E303: Communication Systems

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Principles of 3G (CDMA), 4G (OFDMA) and 5G

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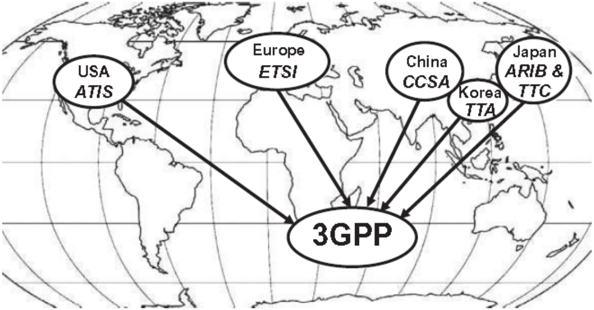
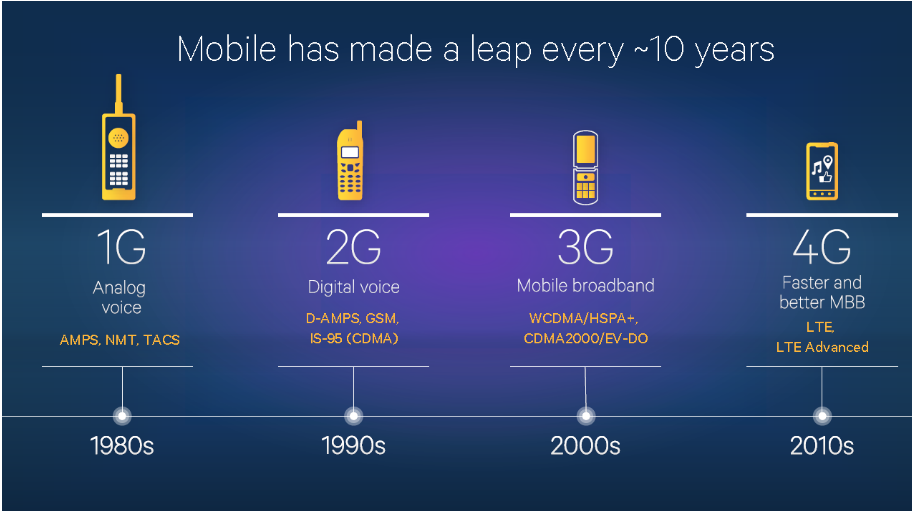
Introduction - 3G, 4G, 5G Mobile Cellular Systems

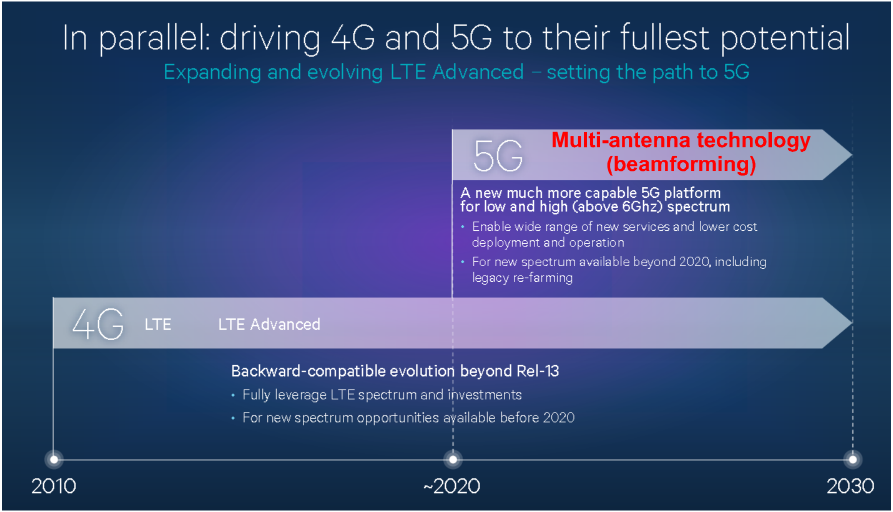
- The 3GPP (**3'd Generation Partnership Project**)
  - developed the 3G standars
  - developed the 4G standards
  - is developing standards towards next generation (5G)
- 3GPP **expanded in 2011** to include 380 individual member companies and **5 Standards Development Organisations** as shown below



Mobile Evolution - Motivation



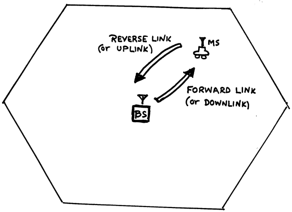
Mobile Evolution - Motivation (cont.)



Basic Elements of Mobile Cellular Systems

- A mobile cellular system consists of
  - **base stations** ,
  - **cells** (a cell is the area serviced by a base station) and
  - **mobiles** (subscribers).
- When a call originates, the base station negotiates with the mobile on various aspects (such as the channel used etc.), before establishing communications. After this, as the mobile moves from cell-to-cell, the service is handed (**hand-off or handover**) from one base station to another.
- Only **one base station** (BS) will service a mobile at any one time.
- Note:
  - base station to mobile is known as **FORWARD LINK** **(or Downlink)**
  - mobile to base station is known as **REVERSE LINK** **(or Uplink)**

- Type of channels:



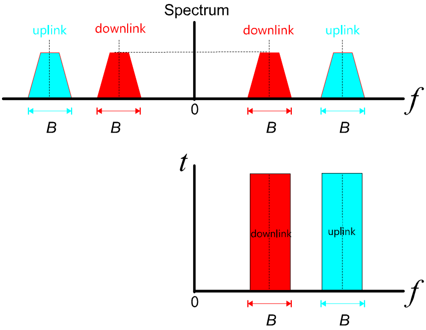
- Examples of uplink and downlink channels:

UPLINK	DOWNLINK
Traffic Channel	Traffic Channel
Access Channel	Pilot Channel
	Synchron.Channel
	Paging Channel

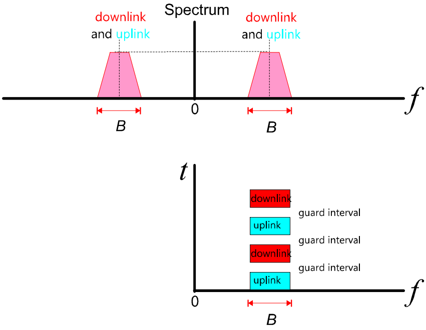
FDD and TDD

- Based of the spectrum used in "uplink" and "downling", there are two systems
  - FDD (Frequency Division Duplex), and
  - TDD (Time Division Duplex)
  - Definitions:

FDD:



TDD:



Channel Reuse and Reuse Distance

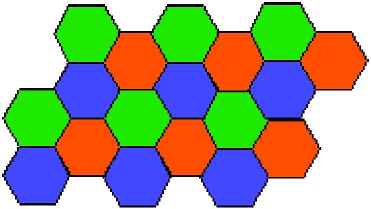
- Most cellular systems use frequency division multiplex access (FDMA) and/or time division multiplex access (TDMA) technique to improve the system capacity.
- Example: 2G cellular systems = FDMA/TDMA
- In these systems, each user is assigned one time/frequency-slot.
  - When the system gets larger,

    $$\text{time/frequency-slots} \neq \text{unique for each and every user}$$

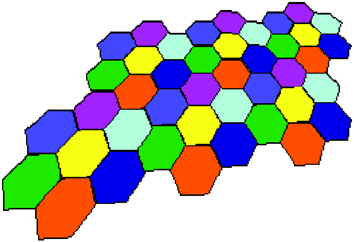
    as this will limit the system capacity. Therefore these slots (time/frequency) have to be reused
  - This implies that there is **interference from other cells** sharing the same channels.

- Cluster= the number of cells which have unique time/freq-slots for each and every user.
  - Available cluster sizes: 1,3,4,7,9,12,...

cluster size=3



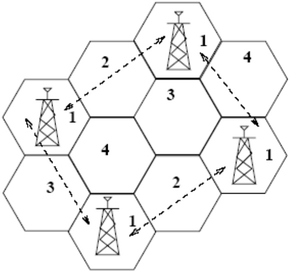
cluster size=7



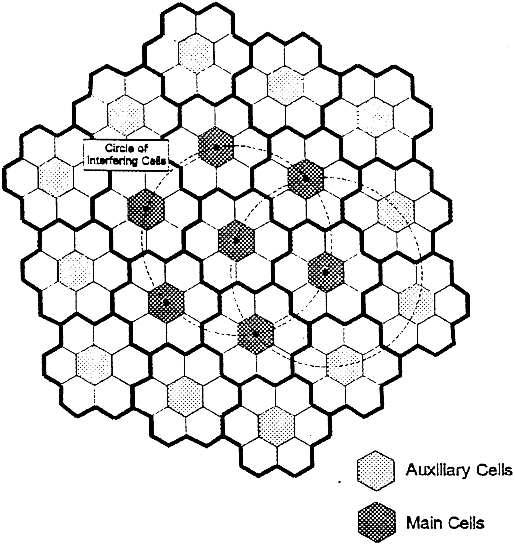
  - The **reuse distance** D, in these systems, is determined by the worst case interference situation.
  - D is defined as the distance between the centers of two co-channel cells.

$$
\begin{aligned}
D &= R\sqrt{3C} \qquad (1)\\
\text{where } C &= \text{cluster size}\\
R &= \text{cell radius}
\end{aligned}
$$

cluster size: 4



cluster size: 7



- D is known as the reuse distance of the system.
- Remember: The **system capacity** could be increased by **increasing** the number of channels available in a single cell, i.e. **reducing** the reuse distance D.
- But this reduction is limited by the co-channel interference, (i.e. the interference from other cells sharing the same channels).
- In a **CDMA system** , the available spectrum and time are not split into distinct slots. Instead the whole (available) spectrum is used by each user.
  - Since the same frequency channel could be used by all the users/subscribers in a cell, the cluster size could be reduced to 1, i.e.

$$\boxed{\textbf{if CDMA then cluster} = 1 \text{ cell } \textbf{and} \quad D = R\sqrt{3}} \tag{2}$$

Signal Overlay

- The spread spectrum signal, from a CDMA system, has a **very low power spectral density** and, therefore, a **CDMA system can overlay on top of 2G** narrow-band mobile cellular systems (of the same frequency band).
- This is because the interference (due to CDMA signals), added to a narrow-band mobile system channel, is very low and, therefore, the presence of CDMA signal will hardly affect the performance of the narrow-band mobile system.
- The CDMA system, however, needs to perform **some extra processing** to reject the narrowband interference due to the presence of the narrow-band signals.
- Comment:
  The capacity and performance of a mobile cellular system could be significantly improved by using CDMA techniques. In the paper "On the Capacity of a Cellular CDMA", IEEE Transactions on Vehicular Technology, Vol.40, 1991 (by Gilhousen et al) the improvement in the capacity is discussed and it is stated that "no other proposed scheme appears to even approach this (CDMA) performance".

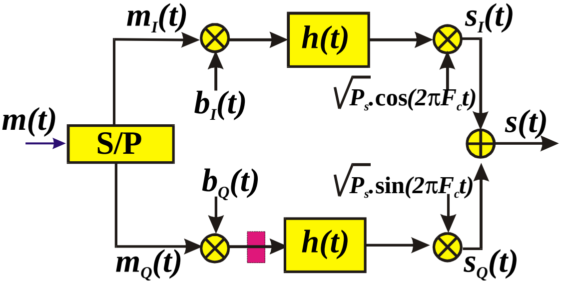
3G: Specifications

	IS-95	UMTS
Generation	2G (USA)	3G (EU)
Type	CDMA	W-CDMA
Frame duration	20msec	10msec
Uplink	$\overbrace{824 - 849\text{MHz}}^{25\text{MHz}}$ mod:QPSK	$\overbrace{1920 - 1980\text{MHz}}^{60\text{MHz}}$ mod:balanced QPSK, i.e. **QPSK2**
Downlink	$\overbrace{869 - 894\text{MHz}}^{25\text{MHz}}$ mod:oQPSK	$\overbrace{2110 - 2170\text{MHz}}^{60\text{MHz}}$ mod:dual QPSK, i.e. **QPSK1**
B_{ss}	1.23MHz	5MHz,10MHz,20MHz
T_c	813.8ns	244ns,122ns, 61ns
$r_c = \frac{1}{T_c}$	$1.2288\frac{\text{Mchips}}{\text{sec}}$	$4.096\frac{\text{Mchips}}{\text{sec}}$ (reduced to $3.084\frac{\text{Mchips}}{\text{sec}}$)
roll-off-factor		0.22;Note: $B_{ss} = \frac{1}{T_c}(1+\text{roll-off-factor})=4.99712\text{MHz}\simeq 5\text{MHz}$
Receiver's type	RAKE	RAKE

3G: DS-QPSK implementation No.1 (QPSK1)

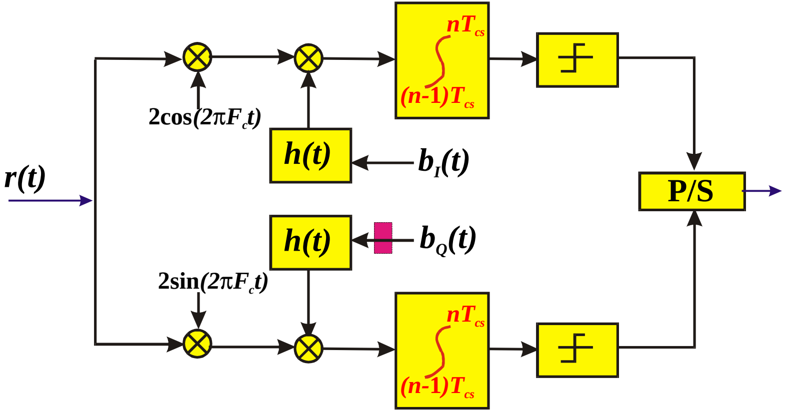
(Note: if $= \frac{T_c}{2}$ delay is inserted then OQPSK1 – offset QPSK1)

- Transmitter:



$$s(t) = \sqrt{2P_s}.\cos\left(2\pi F_c t + \tan^{-1}\frac{b_Q(t).m_Q(t)}{b_I(t).m_I(t)}\right)$$

- Receiver:

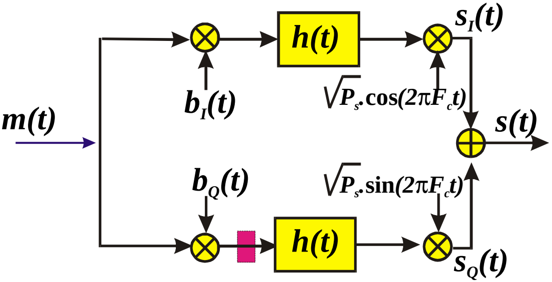


r(t)
2cos(2πF_c t)
h(t)
b_I(t)
nT_cs
(n-1)T_cs
P/S
h(t)
b_Q(t)
2sin(2πF_c t)
nT_cs
(n-1)T_cs

3G: DS-QPSK implementation No.2 (QPSK2)

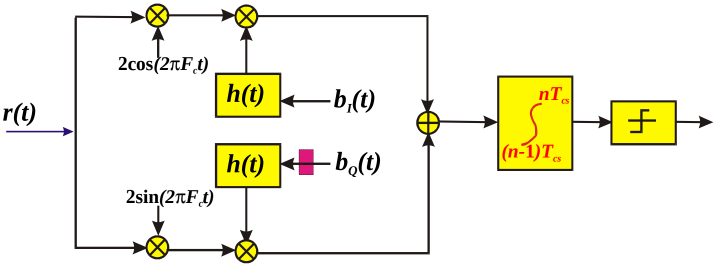
(Note: if  $= \frac{T_c}{2}$ delay is inserted then OQPSK2)

- Transmitter:



$$s(t) = \sqrt{2P_s}.\cos\left(2\pi F_c t + \tan^{-1}\frac{b_Q(t).m(t)}{b_I(t).m(t)}\right)$$

- Receiver:



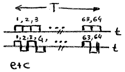
3G: Channelisation Codes & Scrambling Codes

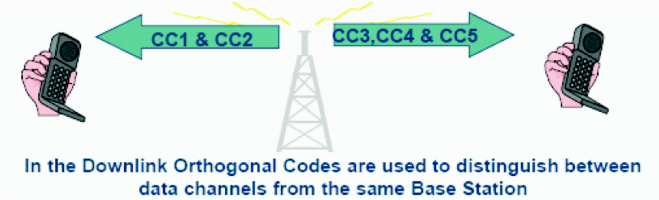
- In 3G WCDMA:
  - **PN-codes** = **channelisation codes** + scrambling codes
- **Channelisation codes** :
  - are used to **differentiate between users/channels** <u>within</u> **a cell**
  - also known as **OVSF** (Orthogonal Variable Spreading Factor) codes
  - these are the **Walsh codes** (see next page)
- Scambling codes:
  - to **differentiate** <u>between</u> **cells**
  - these are **m-sequence** or **gold-codes**

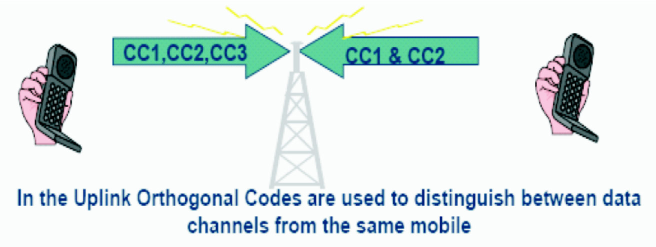
IS95 - Walsh Function of order-64

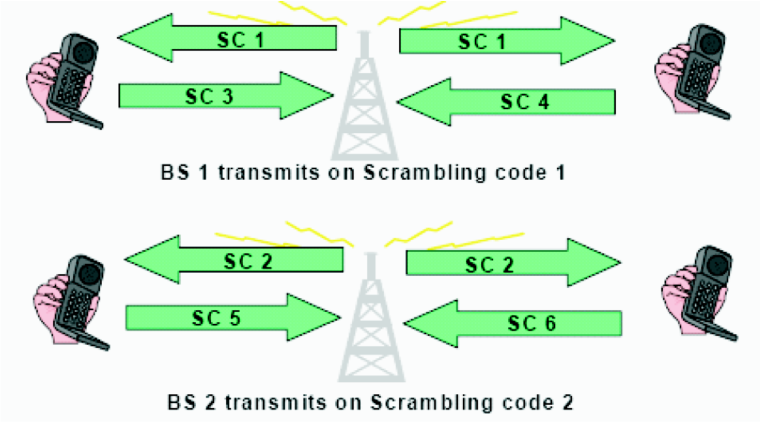
Walsh functions of order 64, as indexed in IS-95 (W_i is the Walsh notation, and H_i is the Hadamard notation)

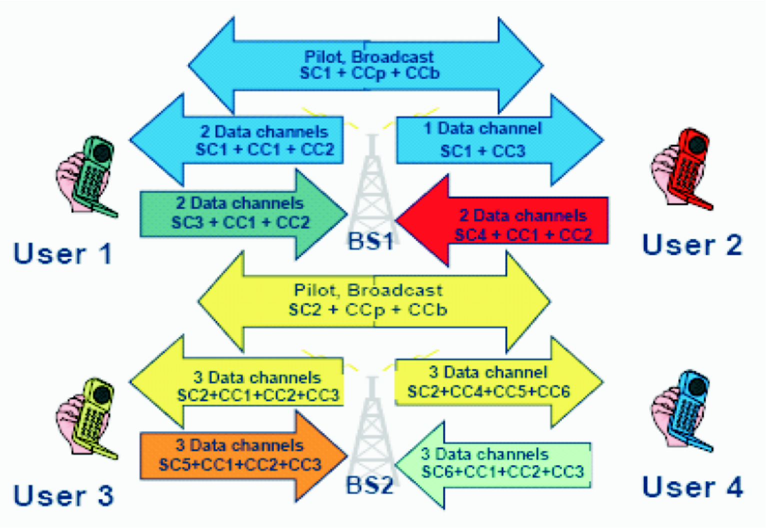
W_0	H_0	0000000000000000	0000000000000000	0000000000000000	0000000000000000
W_{63}	H_1	0101010101010101	0101010101010101	0101010101010101	0101010101010101
W_{31}	H_2	0011001100110011	0011001100110011	0011001100110011	0011001100110011
W_{32}	H_3	0110011001100110	0110011001100110	0110011001100110	0110011001100110
W_{15}	H_4	0000111100001111	0000111100001111	0000111100001111	0000111100001111
W_{48}	H_5	0101101001011010	0101101001011010	0101101001011010	0101101001011010
W_{16}	H_6	0011110000111100	0011110000111100	0011110000111100	0011110000111100
W_{47}	H_7	0110100101101001	0110100101101001	0110100101101001	0110100101101001
W_7	H_8	0000000011111111	0000000011111111	0000000011111111	0000000011111111
W_{56}	H_9	0101010110101010	0101010110101010	0101010110101010	0101010110101010
W_{24}	H_{10}	0011001111001100	0011001111001100	0011001111001100	0011001111001100
W_{39}	H_{11}	0110011010011001	0110011010011001	0110011010011001	0110011010011001
W_8	H_{12}	0000111111110000	0000111111110000	0000111111110000	0000111111110000
W_{55}	H_{13}	0101101010100101	0101101010100101	0101101010100101	0101101010100101
W_{23}	H_{14}	0011110011000011	0011110011000011	0011110011000011	0011110011000011
W_{40}	H_{15}	0110100110010110	0110100110010110	0110100110010110	0110100110010110
W_3	H_{16}	0000000000000000	1111111111111111	0000000000000000	1111111111111111
W_{60}	H_{17}	0101010101010101	1010101010101010	0101010101010101	1010101010101010
W_{28}	H_{18}	0011001100110011	1100110011001100	0011001100110011	1100110011001100
W_{35}	H_{19}	0110011001100110	1001100110011001	0110011001100110	1001100110011001
W_{12}	H_{20}	0000111100001111	1111000011110000	0000111100001111	1111000011110000
W_{51}	H_{21}	0101101001011010	1010010110100101	0101101001011010	1010010110100101
W_{19}	H_{22}	0011110000111100	1100001111000011	0011110000111100	1100001111000011
W_{44}	H_{23}	0110100101101001	1001011010010110	0110100101101001	1001011010010110
W_4	H_{24}	0000000011111111	1111111100000000	0000000011111111	1111111100000000
W_{59}	H_{25}	0101010110101010	1010101001010101	0101010110101010	1010101001010101
W_{27}	H_{26}	0011001111001100	1100110000110011	0011001111001100	1100110000110011
W_{36}	H_{27}	0110011010011001	1001100101100110	0110011010011001	1001100101100110
W_{11}	H_{28}	0000111111110000	1111000000001111	0000111111110000	1111000000001111
W_{52}	H_{29}	0101101010100101	1010010101011010	0101101010100101	1010010101011010
W_{20}	H_{30}	0011110011000011	1100001100111100	0011110011000011	1100001100111100
W_{43}	H_{31}	0110100110010110	1001011001101001	0110100110010110	1001011001101001
W_1	H_{32}	0000000000000000	0000000000000000	1111111111111111	1111111111111111
W_{62}	H_{33}	0101010101010101	0101010101010101	1010101010101010	1010101010101010
W_{30}	H_{34}	0011001100110011	0011001100110011	1100110011001100	1100110011001100
W_{33}	H_{35}	0110011001100110	0110011001100110	1001100110011001	1001100110011001
W_{14}	H_{36}	0000111100001111	0000111100001111	1111000011110000	1111000011110000
W_{49}	H_{37}	0101101001011010	0101101001011010	1010010110100101	1010010110100101
W_{17}	H_{38}	0011110000111100	0011110000111100	1100001111000011	1100001111000011
W_{46}	H_{39}	0110100101101001	0110100101101001	1001011010010110	1001011010010110
W_6	H_{40}	0000000011111111	0000000011111111	1111111100000000	1111111100000000
W_{57}	H_{41}	0101010110101010	0101010110101010	1010101001010101	1010101001010101
W_{25}	H_{42}	0011001111001100	0011001111001100	1100110000110011	1100110000110011
W_{38}	H_{43}	0110011010011001	0110011010011001	1001100101100110	1001100101100110
W_9	H_{44}	0000111111110000	0000111111110000	1111000000001111	1111000000001111
W_{54}	H_{45}	0101101010100101	0101101010100101	1010010101011010	1010010101011010
W_{22}	H_{46}	0011110011000011	0011110011000011	1100001100111100	1100001100111100
W_{41}	H_{47}	0110100110010110	0110100110010110	1001011001101001	1001011001101001
W_2	H_{48}	0000000000000000	1111111111111111	1111111111111111	0000000000000000
W_{61}	H_{49}	0101010101010101	1010101010101010	1010101010101010	0101010101010101
W_{29}	H_{50}	0011001100110011	1100110011001100	1100110011001100	0011001100110011
W_{34}	H_{51}	0110011001100110	1001100110011001	1001100110011001	0110011001100110
W_{13}	H_{52}	0000111100001111	1111000011110000	1111000011110000	0000111100001111
W_{50}	H_{53}	0101101001011010	1010010110100101	1010010110100101	0101101001011010
W_{18}	H_{54}	0011110000111100	1100001111000011	1100001111000011	0011110000111100
W_{45}	H_{55}	0110100101101001	1001011010010110	1001011010010110	0110100101101001
W_5	H_{56}	0000000011111111	1111111100000000	1111111100000000	0000000011111111
W_{58}	H_{57}	0101010110101010	1010101001010101	1010101001010101	0101010110101010
W_{26}	H_{58}	0011001111001100	1100110000110011	1100110000110011	0011001111001100
W_{37}	H_{59}	0110011010011001	1001100101100110	1001100101100110	0110011010011001
W_{10}	H_{60}	0000111111110000	1111000000001111	1111000000001111	0000111111110000
W_{53}	H_{61}	0101101010100101	1010010101011010	1010010101011010	0101101010100101
W_{21}	H_{62}	0011110011000011	1100001100111100	1100001100111100	0011110011000011
W_{12}	H_{63}	0110100110010110	1001011001101001	1001011001101001	0110100110010110



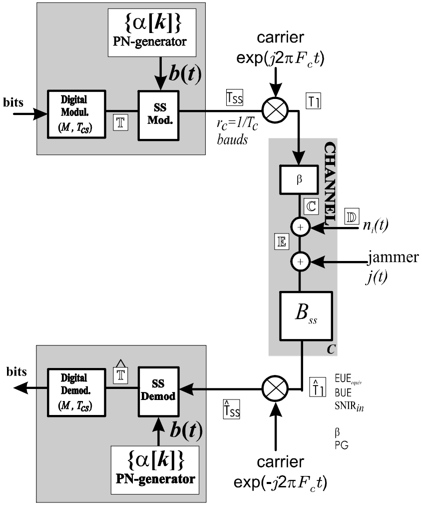

CC1 & CC2
CC3,CC4 & CC5
In the Downlink Orthogonal Codes are used to distinguish between data channels from the same Base Station


CC1,CC2,CC3
CC1 & CC2
In the Uplink Orthogonal Codes are used to distinguish between data channels from the same mobile

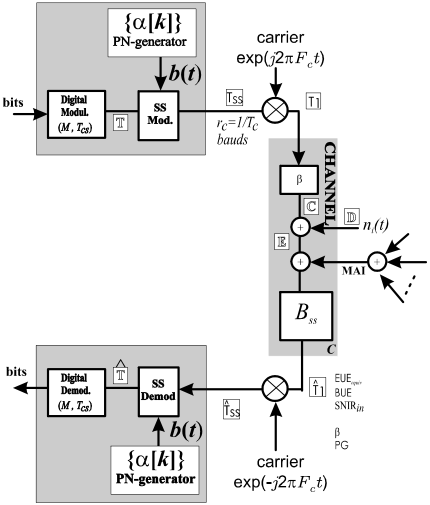

SC 1
SC 1
SC 3
SC 4
BS 1 transmits on Scrambling code 1
SC 2
SC 2
SC 5
SC 6
BS 2 transmits on Scrambling code 2


Pilot, Broadcast
SC1 + CCp + CCb
2 Data channels
SC1 + CC1 + CC2
1 Data channel
SC1 + CC3
2 Data channels
SC3 + CC1 + CC2
2 Data channels
SC4 + CC1 + CC2
BS1
User 1
User 2
Pilot, Broadcast
SC2 + CCp + CCb
3 Data channels
SC2+CC1+CC2+CC3
3 Data channel
SC2+CC4+CC5+CC6
3 Data channels
SC5+CC1+CC2+CC3
3 Data channels
SC6+CC1+CC2+CC3
BS2
User 3
User 4

(a) SSS:



(b) CDMA (K users):



Remember

- **DS-SSS** (Examples: DS-BPSK, DS-QPSK):

$$b(t) = \sum_n \alpha[n].c(t - nT_c) \tag{3}$$

where $\{\alpha[n]\}$ is a sequence of ± 1's;
$c(t)$ is an energy signal of duration T_c

- **FH-SSS** (Examples: FH-FSK)

$$b(t) = \sum_n \exp\{j(2\pi \mathrm{k}[n] F_1 t + \phi[n])\}.c(t - nT_c) \tag{4}$$

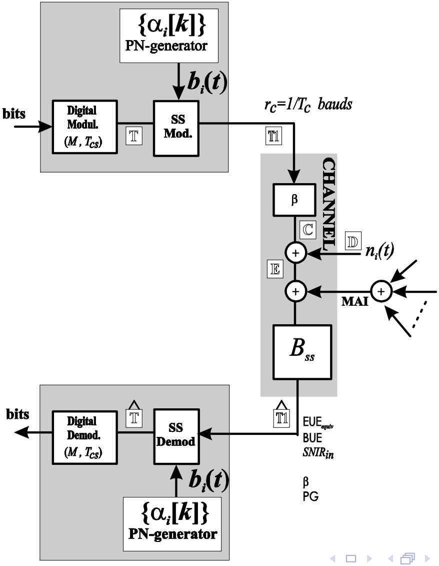
where $\{\mathrm{k}[n]\}$ is a sequence of integers such that

$$\{\alpha[n]\} \mapsto \{\mathrm{k}[n]\} \tag{5}$$

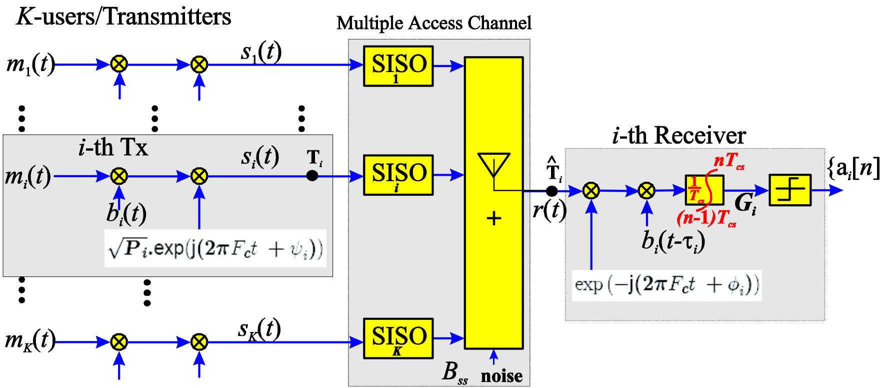
and $\{\alpha[n]\}$ is a sequence of ± 1's;
$c(t)$ is an energy signal of duration T_c

Basics of CDMA

- BLOCK DIAGRAM



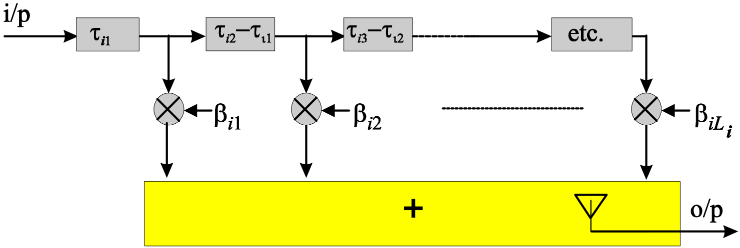
- Example: DS-BPSK CDMA System



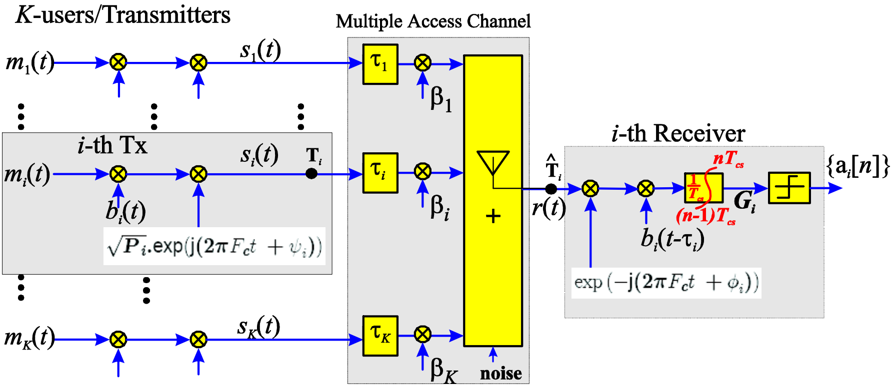
SISO = Scalar-Input Scalar-Output Channel

SISO Multipath Channel

- SISO Multipath channel of the *i*-th user



- In the absence of multipaths the above diagram has only τ_{i1} and β_{i1} terms.
- For the simplicity we will drop the second subscript and we will use τ_i and β_i,and thus the BPSK/DS-CDMA in the absence of multipaths may be represented as follows: $\searrow$


K-users/Transmitters
Multiple Access Channel
$m_1(t)$
$s_1(t)$
τ_1
β_1
i-th Tx
$m_i(t)$
$s_i(t)$
T_i
$b_i(t)$
$\sqrt{P_i}.\exp(j(2\pi F_c t + \psi_i))$
τ_i
β_i
+
$m_K(t)$
$s_K(t)$
τ_K
β_K
noise
$\hat{T}_i$
$r(t)$
i-th Receiver
nT_{cs}
$\frac{1}{T_{cs}}\int$
$(n-1)T_{cs}$
G_i
$b_i(t-\tau_i)$
$\exp(-j(2\pi F_c t + \phi_i))$
$\{a_i[n]\}$

Basic Properties of CDMA Systems

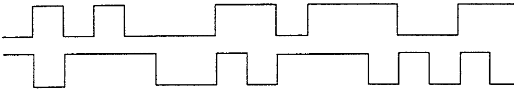
- CDMA is one of the applications of spread spectrum communications which is used in civilian, commercial and military communication.
- Two systems: DS-CDMA (i.e averaging system) and FH-CDMA (i.e. avoidance system).
  In this course only DS-CDMA will be considered.
- Assign a specific PN-code to each user
- PN-code (having the status of 'password') acts like a 'channel'
- DS-CDMA: two main cases
  - PN-signal period $= N_c T_c = T_{cs}$ (known as '**short codes**' CDMA)
  - PN-signal period $= N_c T_c \gg T_{cs}$ (known as '**long codes**' CDMA)

- DS-CDMA: two main types

1. synchronous DS-CDMA

   i-th user

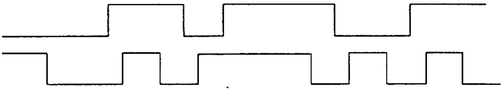
   j-th user



2. non-synchronous DS-CDMA

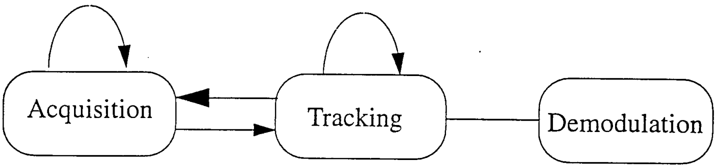
   i-th user

   j-th user



DS-CDMA: Synchronization

- The Rx requires a replica of the PN code, with the correct clock phase, in order to despread the signal.
- Therefore, Rx = "synchronization circuits" + "demod. circuits"
- The process of synchronizing the receiver to the transmitter's PN code consists of two stages:
  - **Acquisition** (coarse synchronization).
  - Tracking (fine synchronization).

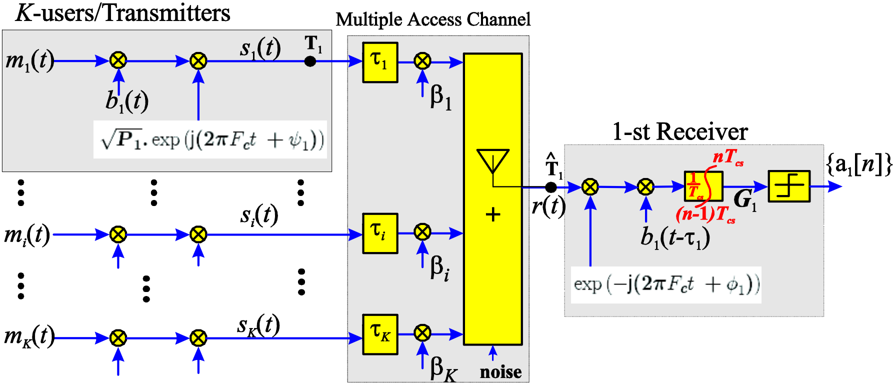


- Operation: **acquisition** ; tracking + demodulation; **loose tracking** ; **acquisition** ; tracking+demodulation; ......etc.........

Analysis of a DS BPSK CDMA System

- objective: to relate the BER p_e with the total number of users K as well as with the EUE_{equ} at the receiver.
  i.e.
  $$p_e = \mathrm{f}\left\{\text{EUE}_{equ}, K\right\} \tag{6}$$
- Main Assumptions
  - single cell system of K users,
  - $\nexists$ multipaths
  - PN code period $= N_c = \text{PG} = \frac{T_{cs}}{T_c}$
  - System=perfectly power-controlled
    (all SS signals arrive at the receiver with the same power)
    - ★ NB: power control can often be implemented in practice with great accuracy.
  - System $=$ totally asynchronous (there is no common timing reference for the transmitters/users)
    - ★ NB: This is actually an advantage of CDMA over other multiple access techniques, because all users can transmit independently and no signalling information is required.

DS/BPSK CDMA System: Modelling and Analysis



- Note that the carrier of i^{th} transmitter is $\sqrt{P_i}.\exp\left(j(2\pi F_c t + \psi_i)\right)$

- i-th user's data signal $m_i(t)$ and PN-signal $b_i(t)$:

$$\begin{cases} m_i(t) \equiv \sum_n \mathrm{a}_i[n].\ c_1(t - n.T_{cs})\,;\ \ nT_{cs} < t \leq (n+1)T_{cs} \\ b_i(t) = \sum_k \alpha_i[k].\ c_2(t - kT_{\mathbf{c}})\,;\ \ kT_c < t \leq (k+1)T_c \\ \text{with}\ \ T_{cs} = N_c T_c;\ \ \left\lfloor \frac{k}{N_c} \right\rfloor = n; \end{cases} \tag{7}$$

- The period of each user's PN-sequence is selected as $N_c = \frac{T_{cs}}{T_c}$, and therefore there is one code period per data bit (or N_c chips per bit). Thus, for the BPSK case, the processing gain PG is:

$$\mathrm{PG} = N_c = \frac{T_{cs}}{T_c} \tag{8}$$

- The transmitted signal $s_i(t)$ of the i-th user is therefore

$$s_i(t) = \sqrt{P_i}.m_i(t).b_i(t).\exp\left(j\left(2\pi F_c t + \psi_i\right)\right) \tag{9}$$

where F_c is assumed common for all carriers.

SNIRout as a function of EUE, Nc and K

- For a **perfectly synchronised system** , at the ouput of the correlator (i.e. G_1) we have:

$$\text{SNIR}_{\text{out}} \approx 2.\text{EUE}_{equ} = 2\frac{E_b}{N_j + N_0} \tag{10}$$

- However,

$$N_j = (K-1).\frac{P}{B_{ss}} = (K-1).P.T_c = \frac{(K-1).\overbrace{PT_{cs}}^{=E_b}}{N_c} = \frac{(K-1).E_b}{N_c} \tag{11}$$

- Therefore

$$\begin{aligned}\text{SNIR}_{\text{out}} &\approx 2.\text{EUE}_{equ} \\ &= 2\frac{E_b}{\frac{(K-1).E_b}{N_c} + N_0} = \frac{1}{\frac{K-1}{2N_c} + \frac{1}{2\ \text{EUE}}}\end{aligned} \tag{12}$$

BER as a function of EUE, Nc and K

- We have seen that

$$\mathrm{SNIR}_{out} \approx \left\{ \frac{K-1}{2N_c} + \frac{1}{2\ \mathrm{EUE}} \right\}^{-1} \quad (13)$$

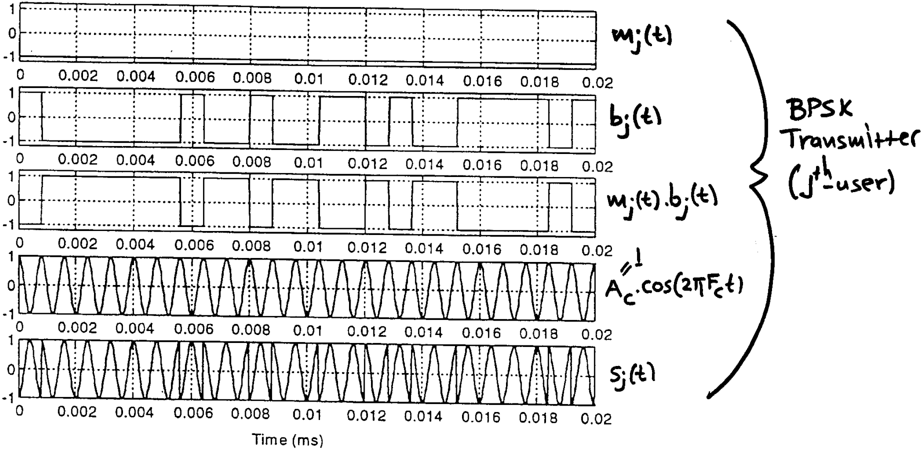
However,

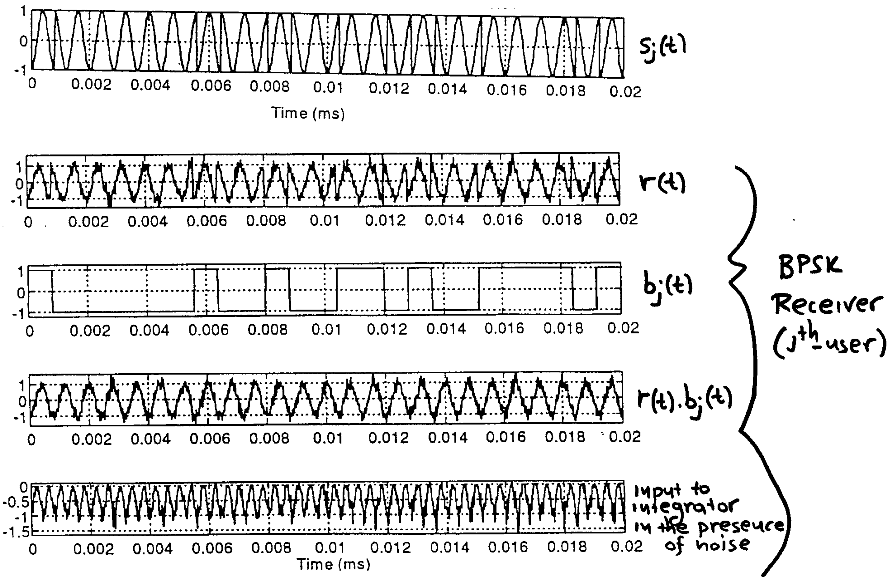
$$p_e = \mathrm{T}\left\{ \sqrt{\mathrm{SNIR}_{out}} \right\} \quad (14)$$

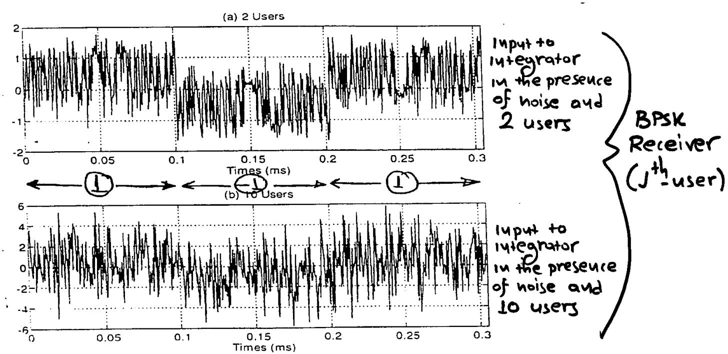
which implies that

$$p_e = \mathrm{T}\left\{ \sqrt{2\mathrm{EUE}_{equ}} \right\} = \mathrm{T}\left\{ \frac{1}{\sqrt{\frac{K-1}{2N_c} + \frac{1}{2\ \mathrm{EUE}}}} \right\} \quad (15)$$

BPSK Examples




$s_j(t)$
Time (ms)
$r(t)$
$b_j(t)$
$r(t).b_j(t)$
input to integrator in the presence of noise
Time (ms)
BPSK Receiver (j^{th} user)


(a) 2 Users
Times (ms)
(b) 10 Users
Times (ms)
Input to integrator in the presence of noise and 2 users
Input to integrator in the presence of noise and 10 users
BPSK Receiver (J^th user)
1
-1
1

Power Control

- In order to achieve the full benefits of using CDMA, the transmitted signal powers P_{s_i} **should be controlled** in such a way that received signal power, from all the users at a cell, are the same.
  This makes **power control** a **key feature** of CDMA mobile systems.

Voice Activity Factor

- Human speech contains a lot of pauses where there is no data to transmit.
  Thus a speaker is active for about half the time due to listening and pauses in speech.

The fraction of time that a speaker is active is known as the voice activity factor a

- Extensive studies have shown that $0.35 < a < 0.5$.
  A popular value used is $a = 3/8 = 0.375$
- The voice activity feature can be taken into account in a communication system by suppressing the transmission when voice is absent.
  Assuming that we have a scheme where **the carrier is turned-off during the speech idle periods** then a reduction in interference (by a factor of the voice activity) can be achieved.

- implementation of voice activity: $\begin{cases} \text{TDMA/FDMA:} & \text{very difficult} \\ \text{CDMA:} & \text{very easy} \end{cases}$
- For a large number of users the **capacity increases** by a factor $1/a$.
- Therefore, using the voice activity monitoring approach the capacity and the performance of a CDMA system will be improved (this improvement cannot be obtained in FDMA/TDMA systems)
- In particular the power of a user's signal at a specific time instant can be expressed $1 \times P_{user}$ with probability a and $0 \times P_{user}$ with probability $(1-a)$.
- Using voice activity the performance can be improved even more.

$$\textbf{BPSK} \quad : \quad \text{SNIR}_{\text{out}} = 2.\text{EUE}_{equ} = 2\frac{E_b}{N_j + N_0} \tag{16}$$

$$\text{where } N_j = \frac{(K-1).P_s.a}{B_{ss}} \tag{17}$$

- Therefore we can model the "on-off" activity of each user a binomial distribution, which implies that the probability that k user (out of K) are active is given as follows:

$$\Pr(k \ \text{ users are active}) = \binom{k}{K} a^k (1-a)^{K-k} \tag{18}$$

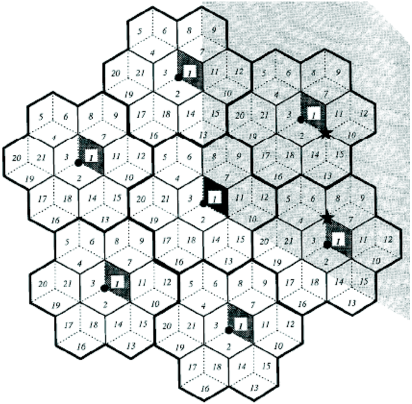
where K is the number of users per cell

- Note that as $K = \uparrow \Rightarrow$spread of distribution$=\downarrow$
- Set a threshold K_{th} , ϵ_{th} such that:

$$\Pr(\text{number of active users} > K_{th}) < \epsilon_{th} \tag{19}$$

Sectorization

- It is used in TDMA/FDMA and CDMA systems



Sectorization

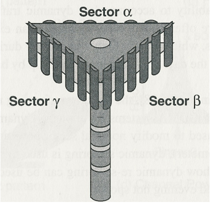
- **Sectorization** is achieved by using directional antennas instead of omnidirectional antennas.
- Each cell is divided to three sectors using **three directional antennas** each having 120° beamwidth.
- Using sectorization the performance can be improved even more. (The expected value of the total interference is reduced by a factor of $s = 3$ wrt single omnidirectional antenna case)

$$\textbf{BPSK} \quad : \quad \text{SNIR}_{\text{out}} = 2.\text{EUE}_{equ} = 2\frac{E_b}{N_j + N_0} \tag{20}$$

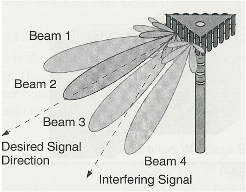
$$\text{where } N_j = \frac{(K-1).P_s.s}{B_{ss}} \tag{21}$$

In practice: $3 \text{ dB} < \text{SNIR}_{\text{out}} < 15\text{dB}$

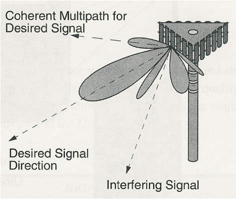
- A better approach is to use **three linear antenna arrays** (smart antennas)



antenna array



switched beam array system



adaptive array system

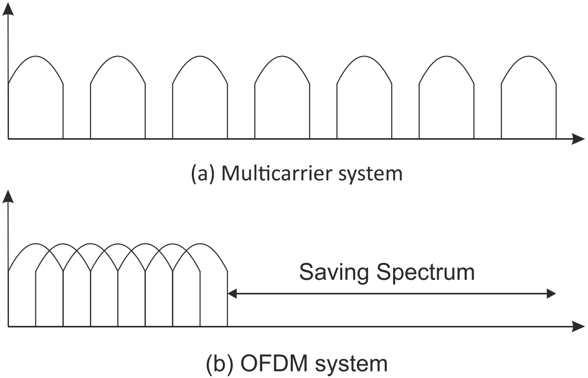
(see MEng 4thYear: E4.01)

4G

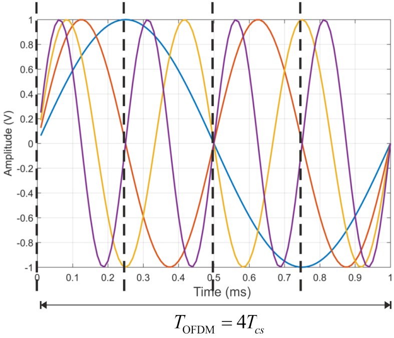
Overview of OFDM

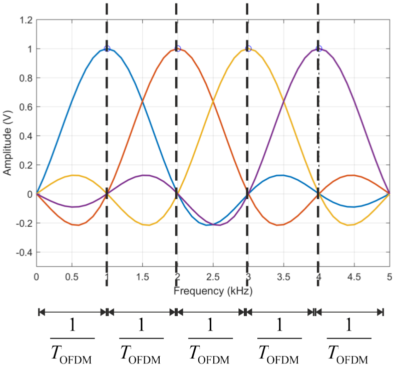
Introduction

- Orthogonal Frequency Division Multiplex (OFDM).
- Special case of multicarrier transmission $\longrightarrow$ overlapping and orthogonal narrowband subchannels.



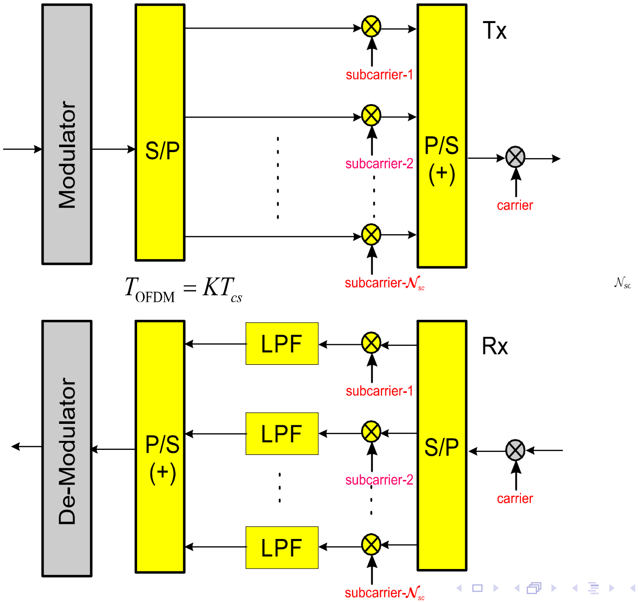
OFDM Subcarriers



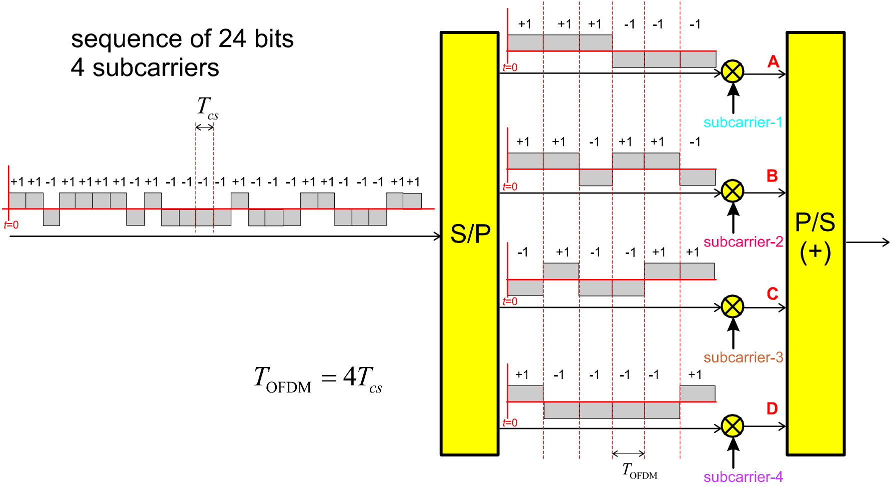


- The chosen subcarriers are harmonics and hence orthogonal to each other.
- No guard band between subcarriers are needed.
- The peak of a subarrier is precisely at the zero-crossings of its adjacent subcarriers.

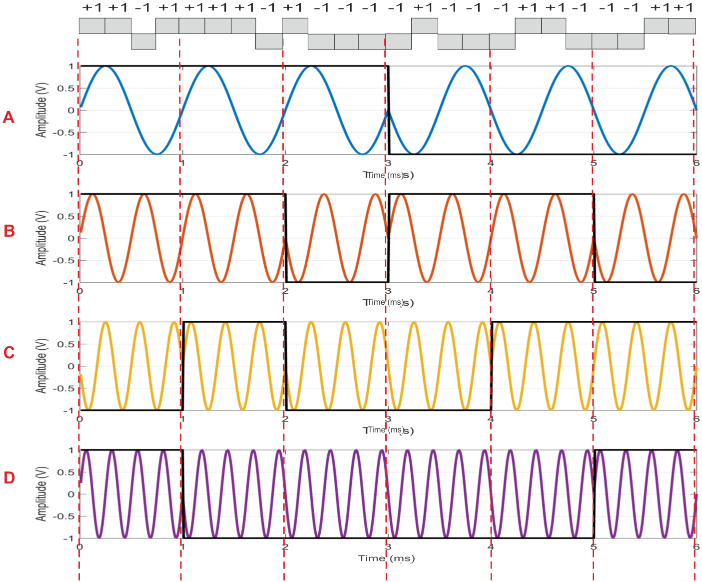
OFDM - Analogue Block Diagram



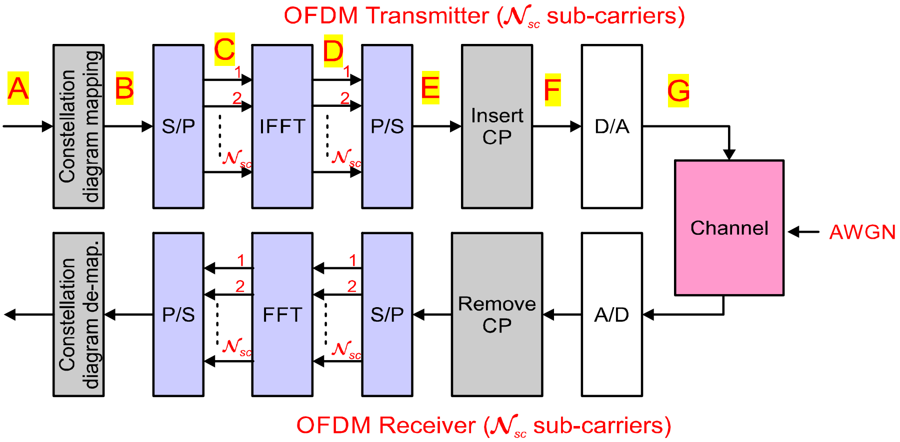
OFDM TX: Example of 4 Subcarriers



OFDM Tx Output



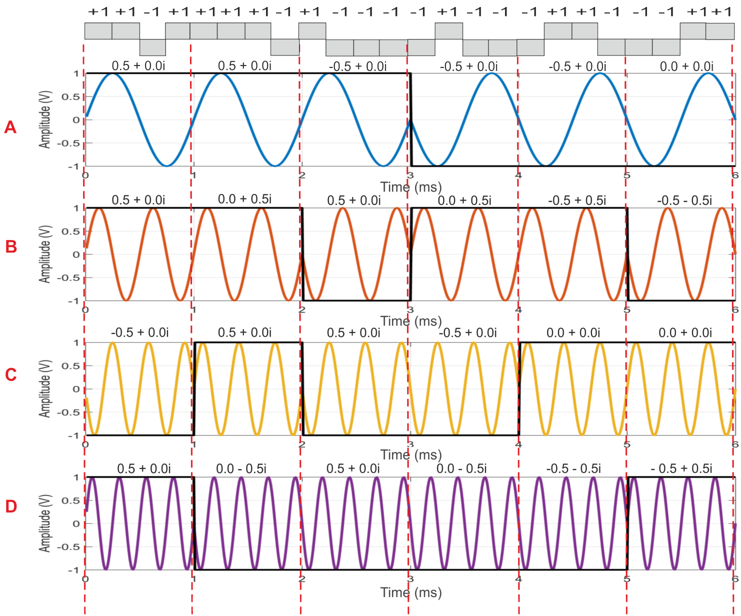
OFDM - Digital Block Diagram (in Practice)



- The stream of modulated symbols is demultiplexed onto $\mathcal{N}_{sc}$ **parallel streams** (using a S/P converter) - where $\mathcal{N}_{sc}$ is the number of subcarriers
- The $\mathcal{N}_{sc}$ parallel streams are fed to the **IFFT** .
- **Remember** :

Frequency-Domain (FD) samples	Time-Domain (TD) Samples
$X[k] \stackrel{\text{iFFT}}{\longmapsto}$	$x(t_\ell) = \frac{1}{\mathcal{N}_{sc}} \sum_{k=0}^{\mathcal{N}_{sc}-1} X[k] \exp(j2\pi k \frac{\ell}{\mathcal{N}_{sc}})$
$X[k] = \sum_{\ell=0}^{\mathcal{N}_{sc}-1} x(t_\ell) \exp(-j2\pi k \frac{\ell}{\mathcal{N}_{sc}})$	$\stackrel{\text{FFT}}{\longleftarrow} x(t_\ell)$
$\forall k = 0, 1, ..., \mathcal{N}_{sc} - 1$	$\forall \ell = 0, 1, ..., \mathcal{N}_{sc} - 1$

- Orthogonality: $\sum_{\ell=0}^{\mathcal{N}_{sc}-1} \exp(-j(2\pi k \frac{\ell}{\mathcal{N}_{sc}}) \exp(-j(2\pi m \frac{\ell}{\mathcal{N}_{sc}}) = 0, \forall k \neq m$
- The time samples at the output of the iFFT are multiplexed using a **P/S Converter** ,
- **Cyclic prefixes** are inserted.



+1 +1 -1 +1 +1 +1 +1 -1 +1 -1 -1 -1 -1 +1 -1 -1 -1 +1 +1 -1 -1 -1 +1 +1
A
0.5 + 0.0i
0.5 + 0.0i
-0.5 + 0.0i
-0.5 + 0.0i
-0.5 + 0.0i
0.0 + 0.0i
B
0.5 + 0.0i
0.0 + 0.5i
0.5 + 0.0i
0.0 + 0.5i
-0.5 + 0.5i
-0.5 - 0.5i
C
-0.5 + 0.0i
0.5 + 0.0i
0.5 + 0.0i
-0.5 + 0.0i
0.0 + 0.0i
0.0 + 0.0i
D
0.5 + 0.0i
0.0 - 0.5i
0.5 + 0.0i
0.0 - 0.5i
-0.5 - 0.5i
- 0.5 + 0.5i
Amplitude (V)
Time (ms)

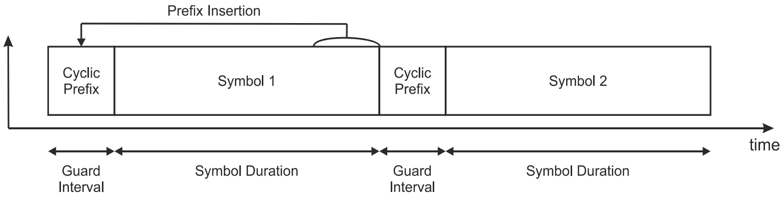
	TS1 (iFFT output)				TS2 (iFFT output)			
1st	$+1$	0.5+0.0j	0.5	**0** °	$+1$	0.5+0.0j	0.5	**0** °
2nd	$+1$	0.5+0.0j	0.5	**0** °	$+1$	0.0+0.5j	0.5	**90** °
3rd	-1	-0.5+0.0j	0.5	**180** °	$+1$	0.5+0.0j	0.5	**0** °
4th	$+1$	0.5+0.0j	0.5	**0** °	-1	0.0+0.5j	0.5	**-90** °

	TS3 (iFFT output)				TS6 (iFFT output)			
1st	$+1$	-0.5+0.0j	0.5	**180** °	-1	-0.5+0.0j	0.5	**180** °
2nd	-1	0.5+0.0j	0.5	**0** °	$+1$	0.0+0.5j	0.5	**90** °
3rd	-1	0.5+0.0j	0.5	**0** °	-1	-0.5+0.0j	0.5	**180** °
4th	-1	0.5+0.0j	0.5	**0** °	-1	0.0+0.5j	0.5	**-90** °

	TS5 (iFFT output)				TS6 (iFFT output)			
1st	-1	0.0+0.0j	0	**0** °	-1	0.0+0.0j	0	**0** °
2nd	$+1$	-0.5+0.5j	$\frac{\sqrt{2}}{2}$	**135** °	-1	-0.5-0.5j	$\frac{\sqrt{2}}{2}$	**-135** °
3rd	$+1$	0.0+0.0j	0	**-90** °	$+1$	0.0+0.0j	0	**-90** °
4th	-1	-0.5+0.5j	$\frac{\sqrt{2}}{2}$	**-135** °	$+1$	-0.5+0.5j	$\frac{\sqrt{2}}{2}$	**135** °

Cyclic Prefix, CP

- The **cyclic prefix** is a **guard interval (GI)** placed to protect OFDM signals from intersymbol interference in the presence of multipath.



- The last section of a symbol is used as a prefix in the front of the symbol.
- The duration of the guard interval T_{GI} should be

$$T_{\mathrm{GI}} > T_{\mathrm{spread}}, \quad (22)$$

to minimise **inter-symbol interference** (ISI).

OFDM: Advantages/Disadvantages

- **Disadvantages**:
  - **High peak-to-average-power-ratio (PAPR) [CR]** . An OFDM signal has a relatively large dynamic range, or PAPR. The RF amplifier is hence required to have a larger linear range resulting in a degraded efficiency level.
  - **Carrier Offset and drift sensitivity** . OFDM is more sentitive to carrier offset and drift than single carrier systems.
- **Advantages**:
  - **High spectrum efficiency** . The closely-spaced overlapping sub-carriers yield high spectrum efficiency.
  - **Less sensitive to frequency selective fading** . The overall channel is divided into multiple narrowband channels that experience flat fading individually.
  - **Easy channel equalisation** . The flat fading narrowband sub-channels are easy to equalise, compared to CDMA.

Where OFDM is Used

Wireless Standards

- **Cellular (Mobile) telecommunications** : LTE and LTE-A
- **Wi-Fi standards** : 802.11a, 802.11g, 802.11n, 802.11ac and HIPERLAN/2
- **Mobile broadband wireless access (MBWA) standard:** IEEE 802.20.
- **Broadcast standards:** DAB Digital Radio, DVB and Digital Radio Mondiale.
- **Mobile TV standard** as DVB-H, T-DMB, ISDB-T and MediaFLO forward link.

Cable Standards

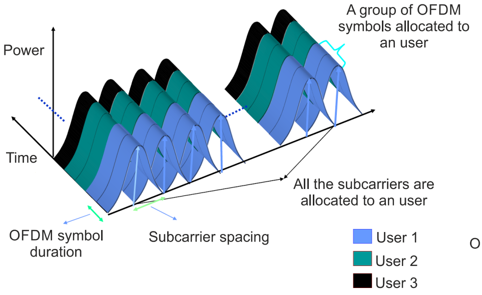
- ADSL and VDSL broadband utilising copper wiring.
- Cable TV, with DVB-C2.
- Power Line Communications
- Data over cable service interface specification (DOCSIS)

Abbreviations

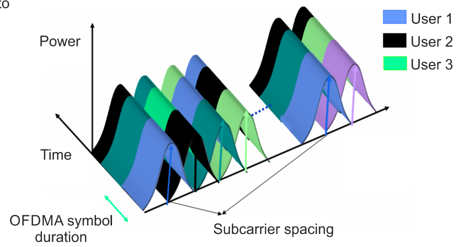
LTE	Long-Term Evolution
DAB	Digital Audio Broadcasting
DVB	Digital Video Broadcasting
DMB	Digital multimedia broadcasting
ISDB	Integrated Services Digital Broadcasting
MediaFLO	Media Forward Link Only
ADSL	Asymmetric Digital Subscriber Line
VDSL	Very-high-bit-rate Digital Subscriber Line

OFDM vs OFDMA

- **OFDMA** is the "**access**" version of OFDM, that is a scheme where the access to resources is shared between users.



(a) OFDM-TDMA Signal



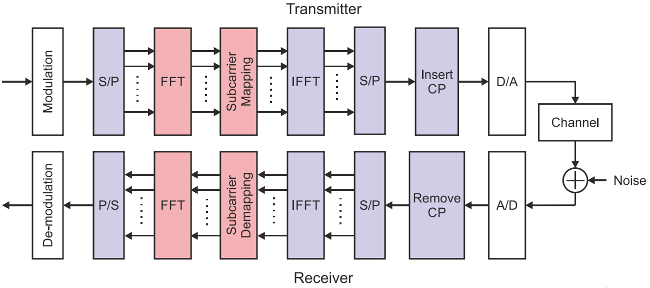
(B) OFDMA Signal

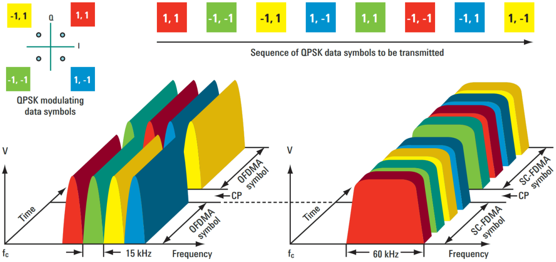
- In **OFDM-TDMA**, time-slots are attributed to each users and the whole OFDM symbol is dedicated to one user.
- In **OFDMA**, both time and frequency are distributed among users.

OFDMA Compared to CDMA

	OFDMA	**CDMA**
Channel Equalisation	OFDMA chops its large bandwith into subchannels that are easy to equalise.	CDMA requires a large bandwidth (more difficult to equalise than OFDM).
Mobility	Sensitive to Doppler shift.	Robust to Doppler shift.
Scalability	Easy to aggregate additional spectrum.	Hard to support more users.
Security	May require additional secutity measures	PN-codes are an additional level of security.

SC-FDMA



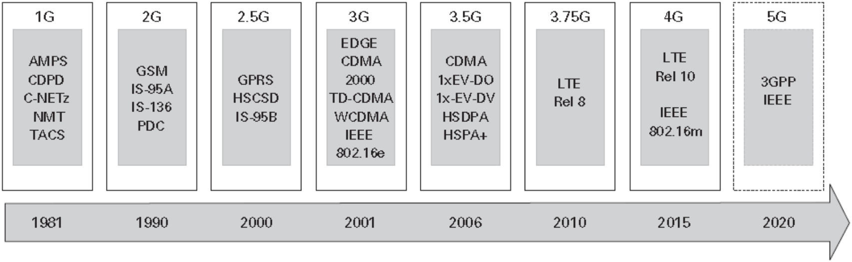


OFDMA
Data symbols occupy 15 kHz for one OFDMA symbol period

SC-FDMA
Data symbols occupy N × 15 kHz for 1/N SC-FDMA symbol periods

5G

Mobile Evolutions from 3G to 5G



Narrowband and Wideband Signals and Systems

US FCC (Federal Communications Commission): Definition

- Fractional Bandwidth B_{fr}:

$$B_{fr} \triangleq \frac{B}{F_c} \tag{23}$$

with B representing the signal bandwidth and F_c denoting the carrier frequency.

- Based on B_{fr}, the **FCC classification** is:

$$0 < B_{fr} < 0.01 \Longleftrightarrow \text{Narrow Band} \tag{24}$$

$$0.01 < B_{fr} < 0.25 \Longleftrightarrow \text{Wide Band} \tag{25}$$

$$0.25 < B_{fr} < 2.00 \Longleftrightarrow \text{Ultra Wide Band} \tag{26}$$

Main Characteristics of 3GPP/ETSI Standards

GSM

Bands: 450 MHz, 800 MHz, 900 MHz, 1800 MHz, 1900 MHz

Band width: 200 kHz

Peak data rate: 9.6 kbps

Round trip time: 600 ms

UMTS

Bands: 850 MHz, 900 MHz, 1700 MHz, 1900 MHz, 2100 MHz

Band width: 5 MHz

Peak data rate: 384 kbps

Round trip time: 75 ms

HSPA+

Bands: 850 MHz, 900 MHz, 1700 MHz, 1900 MHz, 2100 MHz

Band width: 10 MHz

Peak data rate: 42 Mbps

Round trip time: 41 ms

LTE

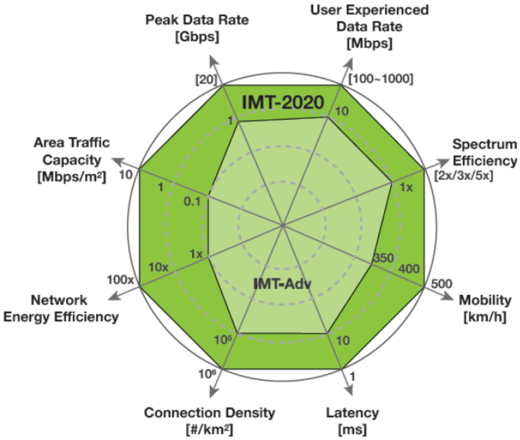
Bands: 700, 800 MHz, 850 MHz, 900 MHz, 1700 MHz,1800 MHz, 1900 MHz, 2100 MHz, 2300 MHz, 2500 MHz, 2600 MHz, 3500 MHz

Band width: 20 MHz

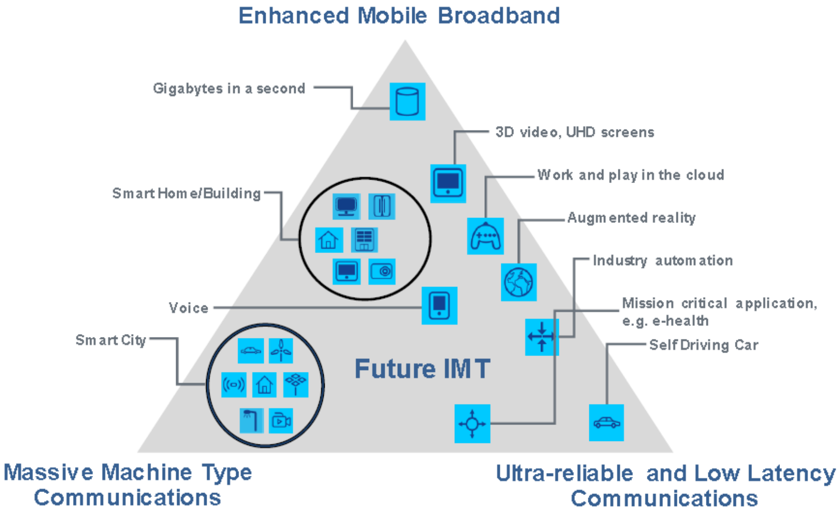
Peak data rate: 326 Mbps

Round trip time: 20 ms

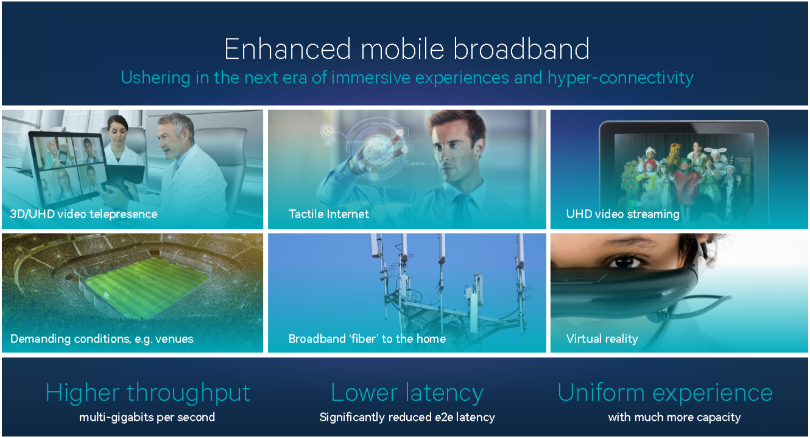
IMT2020 Spinder Diagram



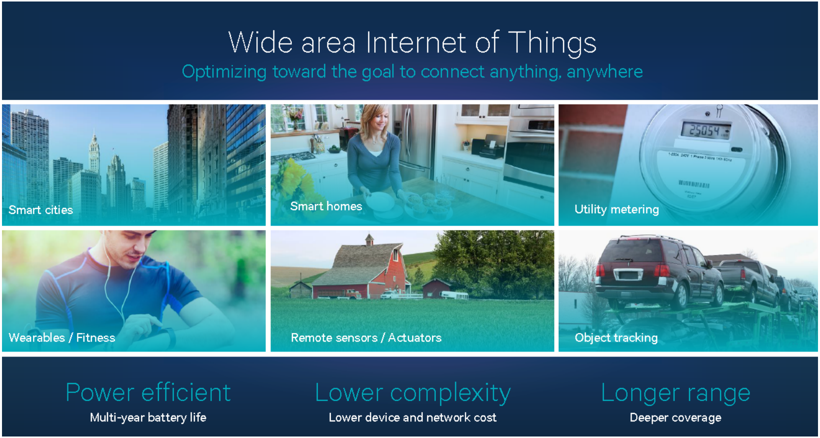
Triangle Diagram



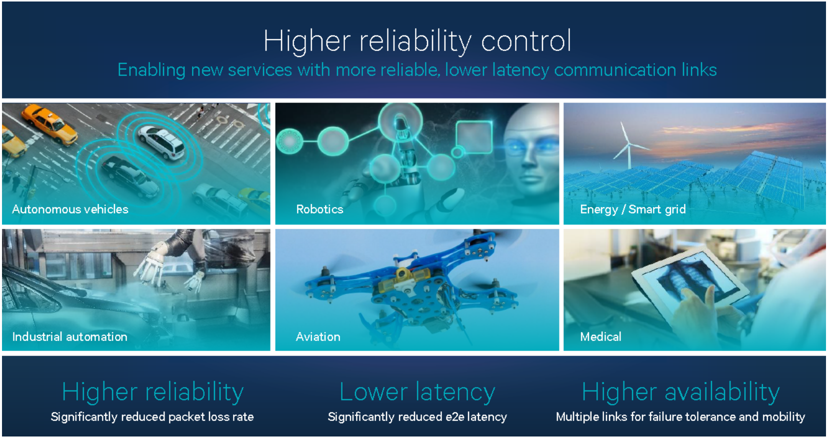
Enhanced Mobile Broadaband



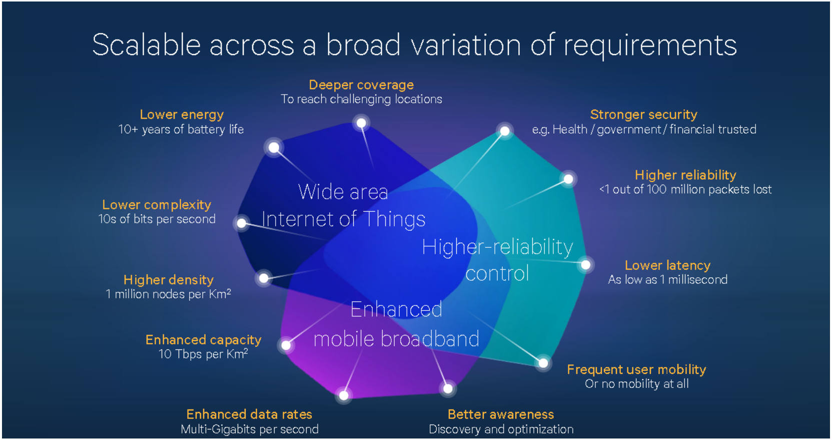
Wide Area IoT



Higher Reliability Control

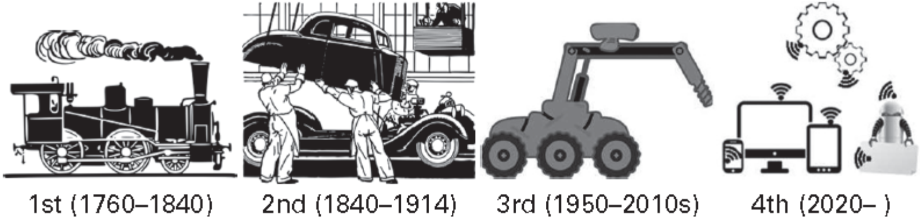


Scalability Across a Broad Variation of Requirements

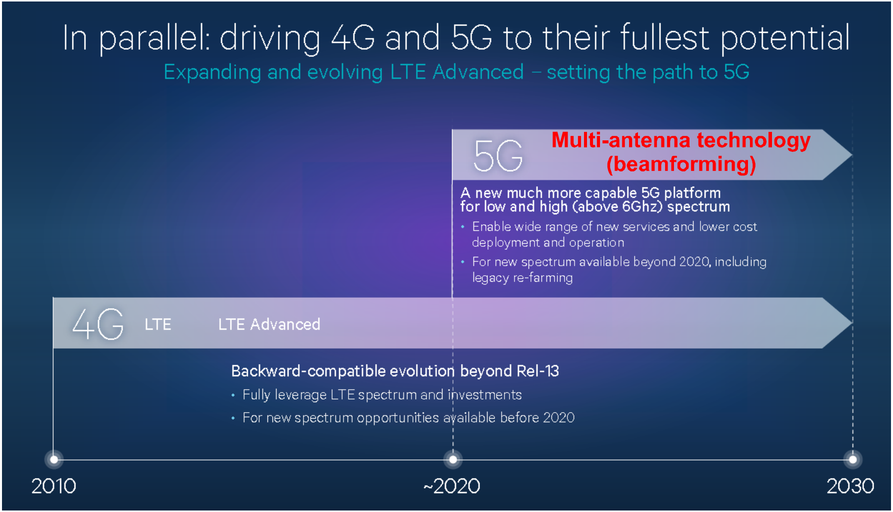


Course Concluded Remarks: Importance of 5G

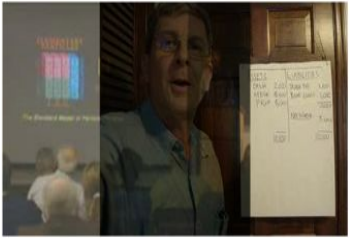
- 5G = 4th stage of Industrial Revolution!!!



Concluded Remarks: Multi-antenna Technology in 5G



Multiple Access Interference Cancellation (ULA, N=5)



Co-Channel Interference Cancellation with Motion (ULA, N=5)