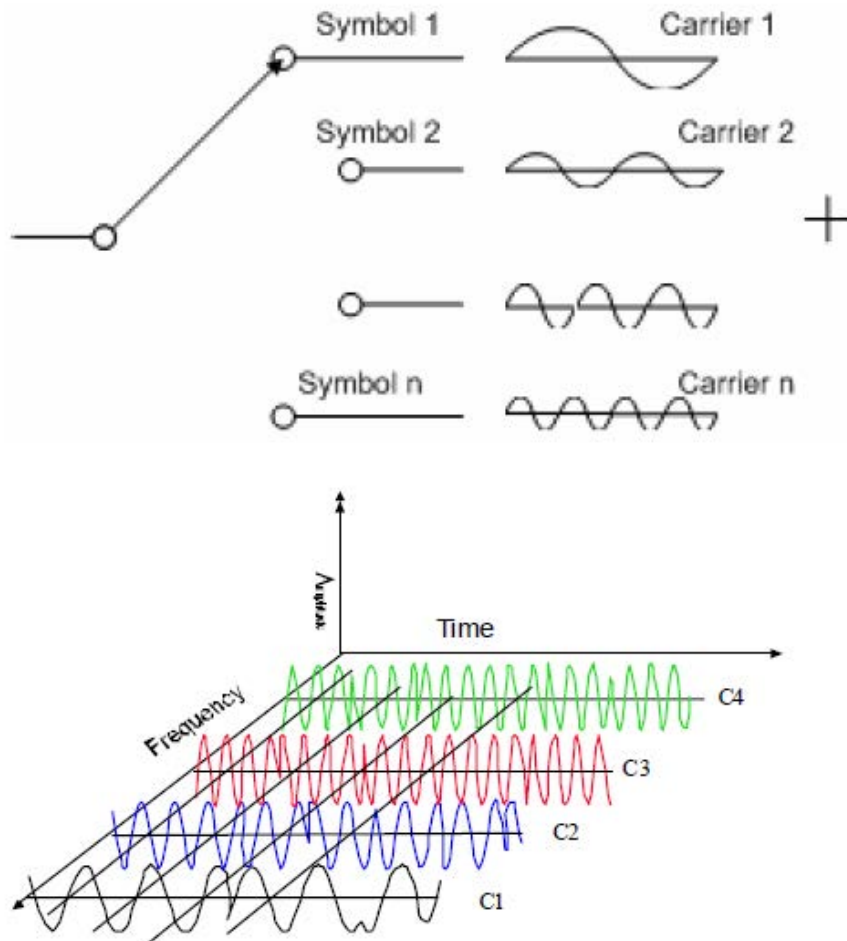
Sub-band spectral interference (ICI)

- 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.





How does OFDM work?

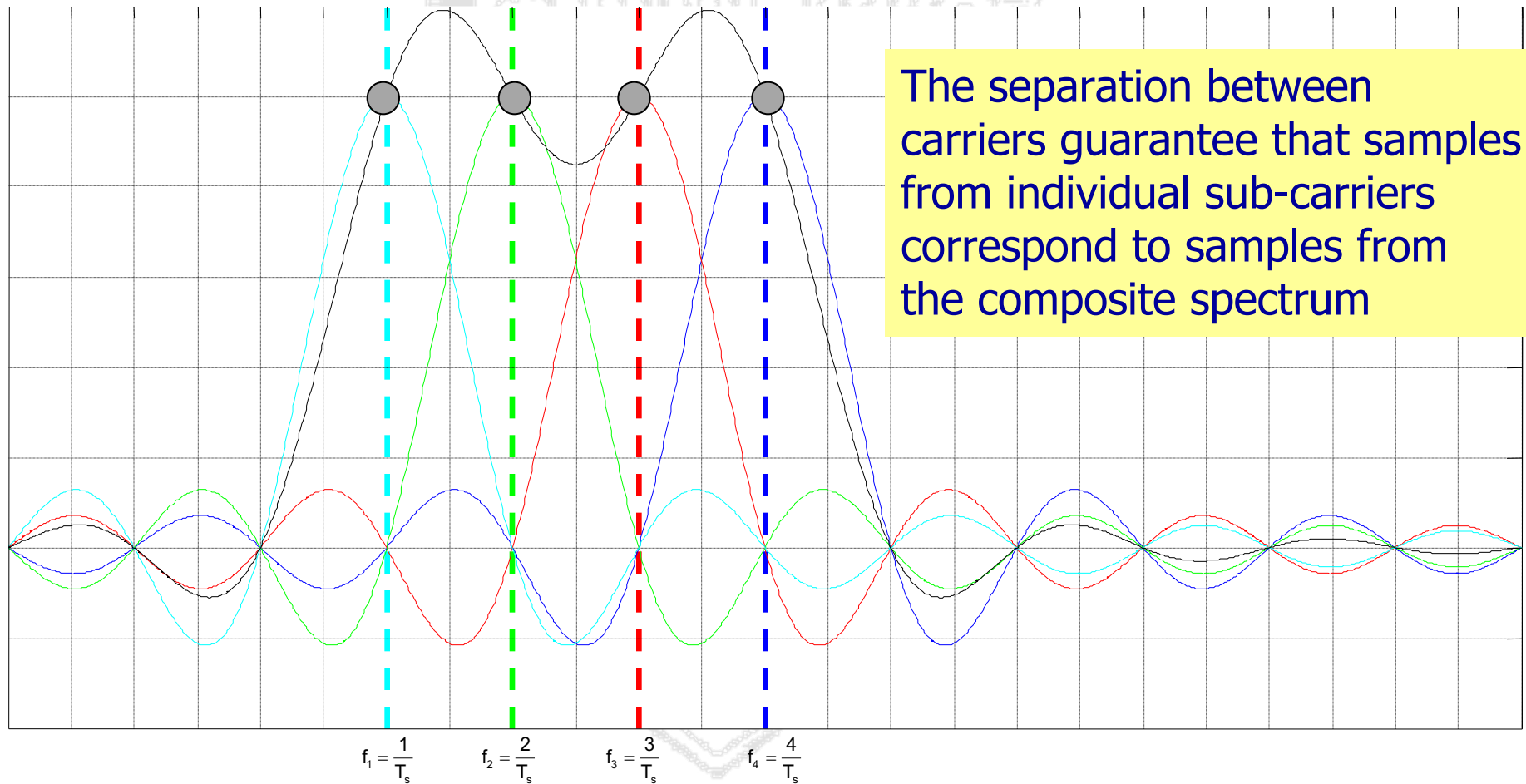


- In principle, similar to CDMA with orthogonal codes!
- Each modulated sub-carrier is 'orthogonal', which means that they do not interfere with each other
- Highly efficient because sub-carriers are as close as they can possibly be



OFDM signal example

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



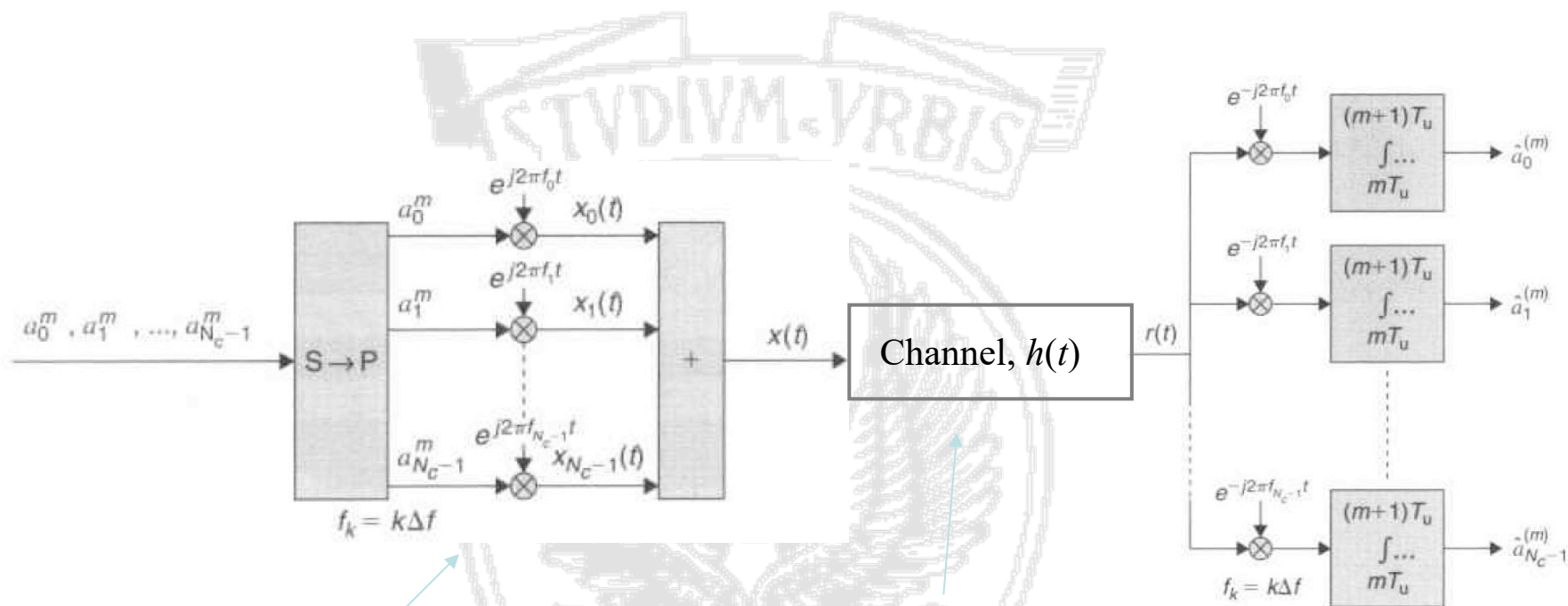


Use of sub-carriers

- Bit-rate using N sub-channels is $1/N$ of total bit-rate
- Zero-crossings of sinc spectra (at $\pm 1/T, \pm 2/T, \dots$) 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)



OFDM Transmission model



Modulator
and transmitter

Wireless channel

Receiver and demodulator



Orthogonality – the essential property

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

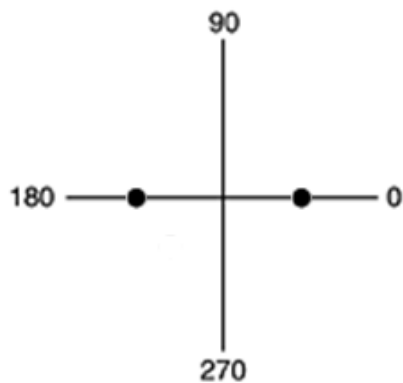
$$\frac{1}{T_U} \int_0^{T_U} \underbrace{\left(\sum_{q=0}^{N_c-1} a_q \cdot e^{j2\pi q \Delta f t} \right)}_{\text{Received signal, } r(t)} \cdot e^{-j2\pi k \Delta f t} dt = \sum_{q=0}^{N_c-1} \frac{a_q}{T_U} \int_0^{T_U} e^{j2\pi(q-k)\frac{1}{T_U} \cdot t} dt = \begin{cases} a_k, & k = q \\ 0, & k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

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

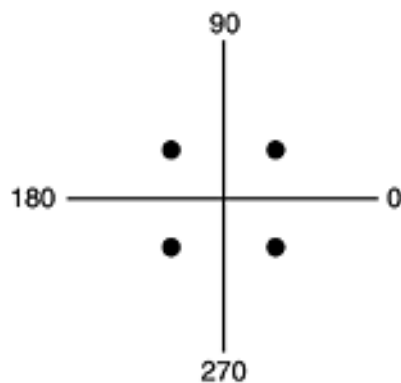


Modulation of sub-carriers

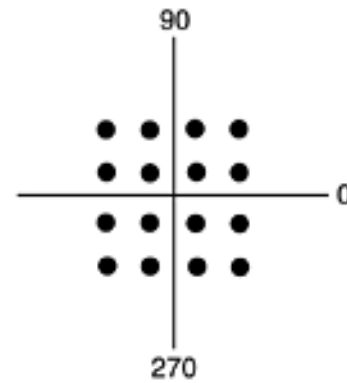
- Choice of or combination of amplitude or phase modulations, e.g.:
 - BPSK (Binary Phase Shift Keying) = 2 phase shifts, 1 amplitude level, 1 bit/symbol
 - QPSK (Quadrature Phase Shift Keying) = 4 phase shifts, 1 amplitude level, 2 bits/symbol
 - QAM-16 = 4 phase shifts, 4 amplitude levels, 4 bits/symbol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



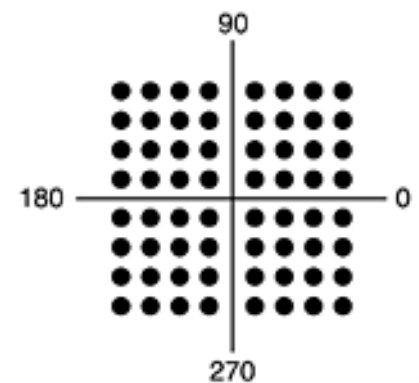
BPSK



QPSK



QAM-16



QAM-64



Example of OFDM

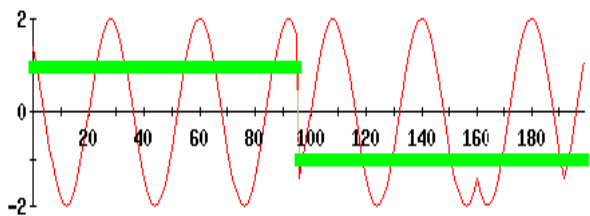
- Lets we have following information bits
 $1, 1, -1, -1, 1, 1, 1, -1, 1, -1, -1, -1, -1, 1, -1, -1, \dots$
- Just converts the serials bits to parallel bits

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

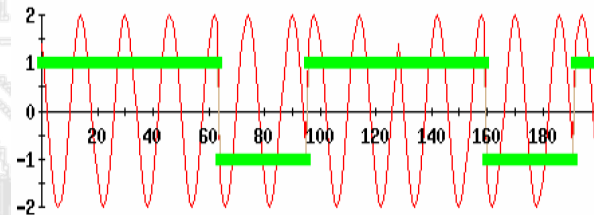


Example of OFDM cont..

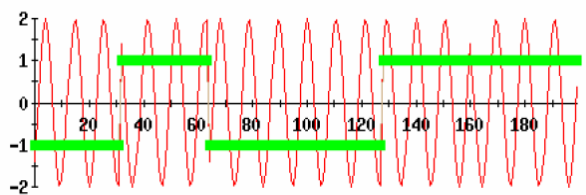
Modulate each column with corresponding sub-carrier using BPSK



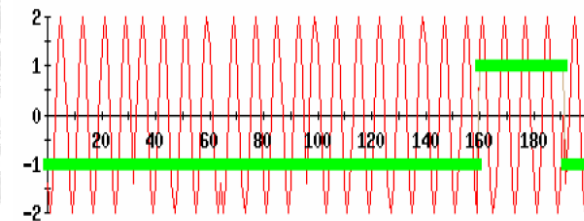
Modulated signal for C1



Modulated signal for C2



Modulated signal for C3



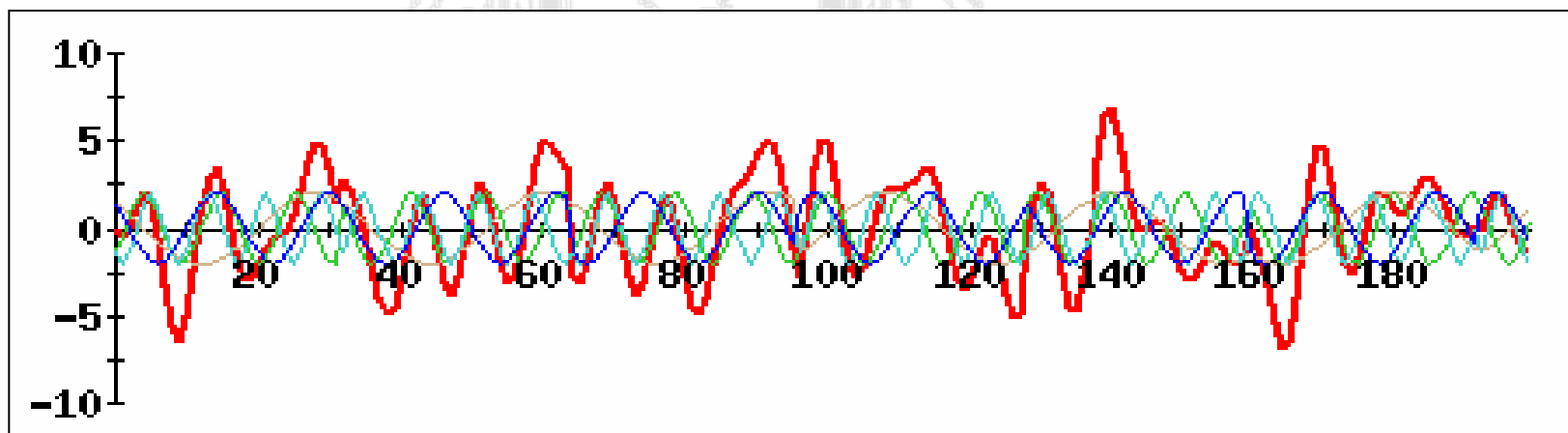
Modulated signal for C4



Example of OFDM cont..

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

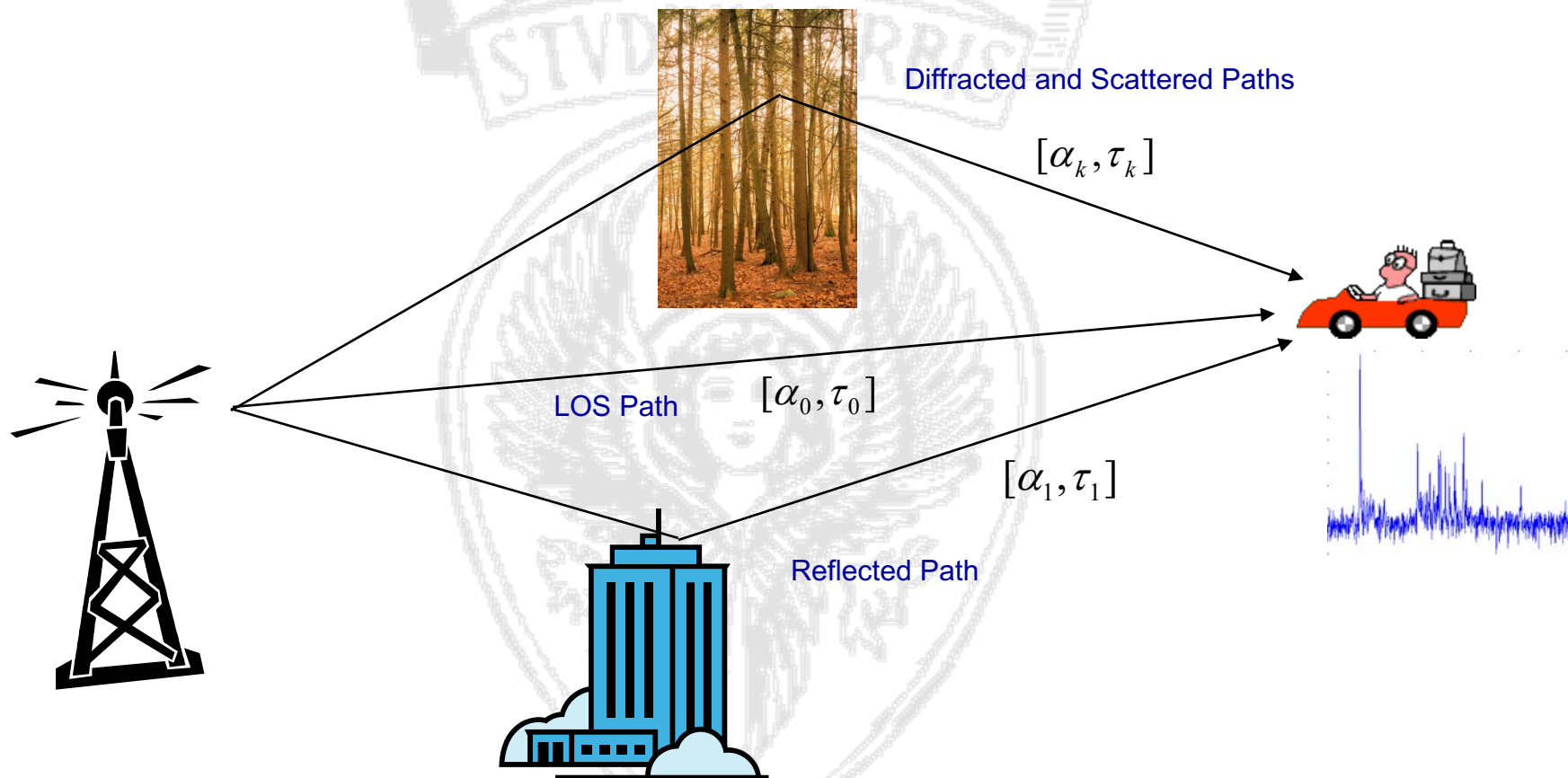
$$V(t) = \sum_{n=0}^{N-1} I_n(t) \sin(2\pi n t)$$



Generated OFDM signal, $V(t)$



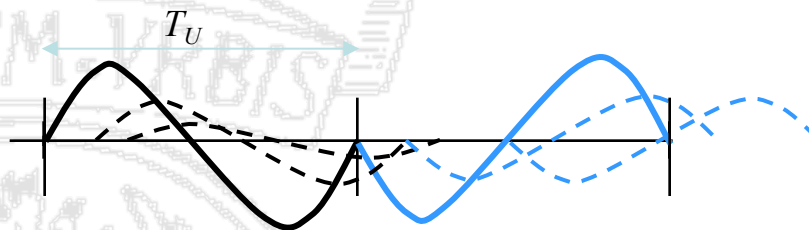
Multipath channel



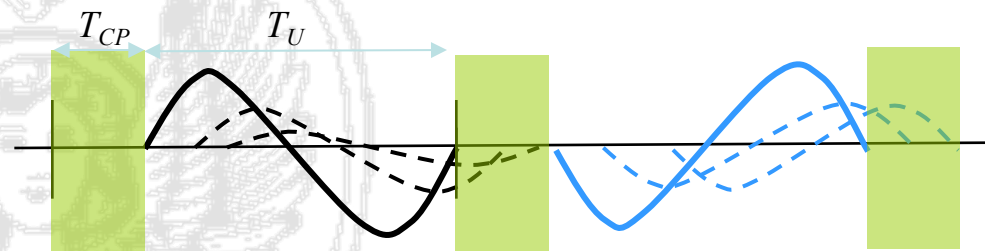


Multipath channel (cyclic prefix)

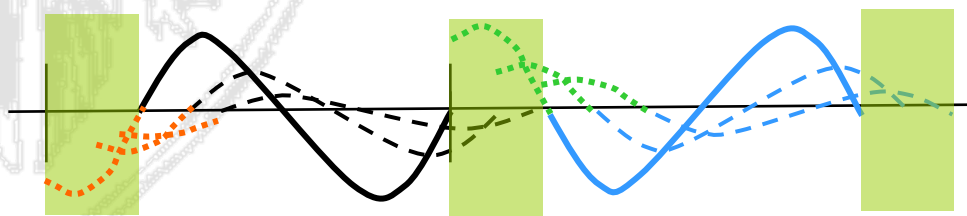
Multipath introduces *inter-symbol-interference* (ISI)



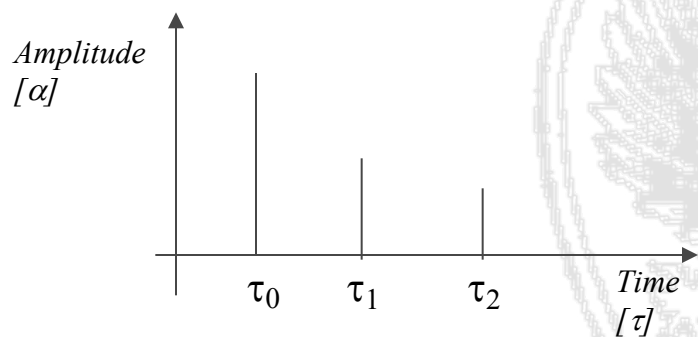
Prefix (guard time) is added to avoid ISI



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

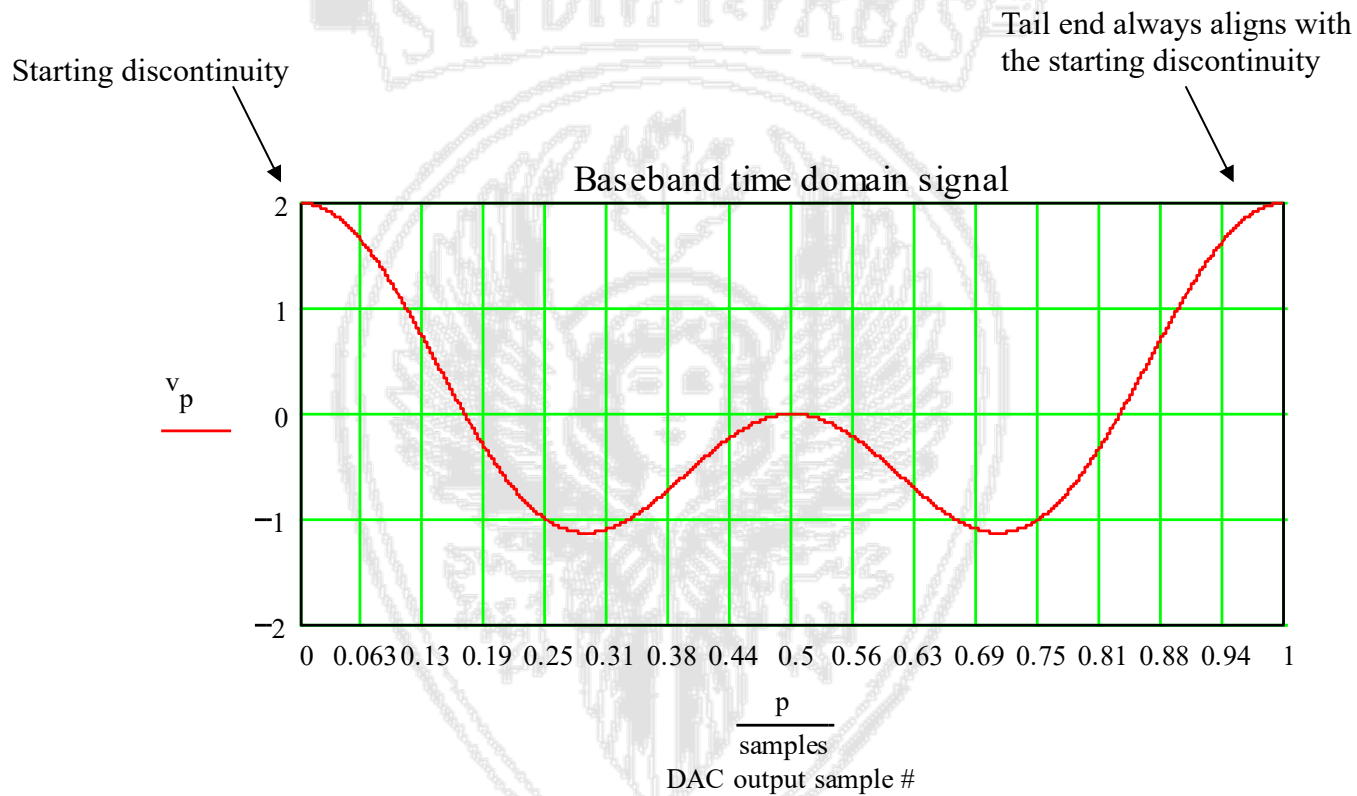


Example multipath profile





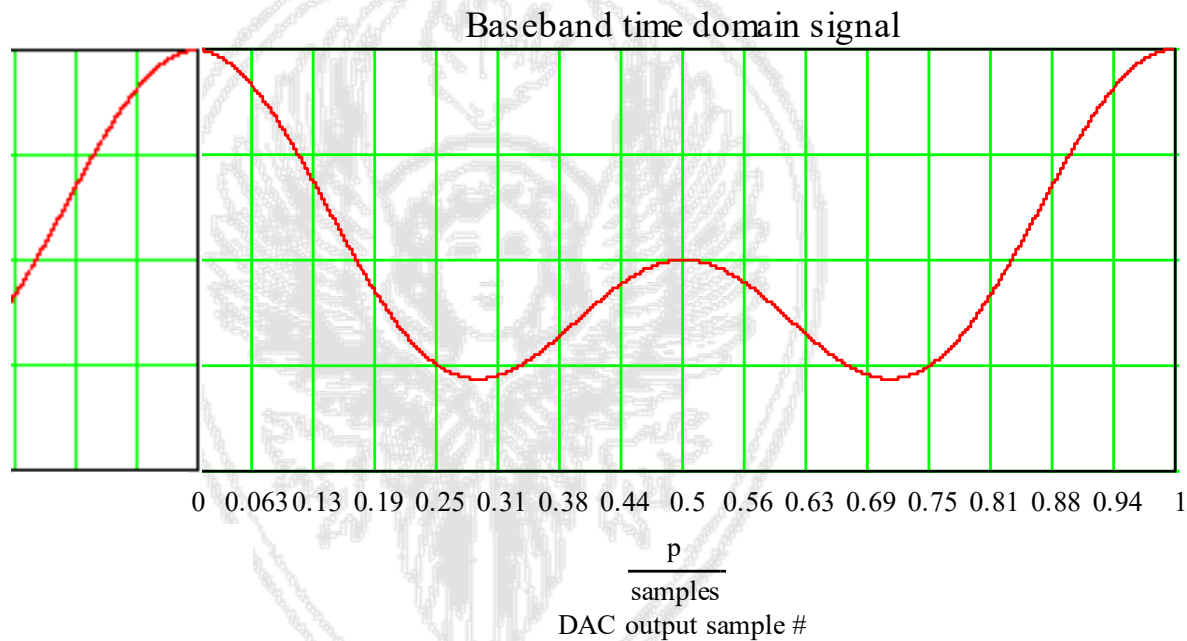
OFDM Cyclic Prefix





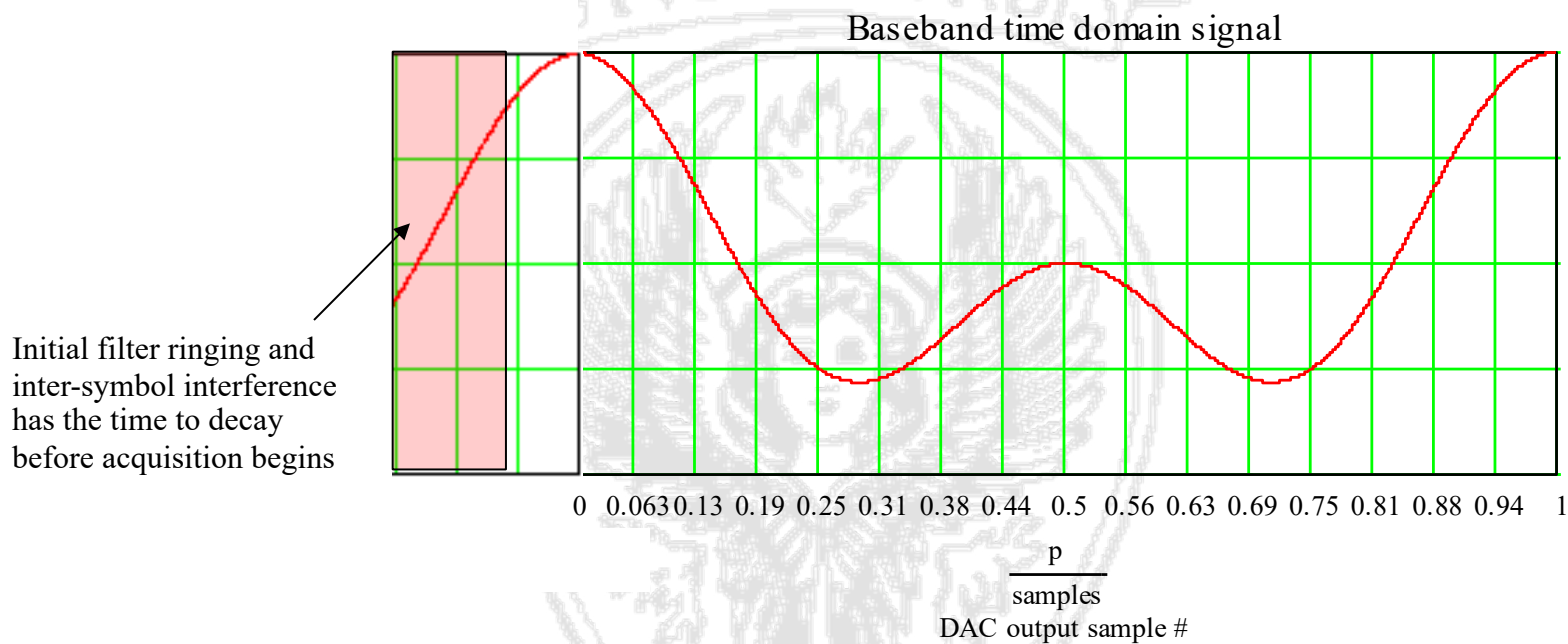
OFDM Cyclic Prefix

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



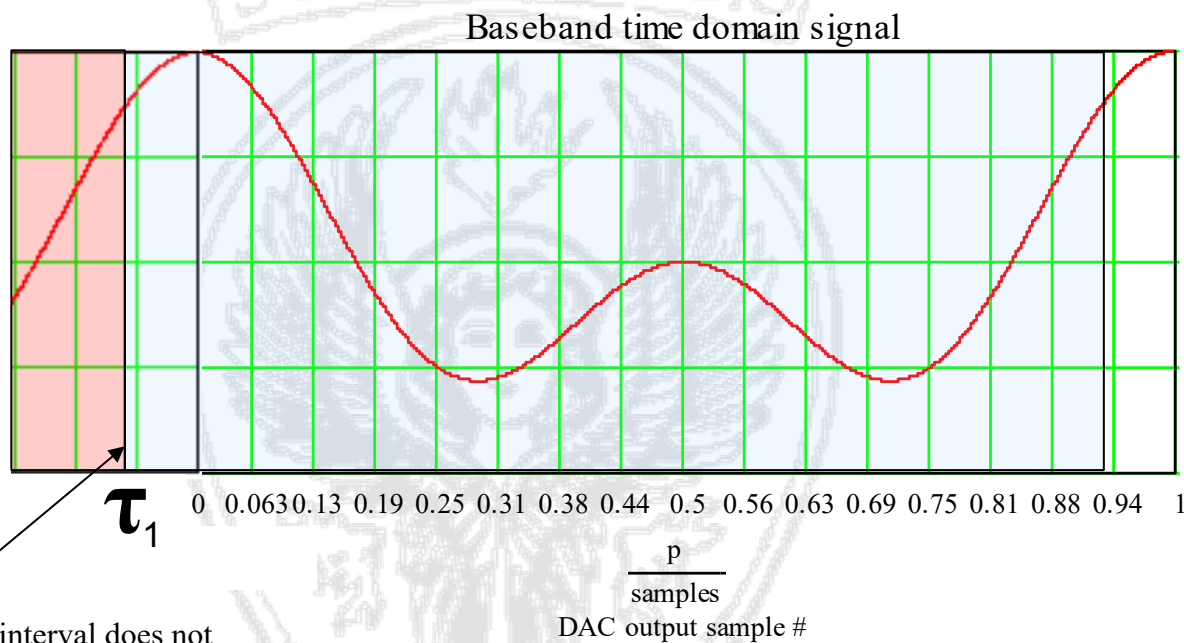


OFDM Cyclic Prefix





OFDM Cyclic Prefix

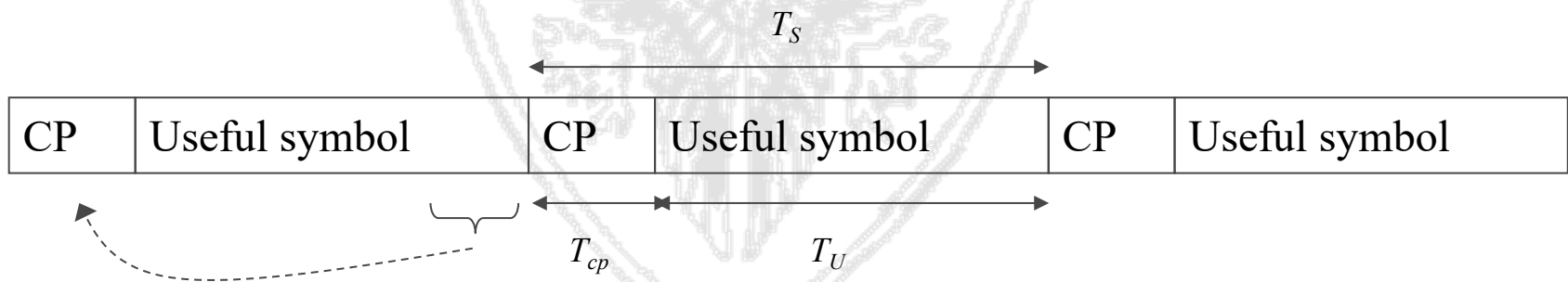


Signal acquisition interval does not have to be precisely aligned to get a valid orthogonal signal set



Cyclic Prefix length

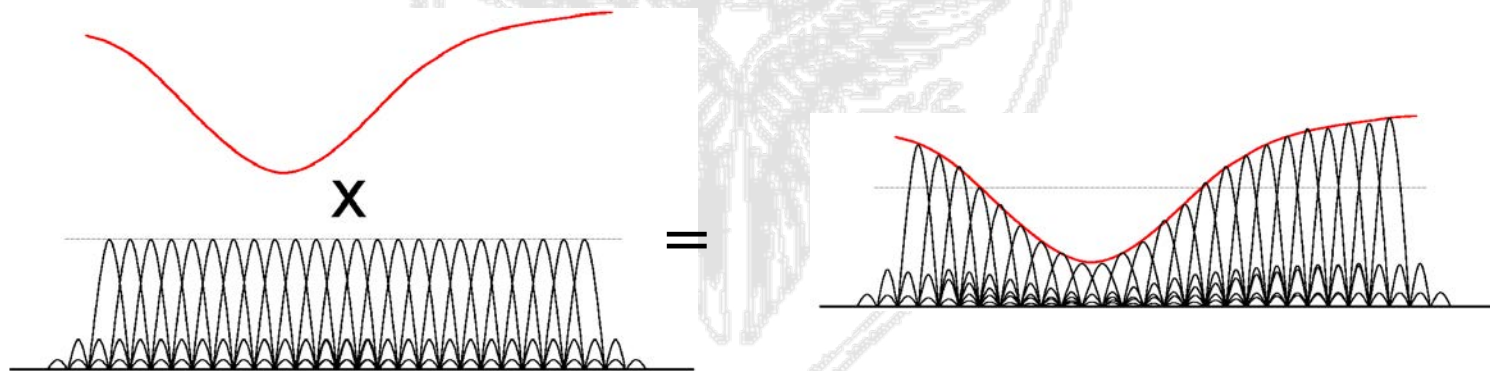
- T_{cp} should cover the maximum length of the time dispersion
- For example, assume $T_{cp} = 0.8 \mu\text{s}$. Since speed of radio waves $\approx 300 \times 10^6 \text{ m/s}$, this allows for a path-length difference of $0.8 \times 300 = 250 \text{ m}$.
- Increasing T_{cp} implies increased overhead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





Multipath channel (frequency diversity)

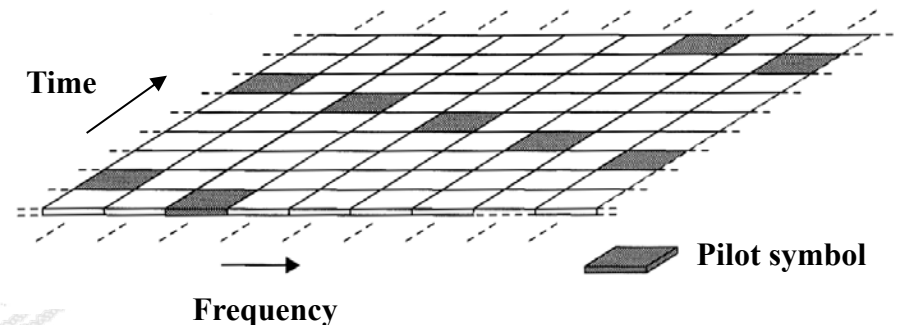
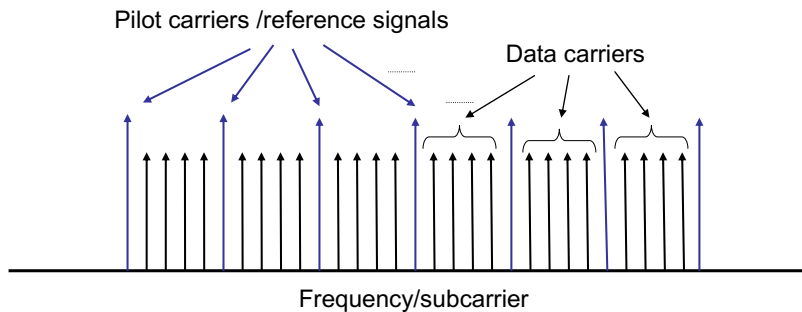
- The OFDM symbol can be exposed to a frequency selective channel
- The attenuation for each subcarrier can be viewed as “flat”
 - Due to the cyclic prefix there is no need for a complex equalizer
- Possible transmission techniques
 - *Forward error correction* (FEC) over the frequency band
 - Adaptive coding and modulation per carrier





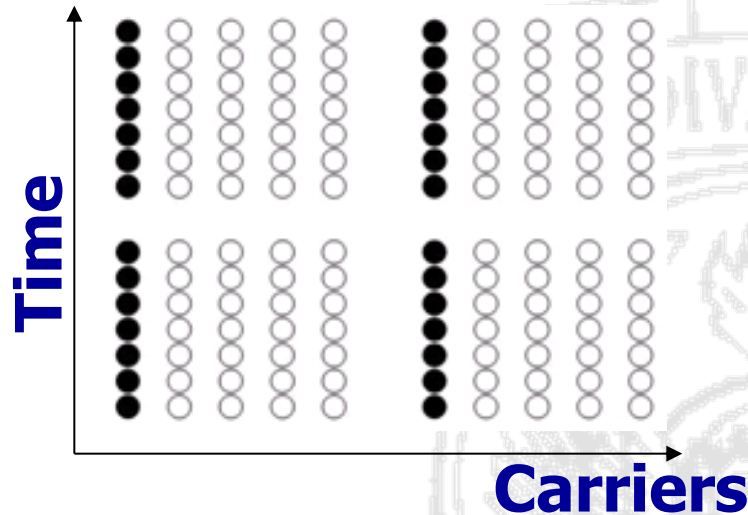
Multipath channel (pilot symbols)

- 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)*



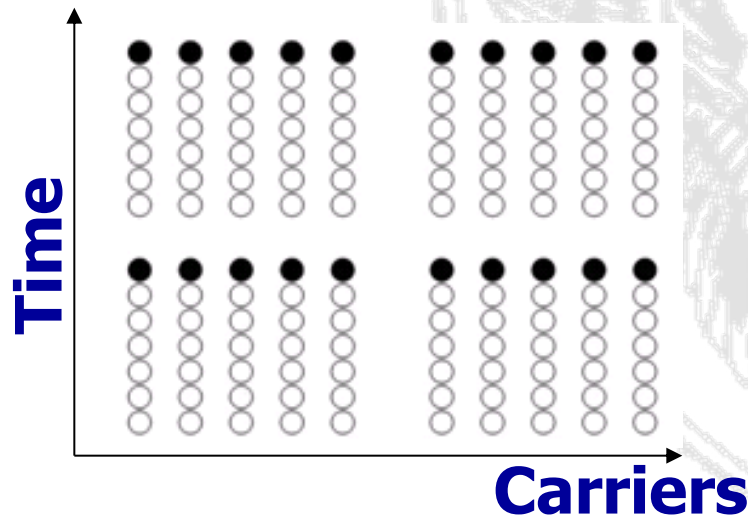


Pilots for Channel Estimation



Comb Type:

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



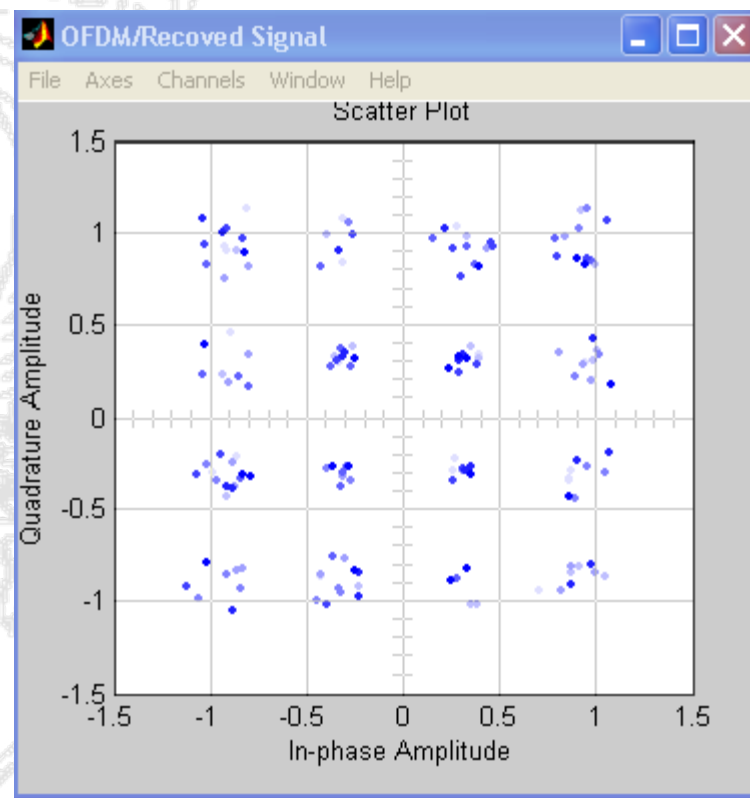
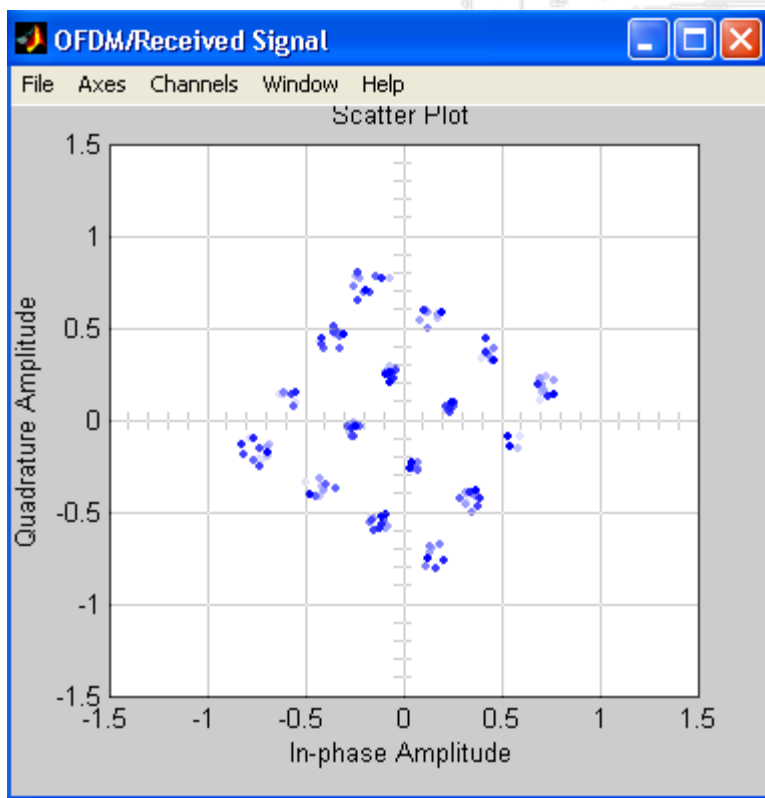
Block Type:

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



Received and Recovered Signals

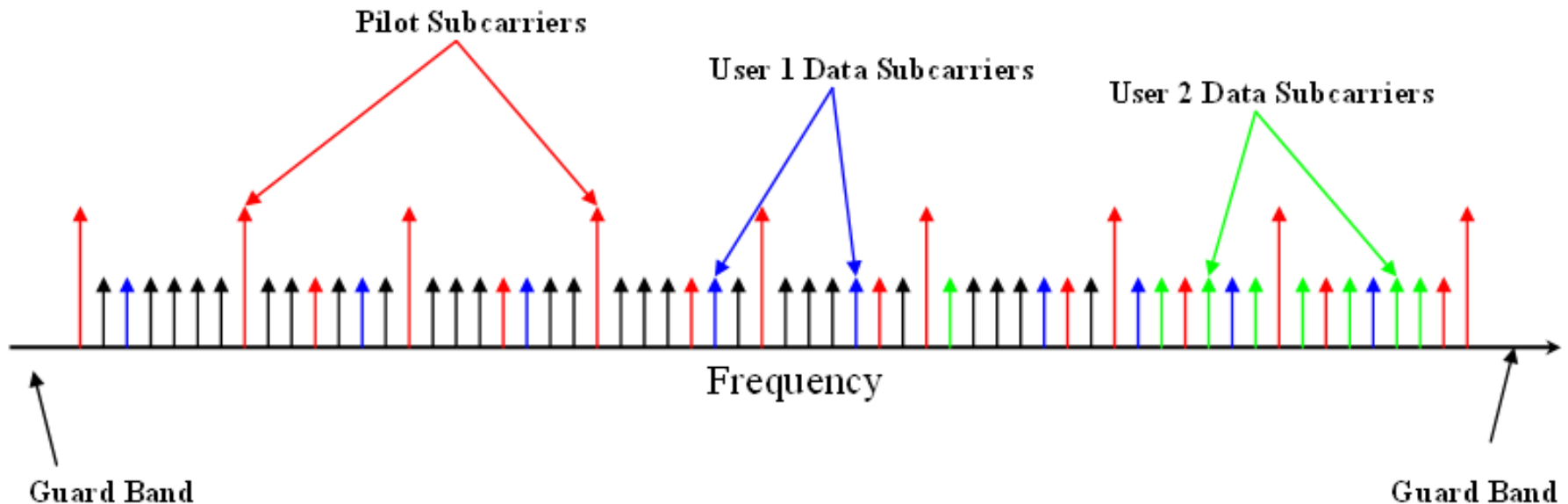
- Recovering signal phases distorted by multi-path fading





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.



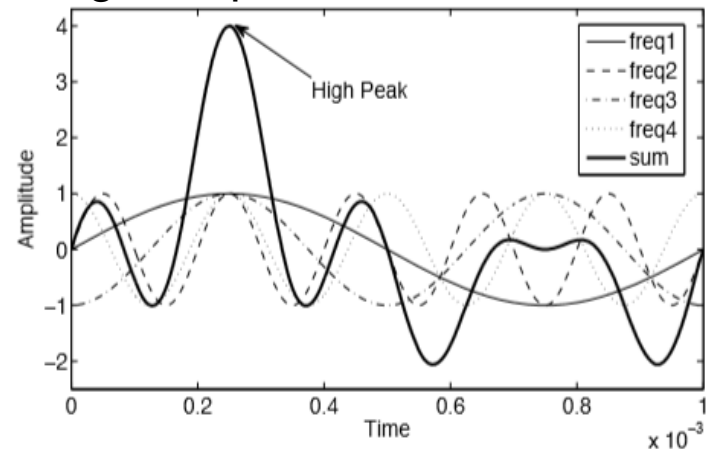


Problems of OFDMA

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.

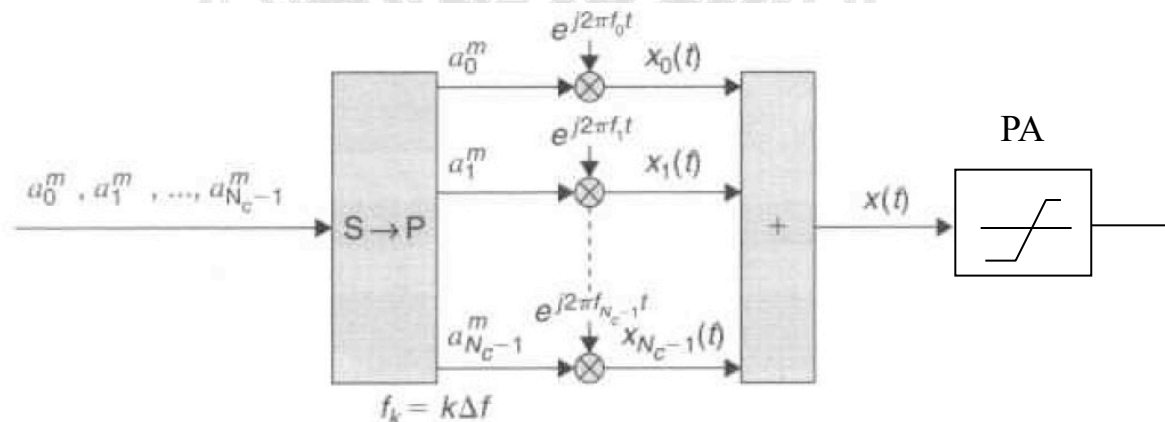


The Peak to Average Power Problem

- 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)

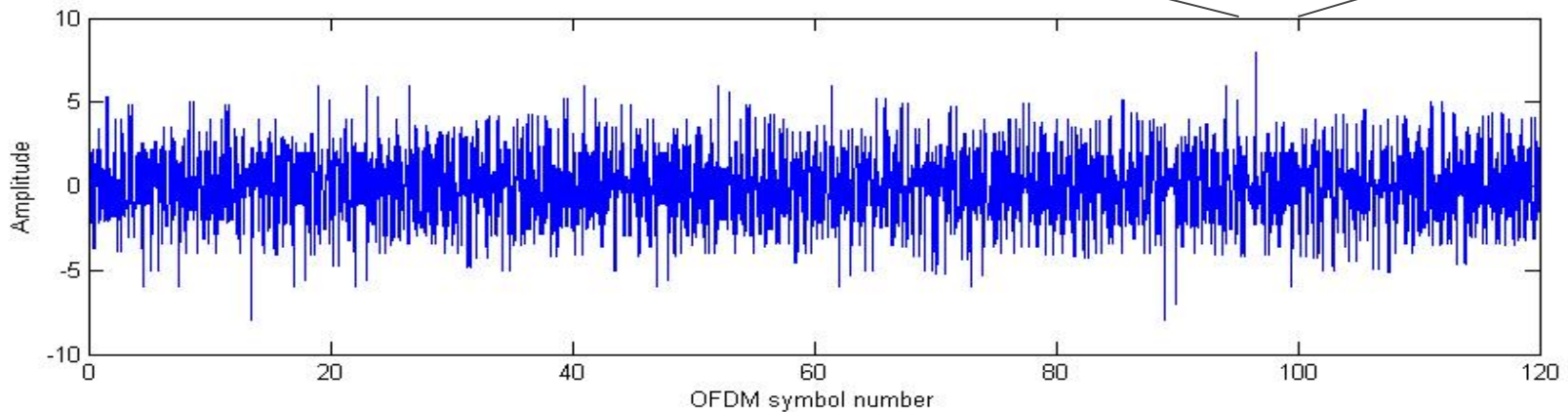
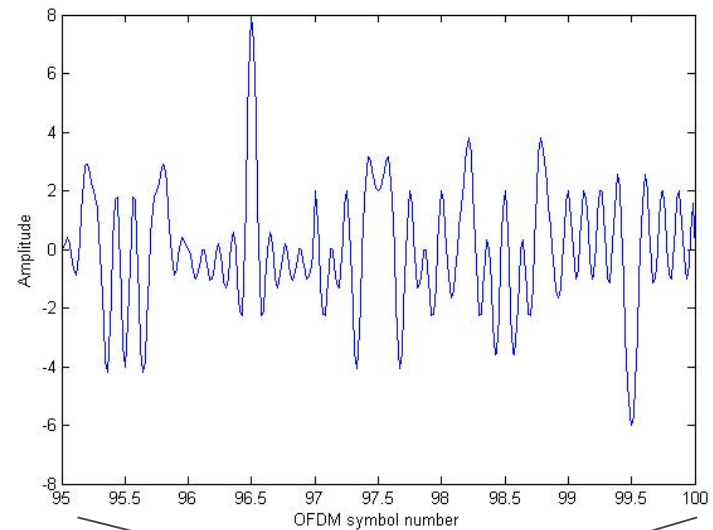


- High peak-to-average-power ratio (PAPR), requires linear transmitter circuitry, which suffers from poor power efficiency.



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 order of thousands!

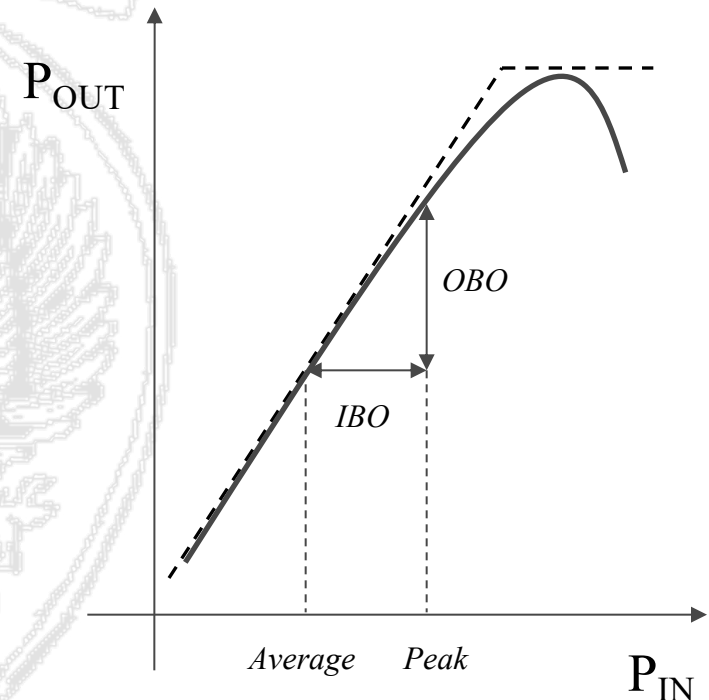
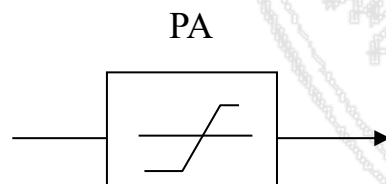




The Peak to Average Power Problem

- 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



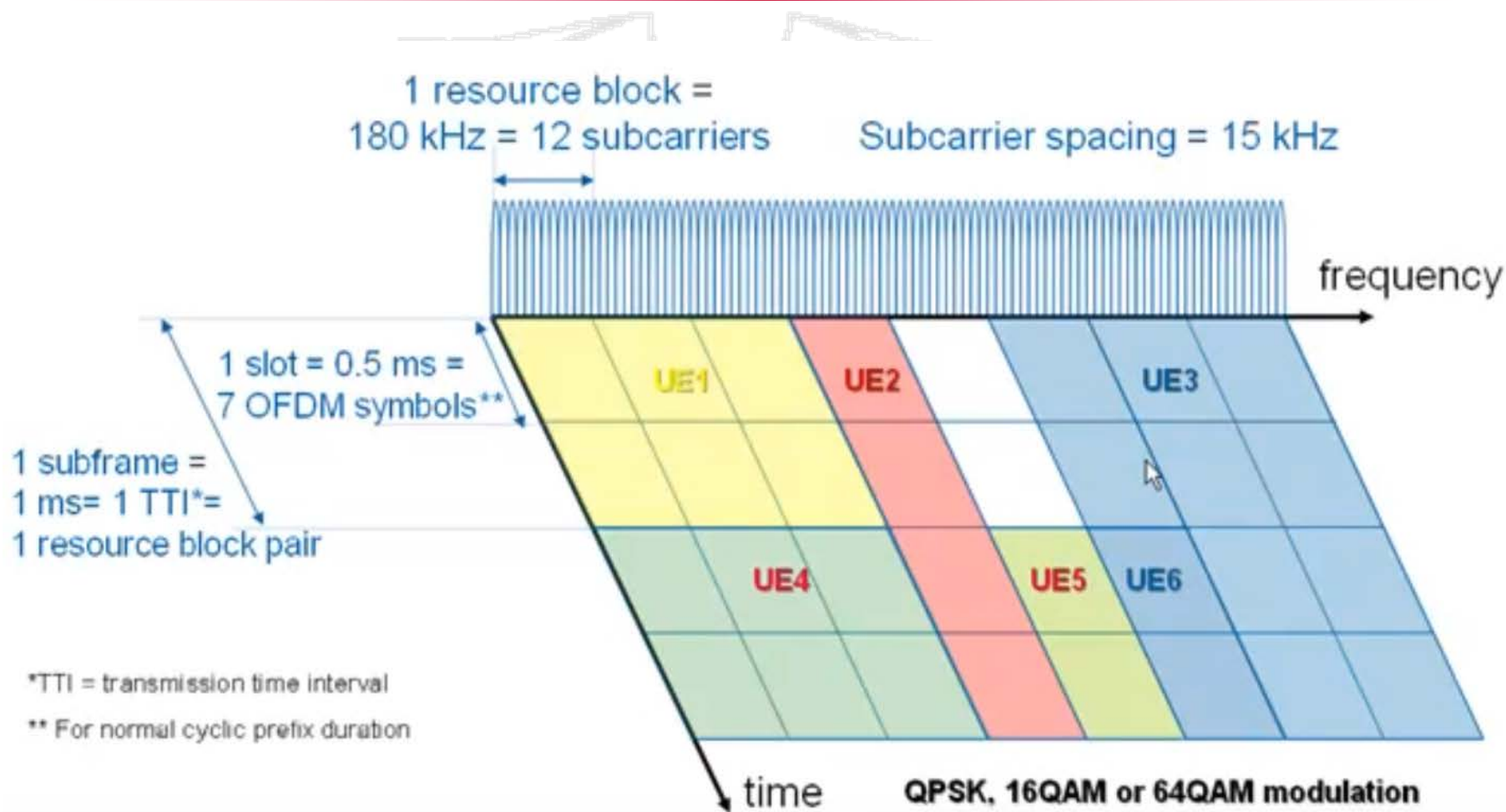


The Peak to Average Power Problem

- 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



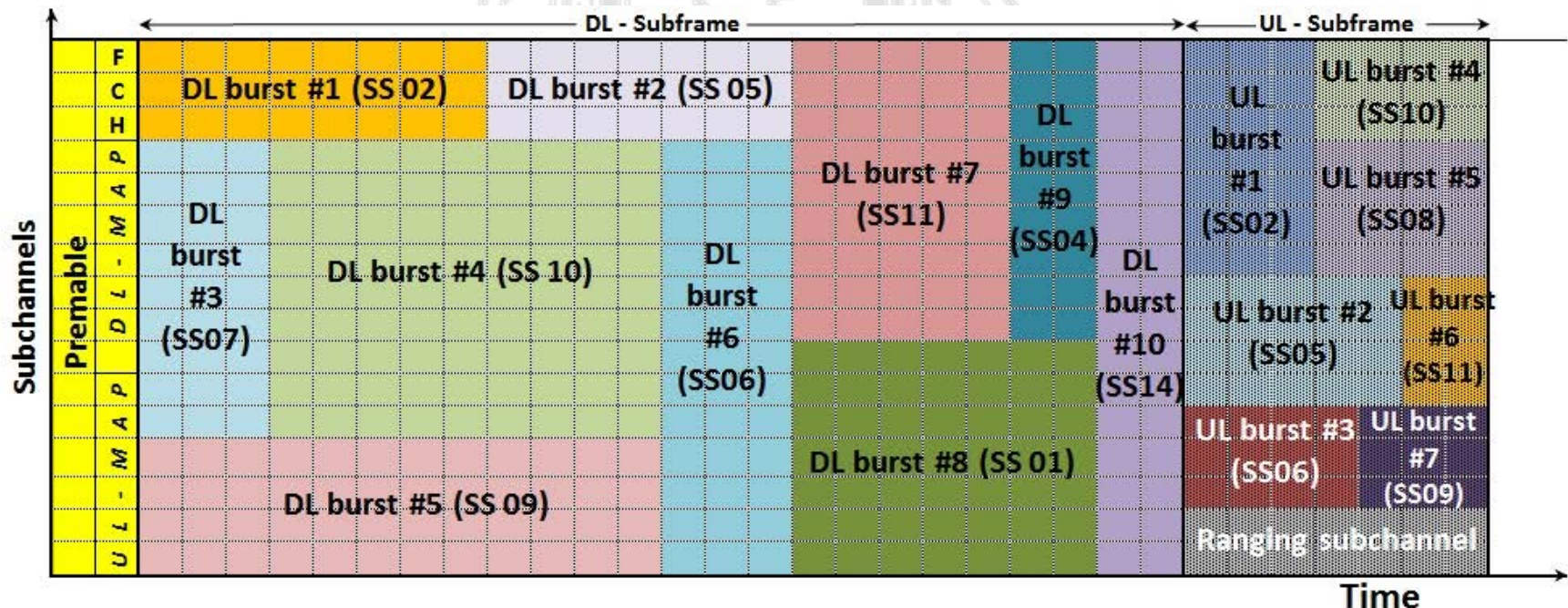
*TTI = transmission time interval

** For normal cyclic prefix duration



OFDMA/TDD structure

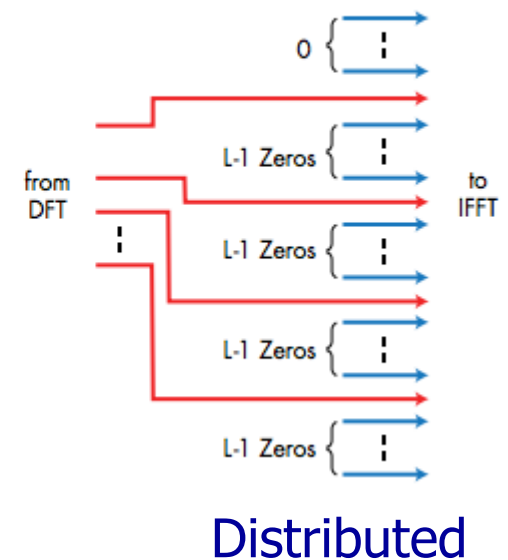
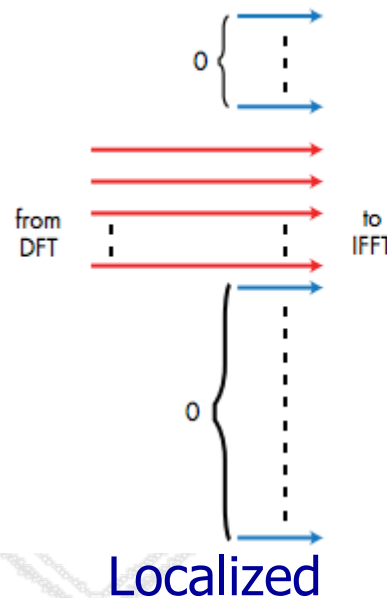
- OFDMA for downlink and SC-FDMA for uplink
- Flexible bandwidth from 1.4 to 20 MHz (i.e., from 6 to 100 resource blocks - RBs)





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





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, ...



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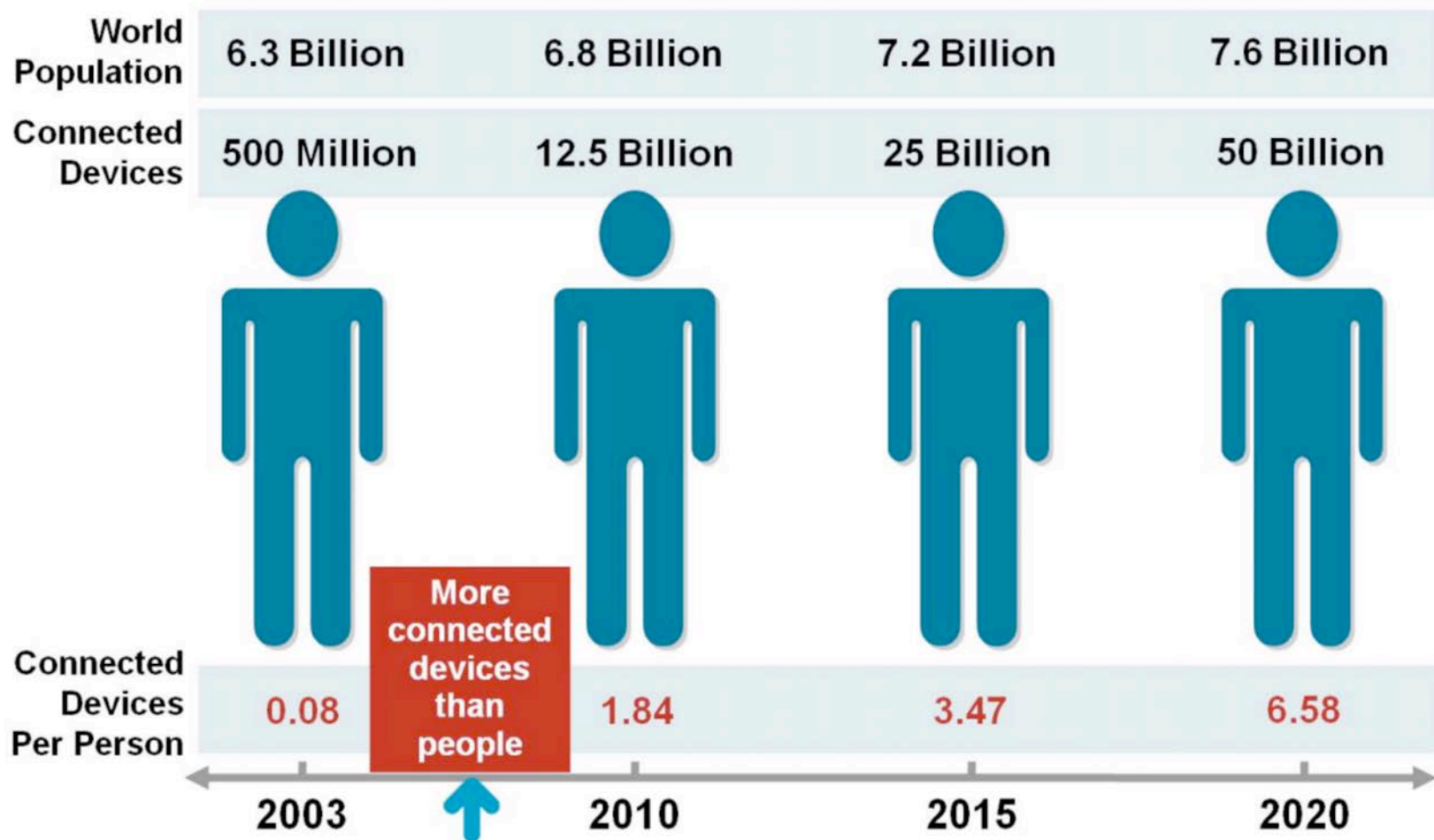


OFDM applications in the IoT





The rise of IoT



Source: Cisco IBSG, April 2011



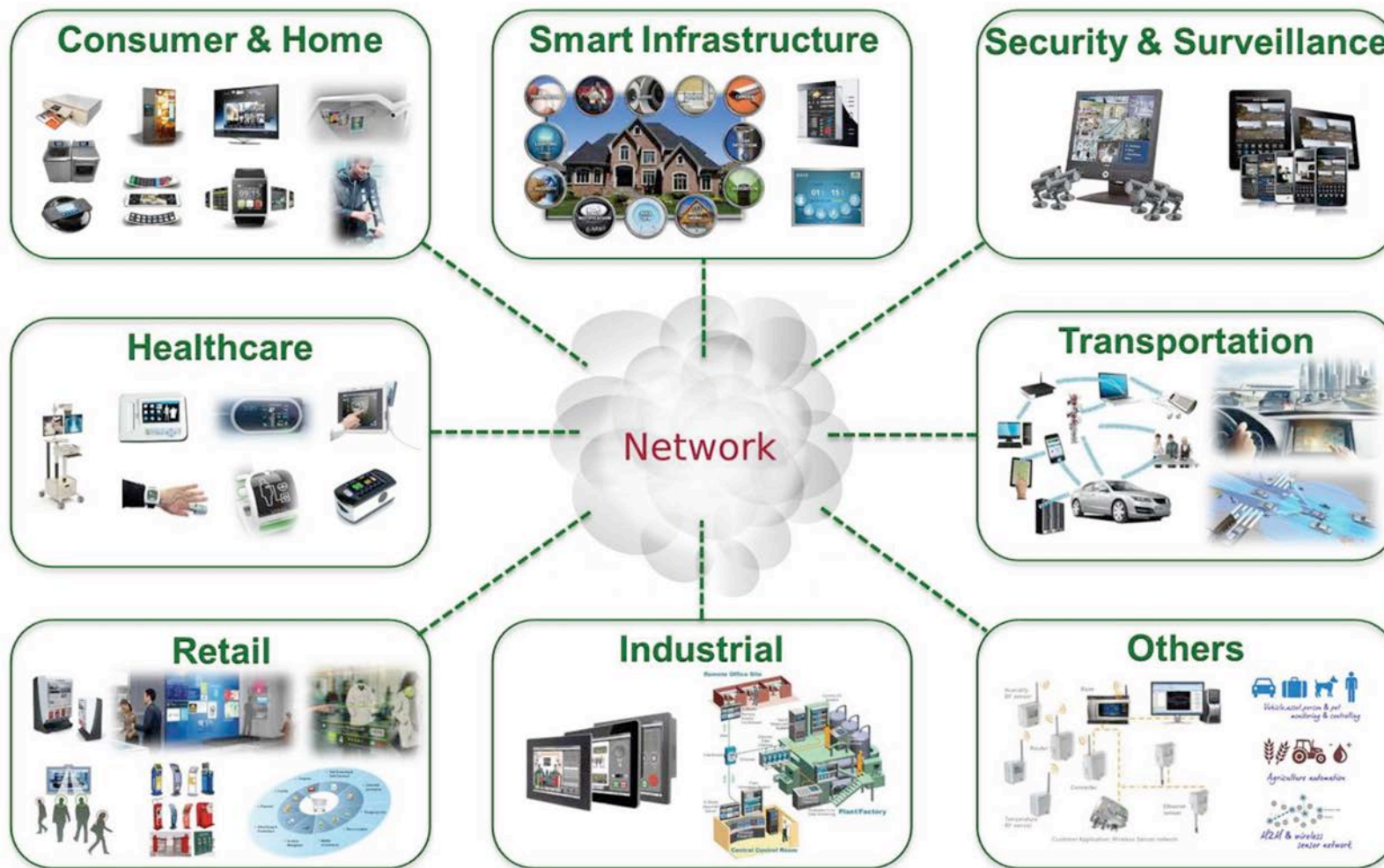
Machine-type communications



	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



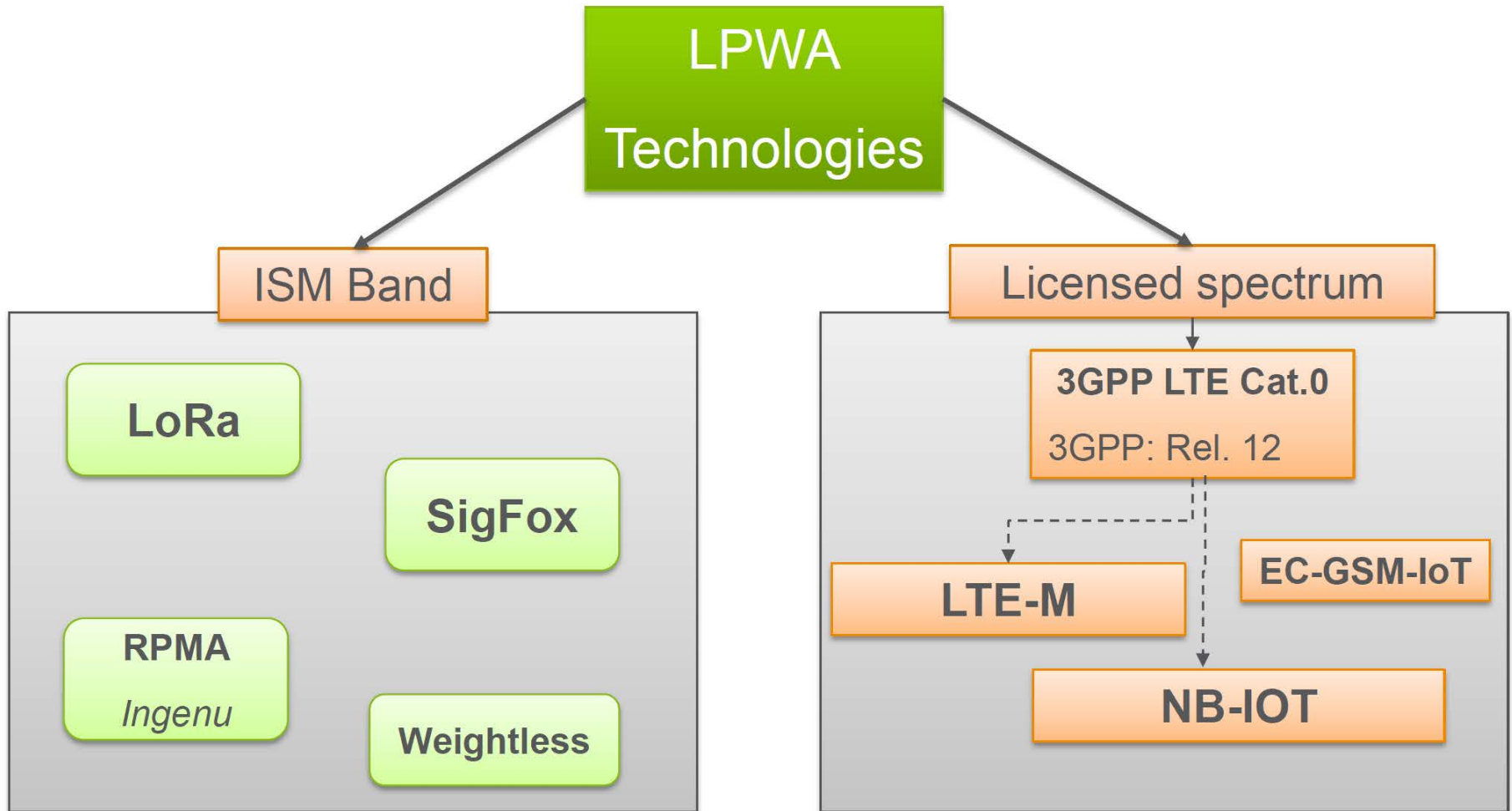


Low Power Wide Area (LPWA) networks

- 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?





Comparison of LPWA technologies

Feature	LORAWAN	SIGFOX	LTE Cat 1	LTE M	NB - LTE
Modulation	SS chip	UNB / GFSK / BPSK	OFDMA	OFDMA	OFDMA
Rx Bandwidth	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 Output 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)

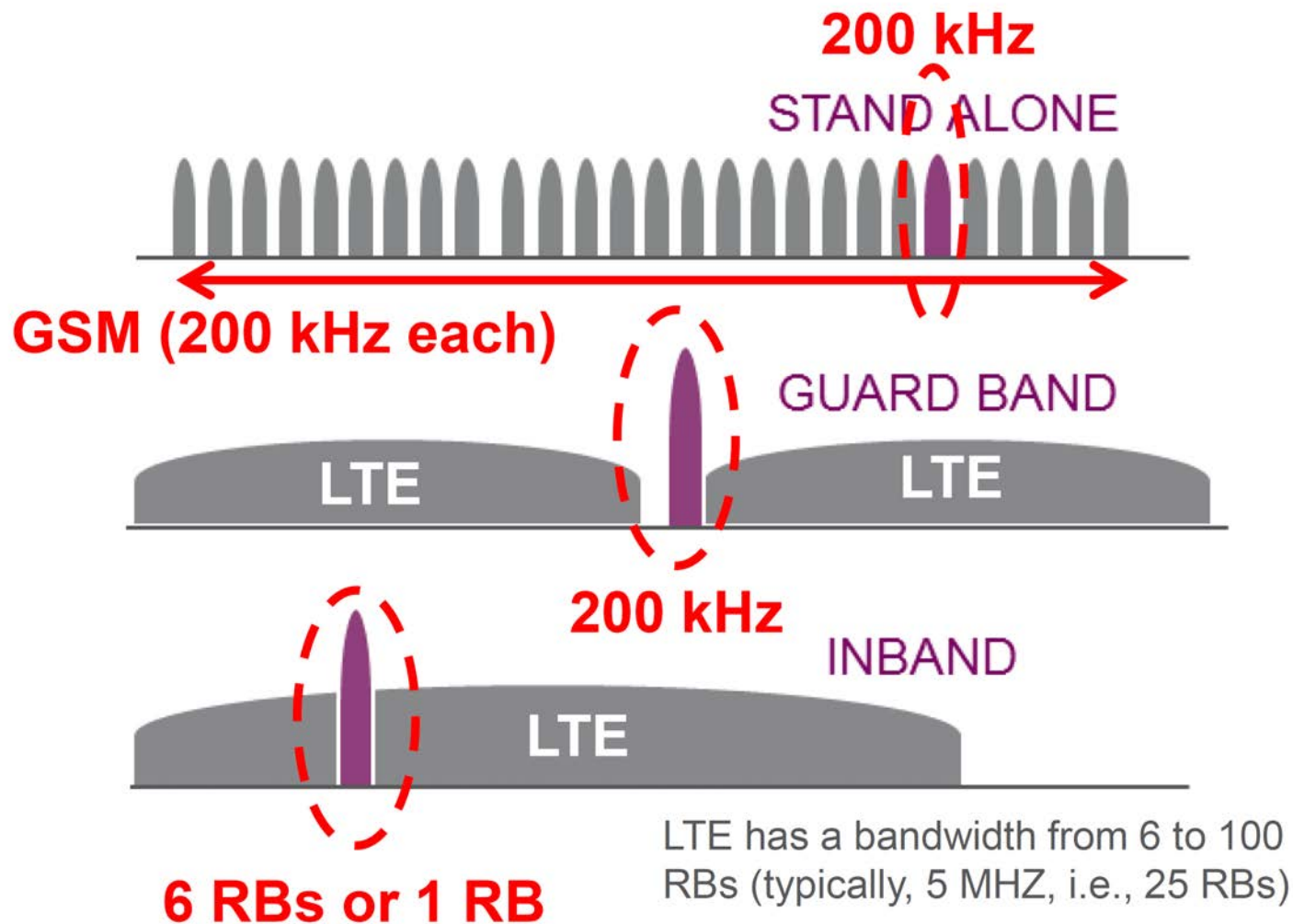


From LTE to 'cellular' IoT

- 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



Lower cost

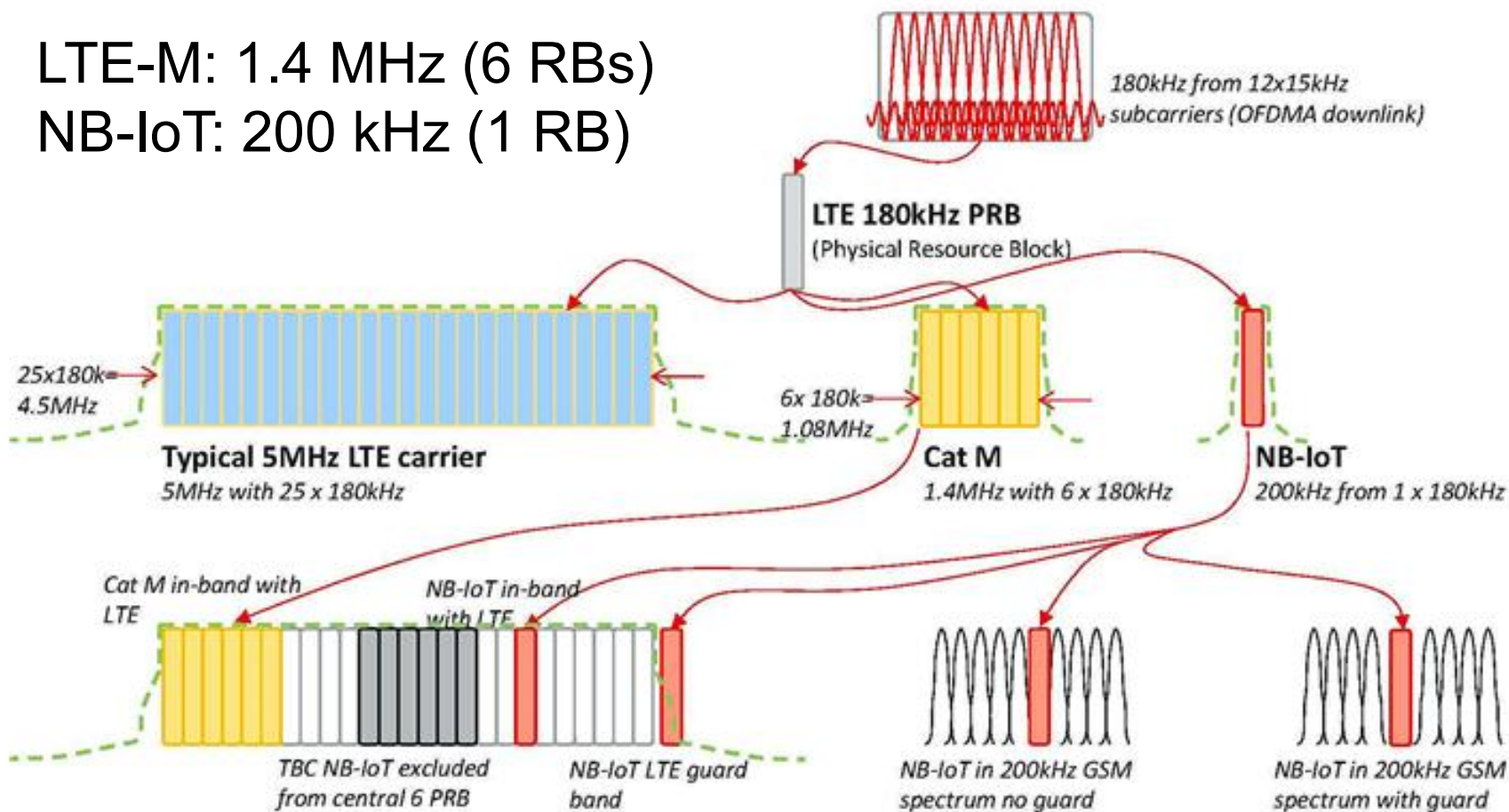




Deployment of LTE-M and NB-IoT

LTE-M: 1.4 MHz (6 RBs)

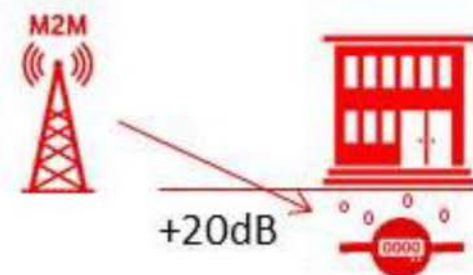
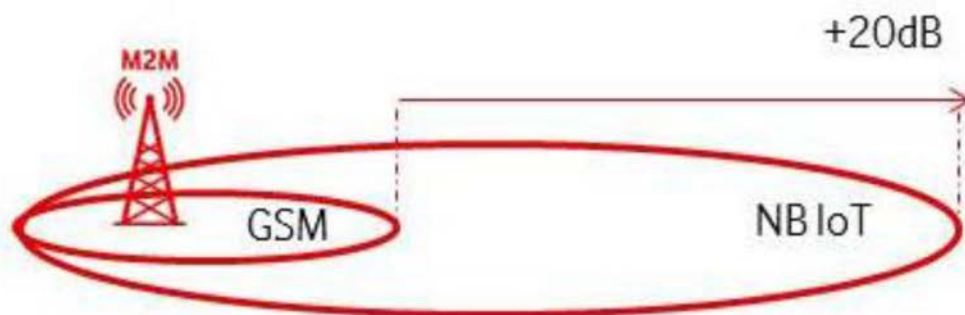
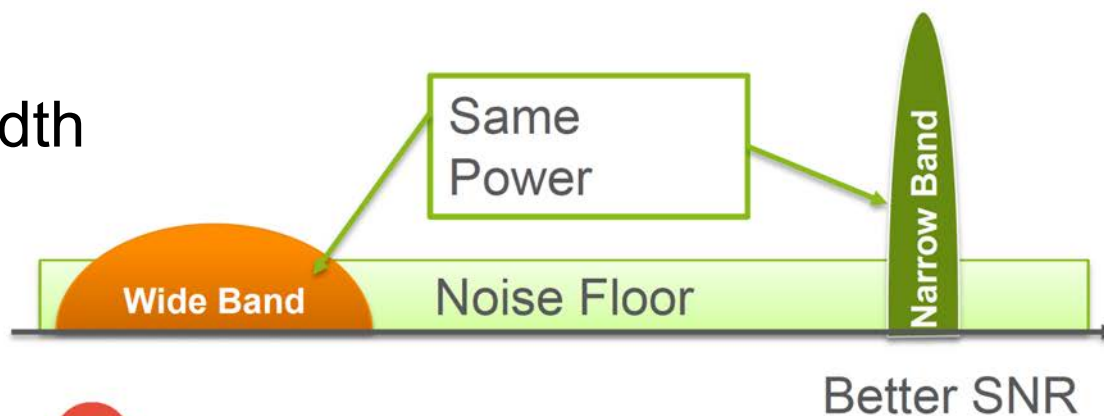
NB-IoT: 200 kHz (1 RB)





Extended coverage

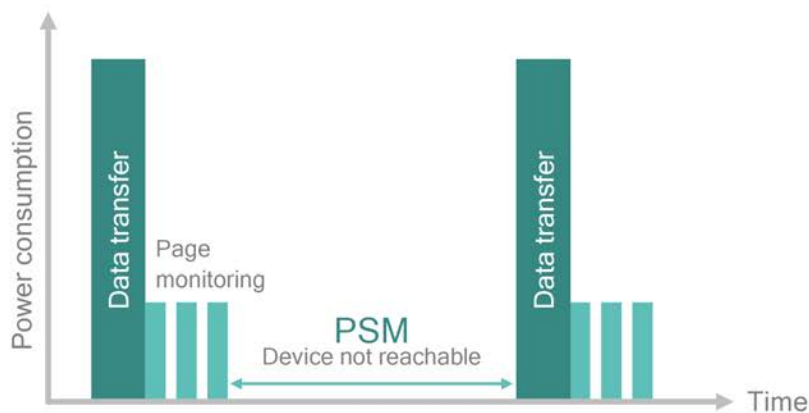
- Lower bandwidth
- Repetitions





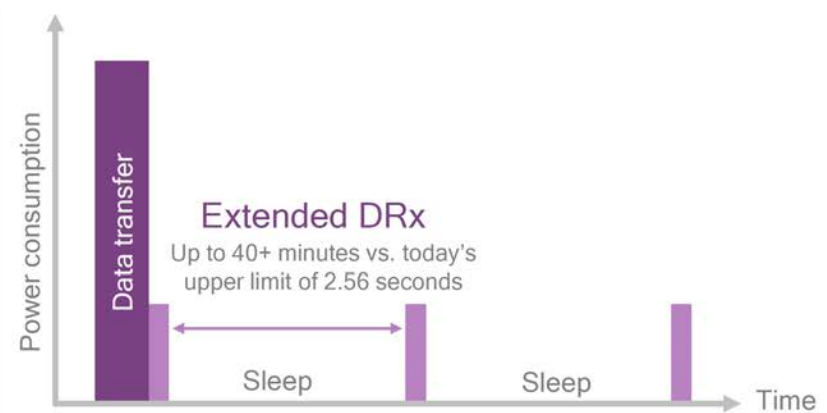
Lower energy consumption

- 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



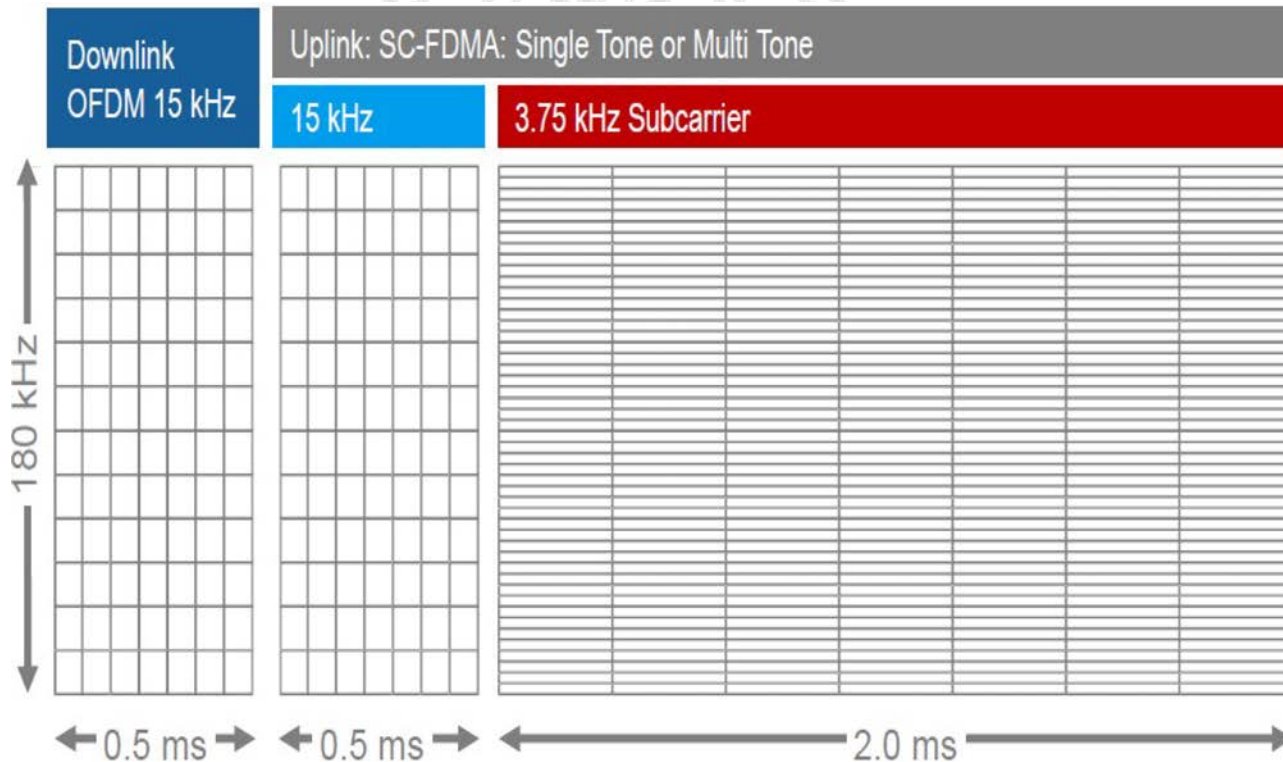
Main characteristics of NB-IoT

- 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



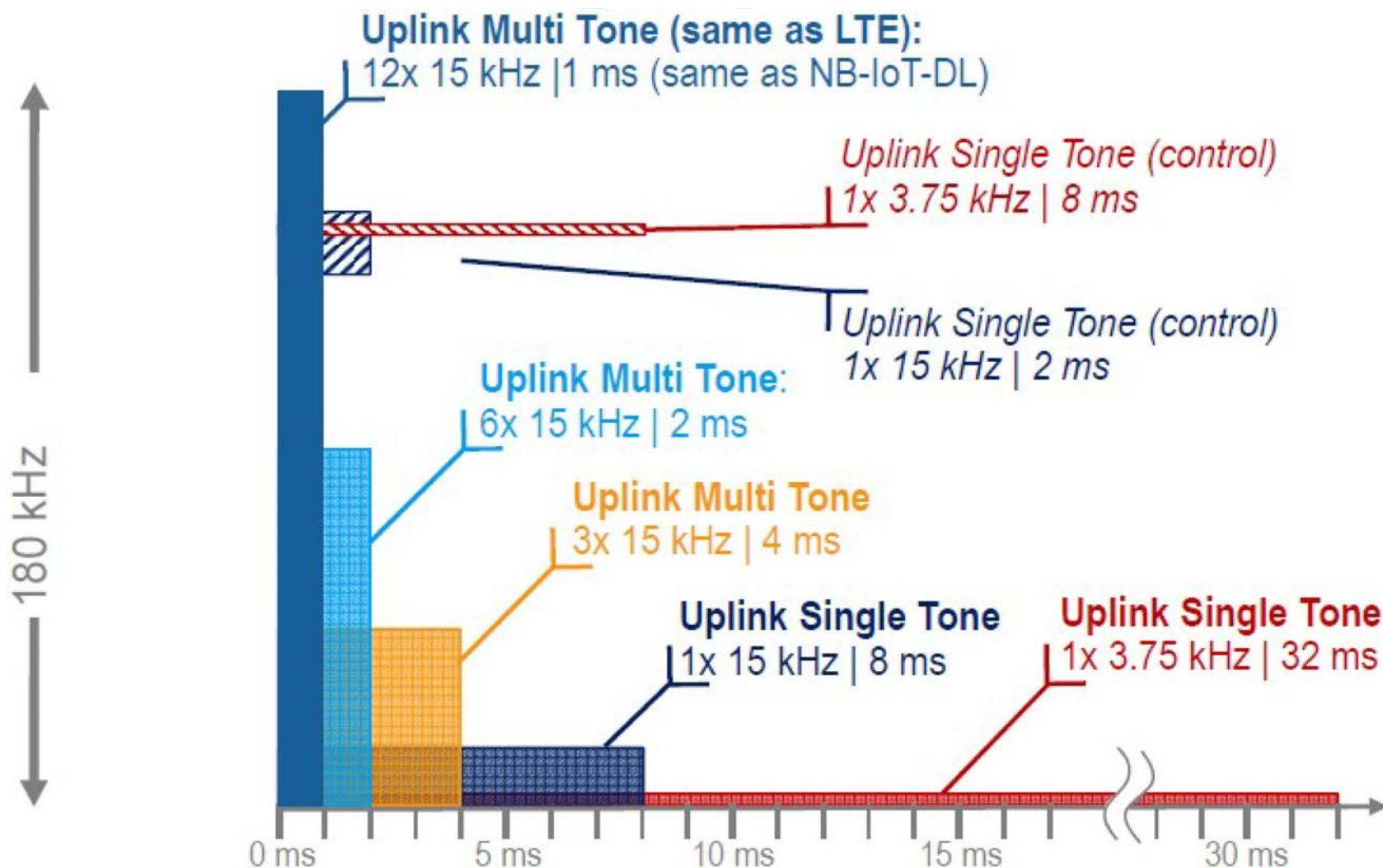
NB-IoT transmission modes

- 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





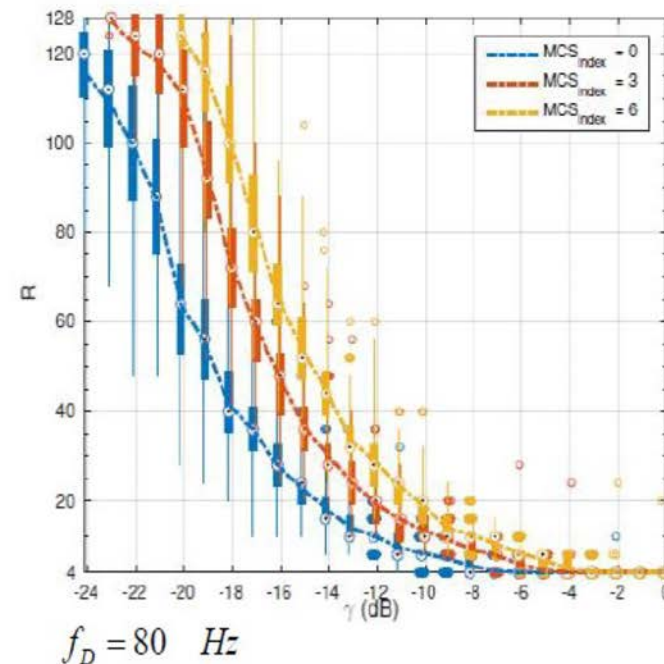
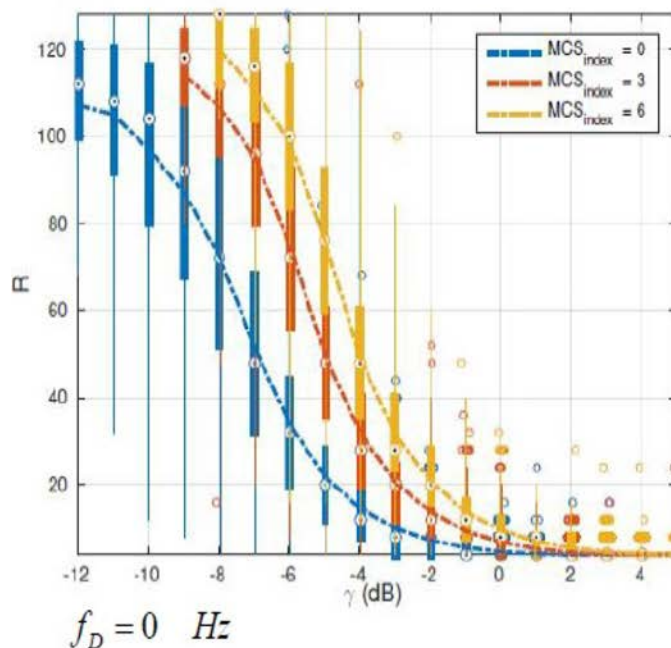
Repetitions and tx params

- Repetitions in NB-IoT are 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

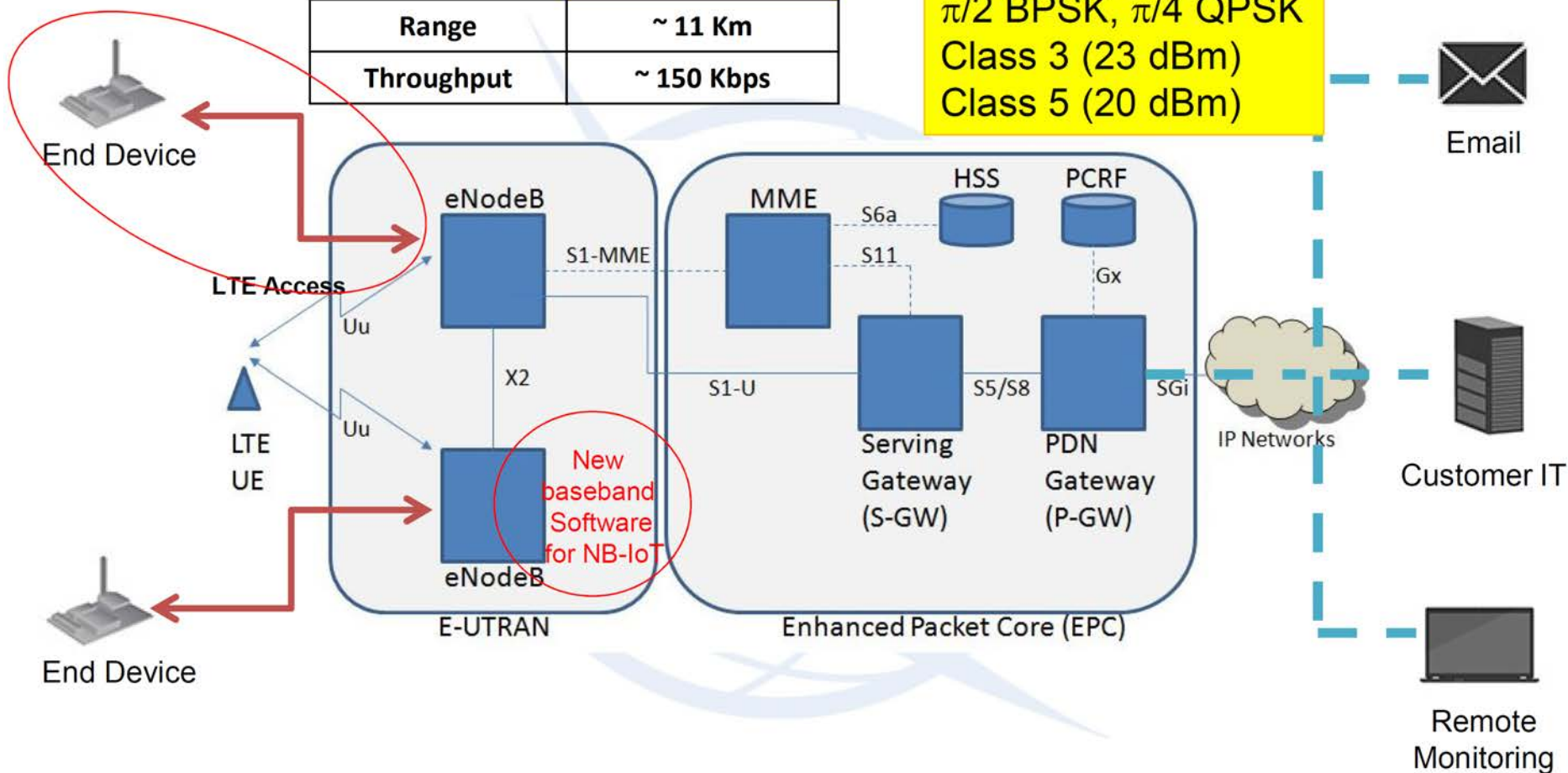




Network architecture

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)





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 (in March 2019)
- SigFox, LoRa, NB-IoT, LTE-M, etc. are complementary
- *Costs??*



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Thank you!
Questions?