E401: Advanced Communication Theory

Professor A. Manikas
Chair of Communications and Array Processing

Imperial College London

Multi-Antenna Wireless Communications

Spatiotemporal Wireless Communications, mmWave & Massive MIMO

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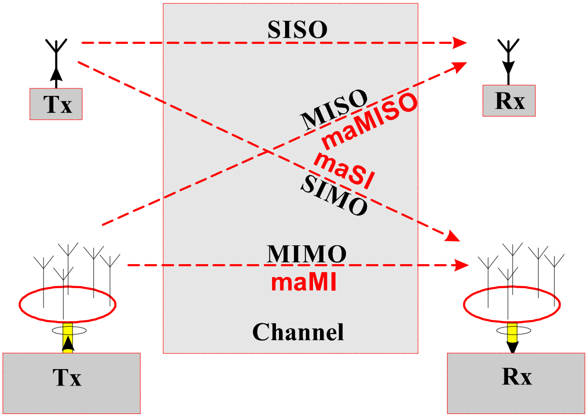
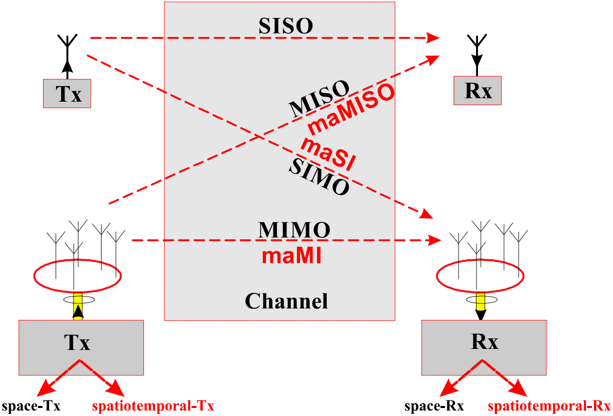
Increasing the Degrees-of-Freedom

- There is an increased interest for beamformer-based communications in 5G. Issues:
  - high path loss,
  - very dense co-channel interference environment, and
  - multipath effects in frequency selective channels.
- **Solution** : to employ **massive MIMO** , i.e. to increase the "degrees-of-freedom" by **increasing** N (remember: $M < N$)
  - Multiple-antenna (MIMO): the technology is becoming mature for wireless communications
  - It has been incorporated into wireless broadband standards like LTE and Wi-Fi.
  - *Non-parametric* massive: problematic (N=$\uparrow$ $\Rightarrow$number-of-unknowns=$\uparrow$)
  - *Parametric* massive: OKAY (N=$\uparrow$ $\Rightarrow$number-of-unknowns$\neq\uparrow$),
- **Alternatively** : use array processing (keep number of antennas fixed & extend the array manifold) $\Rightarrow$ e.g. **spatiotemporal approaches**


SISO
Tx
Rx
MISO
maMISO
maSI
SIMO
MIMO
maMI
Channel
Tx
Rx



- space-only RX: $M < N$
- spatiotemporal Rx: M can be greater than N ($M > N$)

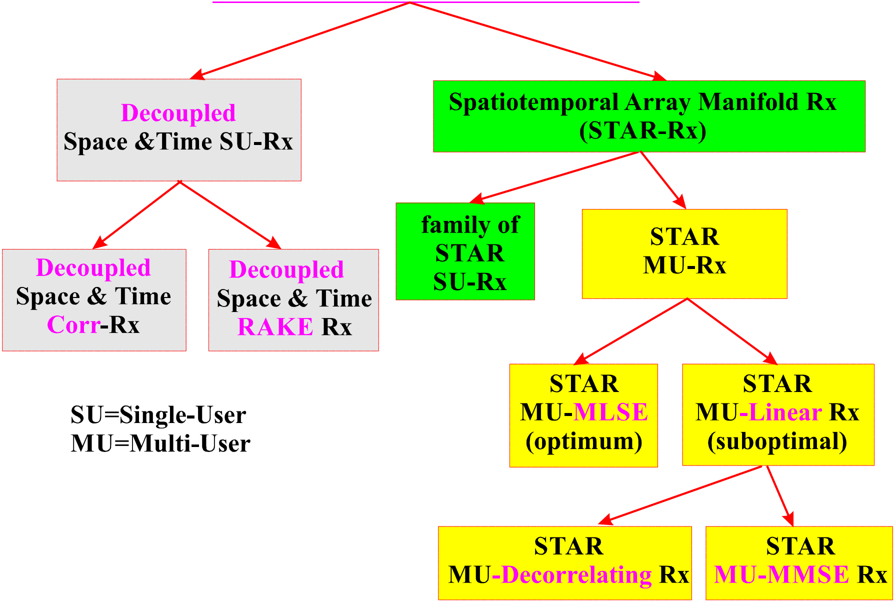
Space-Time Communications

- Space-Time Communications can be employed in both **TDMA/FDMA** and **CDMA** type systems

- In **TDMA/FDMA** the signal is not spread and only few (mainly one or two - i.e. $M < N$) strong cochannel interferences (CCI) are present when the system employs channel reuse between cells.
  The array can be used to null (remove/reduce) these few interferences

- In **CDMA** all active users use the same bandwidth and are separated by employing different PN-codes to reduce/remove the MAI interference from other user.
  i.e. in a **CDMA** environment **the array has to deal with a very large number of weak interferences** $(M > N)$.

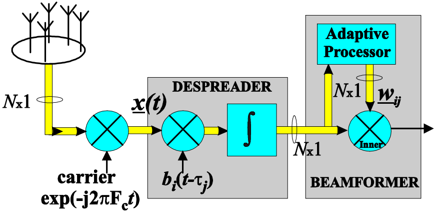
CLASSIFICATION of ST-CDMA Rx



Decoupled Space &Time CDMA Rx

- Two representative examples of decoupled 'Space-Time CDMA Base Station Receiver' architecture are shown below (to receive the j-th path of the i-th user)

1) "**Time**" and then "**Space**"

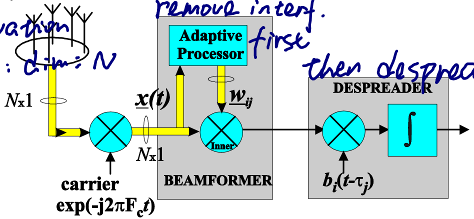


2) "**Space**" and then "**Time**"

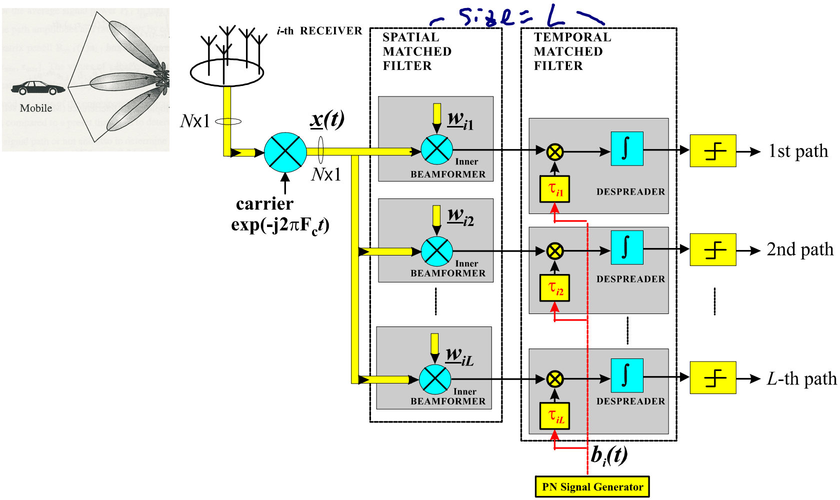
remove interf. first

Observation space: dim: N

then despread.

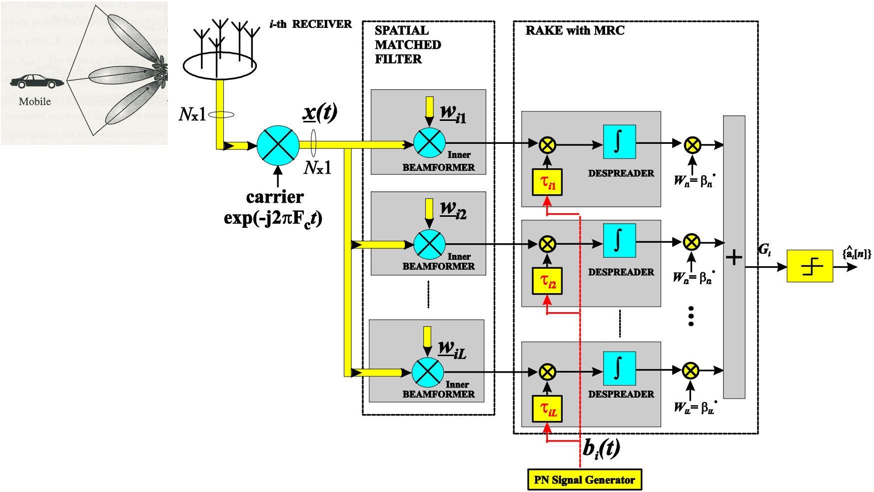


Decoupled Space & Time CDMA Receiver



- each path is received/isolated (i.e. no diversity)

Decoupled Space & Time RAKE CDMA Receiver



- Multipath diversity (all multipaths are separated and combined)

Spatiotemporal Wireless Approaches

- array manifold: we can add more wireless parameters from the Tx, Rx and channel

- For instance

DOA carrier Rx coordinate

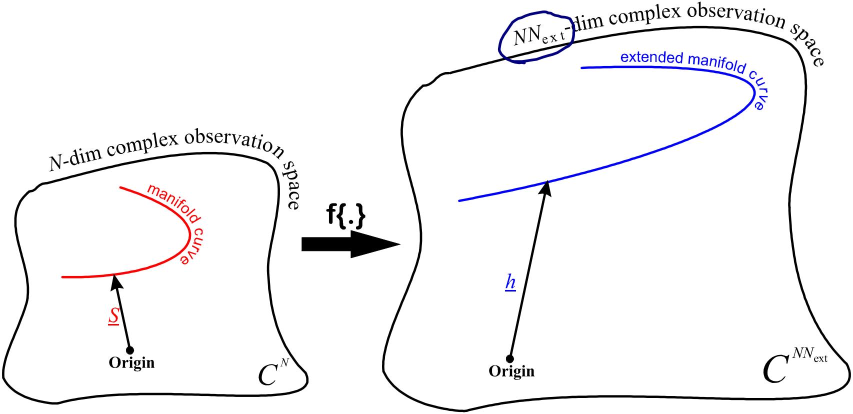
$\underline{S}(\theta, \phi, F_c, c, \underline{r}_x, \underline{r}_y, \underline{r}_z,$
pseudorandom sequ, delay, polarisation parameters,
No.of subcarriers/carriers, bandwidth, Doppler frequency).

$\Downarrow$ h: more params and freedom.

$\Downarrow$

$\underline{h} \triangleq$ spatiotemporal manifold [it is a function of the original $\underline{S}(\theta, \phi, F_c, c, \underline{r}_x, \underline{r}_y, \underline{r}_z)$]

Extended Manifolds



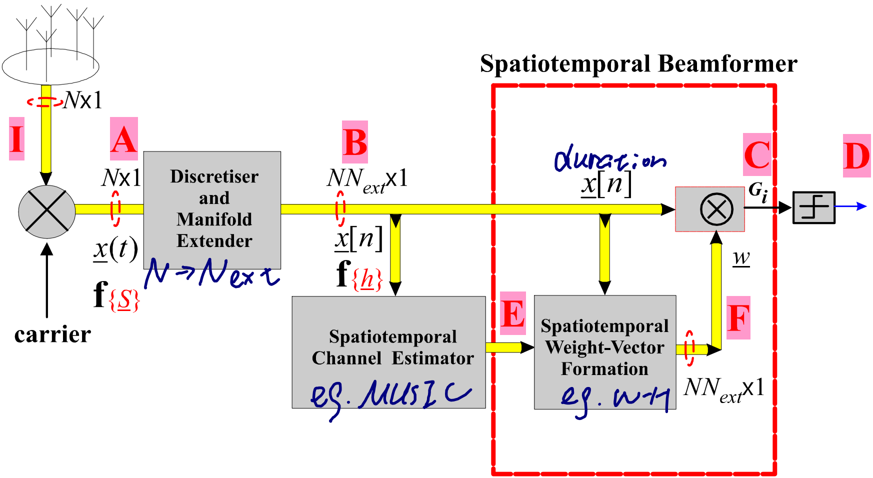
Extension of the spatial manifold to the spatiotemporal domain

- Extended array manifold vectors can be re-expressed as

$$\underline{h} = \mathbb{A}\ \underline{S} \tag{1}$$

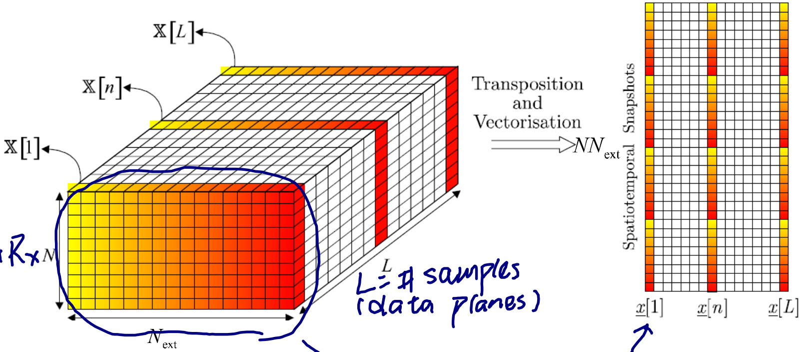
- Each vector $\underline{h}$ is produced by a different $\mathbb{A}$
- spatiotemporal manifold: $\mathcal{H} \triangleq$ locus of all vectors $\underline{h}$
- No need to perform the same analysis multiple times
- Easier to evaluate the effect of changing the system architecture

A Generic Spatiotemporal Rx-Structure



- at point $\boxed{A}$: $\underline{x}(t)$ =function$\{\underline{S}_{ij}\}+\underline{n}(t)$
- at point $\boxed{B}$: $\underline{x}[n]$ =function$\{\underline{h}_{ij}\}+\underline{n}[n]$

3D-data Cube



N_{ext} ~ PN code

3D-data Cube

frame
vectorisation

Vectorisation
of 3D-data Cube

$$\underline{x}[n] = \text{vec}\left\{\mathbb{X}[n]^T\right\} \tag{2}$$

Spatiotemporal Wireless Approaches

Introduction

- In this course we will focus on an extended manifold which is:

$$\underline{S}(\theta, \phi, F_c, c, \underline{r}_x, \underline{r}_y, \underline{r}_z,$$
$$\text{pseudorandom sequ}, \textit{delay}, \text{polarisation parameters},$$
$$\text{No.of subcarriers/carriers}, \text{bandwidth}, \text{Doppler frequency}).$$
$$\Downarrow$$
$$\underline{h} \Rightarrow \underline{\text{s}}\text{patio}\underline{\text{t}}\text{emporal } \underline{\text{ar}}\text{ray (STAR) manifolds}$$

- The above is suitable, for instance, for spatiotemporal CDMA systems

Spatiotemporal Manifold Rx

- For the j^{th} path of the i^{th} user the **array manifold vector** is

$$\underline{S}(\theta_{ij}, \phi_{ij}) = \exp(-j[\underline{r}_1, \underline{r}_2, \ldots, \underline{r}_N]^T \underline{k}(\theta_{ij}, \phi_{ij}) \in \mathcal{C}^{N \times 1}$$

  where $[\underline{r}_1, \underline{r}_2, \ldots, \underline{r}_N]$ represents the array geometry and $\underline{k}(\theta_{ij}, \phi_{ij})$ is the wavenumber vector.

- By taking the **PN-code** and **multipath delay** into consideration, we extend the concept of the array manifold vector to

  $\underline{\text{S}}\text{PATIO}-\underline{\text{T}}\text{EMPORAL}$ $\underline{\text{AR}}\text{RAY}$ (STAR) manifold vector

  defined as follows:

shifting matrix

h = S + { PN code / multipath delay

$$\underline{h}_{ij} \triangleq \underline{S}_{ij} \otimes \mathbb{J}^{l_{ij}} \underline{\mathfrak{c}}_i \in \mathcal{C}^{2\mathcal{N}_c N \times 1} \qquad (3)$$

with $\underline{S}_{ij} \triangleq \underline{S}(\theta_{ij}, \phi_{ij})$ and $\underline{h}_{ij} \triangleq \underline{h}(\theta_{ij}, \phi_{ij}, \ell_{ij})$

- **To achieve this extension,** the array received signal vector $\underline{x}(t) \in \mathcal{C}^{N \times 1}$ is transformed to a discretised signal $\underline{x}[n] \in \mathcal{C}^{2\mathcal{N}_c N \times 1}$

The "Shifting Matrix"

$\underline{\mathbb{J}}^n$: downshift by n

$(\underline{\mathbb{J}}^T)^n$: upshift by n.

- The matrix $\mathbb{J}$ is known as a **shifting matrix** (a $2\mathcal{N}_c \times 2\mathcal{N}_c$ matrix) defined as follows

$$\underline{\mathbb{J}} \cdot \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} 0 \\ a \\ b \\ c \end{bmatrix}$$

$$\underline{\mathbb{J}}^T \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} b \\ c \\ d \\ 0 \end{bmatrix}$$

$$\mathbb{J} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} = \begin{bmatrix} \underline{0}^T_{2\mathcal{N}_c - 1} & 0 \\ \mathbb{I}_{2\mathcal{N}_c - 1} & \underline{0}_{2\mathcal{N}_c - 1} \end{bmatrix} \quad (4)$$

having the property that every time the matrix $\mathbb{J}$ (or $\mathbb{J}^T$) operates on a column vector it down-shifts (or up-shifts) the elements of the vector by one.

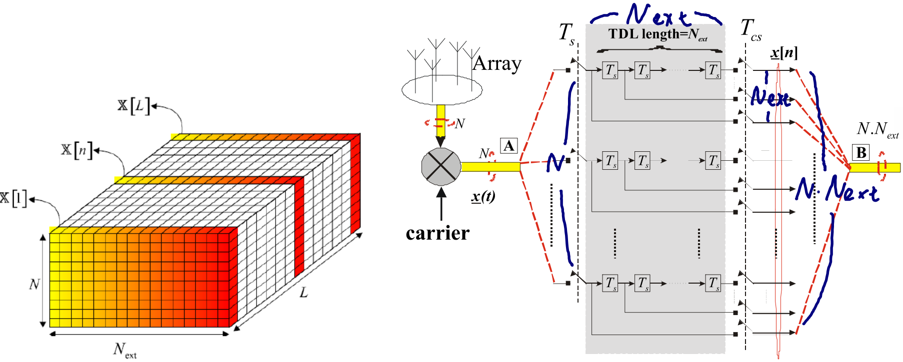
.

- For instance, $\mathbb{J}^{\ell}\underline{x}$ is a version of $\underline{x}$ down-shifted by ℓ elements, while $\left(\mathbb{J}^{T}\right)^{\ell}\underline{x}$ is a version of $\underline{x}$ up-shifted by ℓ elements.

$$\underline{x}=\begin{bmatrix}x_1\\x_2\\x_3\\\vdots\\x_K\end{bmatrix};\quad \mathbb{J}^{3}\underline{x}=\begin{bmatrix}0\\0\\0\\x_1\\x_2\\\vdots\\x_{K-3}\end{bmatrix};\quad \left(\mathbb{J}^{T}\right)^{2}\underline{x}=\begin{bmatrix}x_3\\x_4\\\vdots\\x_K\\0\\0\end{bmatrix}$$

Example: Spatiotemporal Rx Architecture

- $N_{ext} = 2 \times q \times \mathcal{N}_c$, where: $\mathcal{N}_c$=code period; q =oversampling factor.



- Note: In this course: $q = 1$.
  That is, the array received signal vector $\underline{x}(t)$ is discretised by a chip rate sampler, i.e. $T_s = T_c$.

- The discrete samples are then passed through a tapped-delay line of length equal to $2\mathcal{N}_c$.
  This is to ensure that one whole data symbol of the desired user and the corresponding multipath components are captured within this $2\mathcal{N}_c$ interval.
- As shown in preprocessor's figure the received space-time signal vector $\underline{x}[n]$ is formed by concatenating the contents of the tapped-delay lines of all the antennas,

$$\text{i.e. } \underline{x}[n] = \left[\underline{x}_1[n]^T, \underline{x}_2[n]^T, \ldots, \underline{x}_N[n]^T\right]^T \in \mathcal{C}^{2\mathcal{N}_c N\times 1} \quad (5)$$

$$= \text{vec}(\mathbb{X}[n]^T) \quad (6)$$

where $\underline{x}_k[n]$ represents the contents of the tapped-delay line at the k^{th} antenna associated with the n^{th} data symbol period, and

$$\mathbb{R}_{xx} = \mathcal{E}\left\{\underline{x}[n].\underline{x}[n]^H\right\} \in \mathcal{C}^{2\mathcal{N}_c N\times 2\mathcal{N}_c N} \quad (7)$$

- Note that the whole theory of PART C can be applied using the above $\mathbb{R}_{xx}$

Estimation Problem M>N

Spatiotemporal Channel Estimation

- The receiver initially estimates, over an observation time, the spatio-temporal manifold parameters of the desired signal(s), which are then employed to remove the MAI and ISI terms
- The estimation, for instance, can be carried out using the following 2D. 'STAR' subspace cost function $\left(n\text{-}th\right.$ interval):

$$\xi(\theta,\ell)=\frac{1}{\underline{h}(\theta,\ell)^H \mathbb{P}_{\mathrm{n}}\, \underline{h}(\theta,\ell)} \tag{8}$$

- In Equation 8 the matrix $\mathbb{P}_{\mathrm{n}}$ is the projection operator associated with the "noise subspace" of

$$\mathbb{R}_{xx}=\mathcal{E}\left\{\underline{x}\left[n\right].\underline{x}\left[n\right]^H\right\}$$

Main Properties of STAR subspace-type CDMA Receivers:

1. blind (estimation of channel parameters without pilots)
2. separates/estimates all the paths of the desired user in the presence of MAI
3. The number of multipaths that can be resolved is not constrained by the number of array elements (antennas), i.e.

$$M > N$$

4. near-far resistant (i.e. in CDMA there is no need for power control)
5. superresolution capabilities.

STAR Array Pattern

- If the array elements are weighted by complex-weights then the **array pattern** provides the gain of the array as a function of DOAs

$$\text{if } (\theta,\ell) \longmapsto \underline{h}(\theta,\ell) \text{ then } g(\theta,\ell) = \underline{w}^H \underline{h}(\theta,\ell) \tag{9}$$

where $g(\theta,\ell)$ denotes the STAR gain of the array for a signal arriving from direction θ and delayed by τ

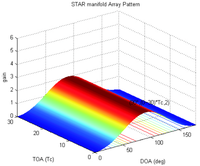
$$\text{where } \ell = \left\lceil \frac{\tau}{T_c} \right\rceil \operatorname{mod} \mathcal{N}_c \tag{10}$$

Then

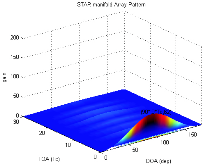
The function $g(\theta,\ell), \forall\theta$ and $\forall\ell$, is known as **the STAR Array Pattern**

- N.B.: default pattern :
  - space only:
    $g(\theta,\ell) = \underline{1}_{2N\mathcal{N}_c}^T \underline{h}(\theta,\ell)$, i.e. $\underline{w} = \underline{1}_{2N\mathcal{N}_c}$ (i.e. no weights)
  - spatiotemporal:
    $g(\theta,\ell) = (1_N \otimes \underline{c})^T\, \underline{h}(\theta,\ell)$, i.e. $\underline{w} = \underline{h}(90^\circ, 0T_c)$, (i.e. no weights)

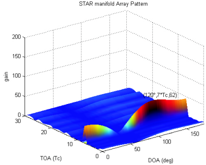
- As an example consider a Uniform Linear Array of N elements using a PN-code of length $\mathcal{N}_c = 31$. The STAR array pattern for $\underline{w} = \underline{\mathfrak{h}}\left(90°, 15T_c\right)$ and $N = 2, 3, 4, 5$ is as follows:



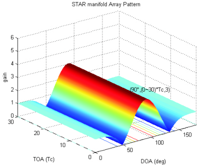
$N = 2, \underline{w} = \underline{1}_{2N\mathcal{N}_c}$



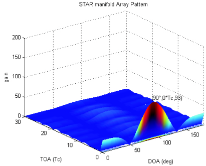
$N = 2, \underline{w} = \underline{h}(90^{\circ}, 0T_c)$



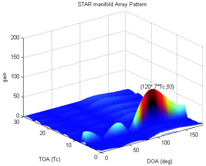
$N = 2, \underline{w} = \underline{h}(120^{\circ}, 7T_c)$



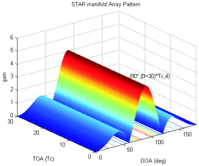
$N = 3, \underline{w} = \underline{1}_{2N\mathcal{N}_c}$



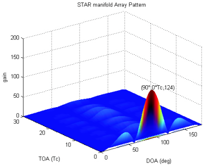
$N = 3, \underline{w} = \underline{h}(90^{\circ}, 0T_c)$



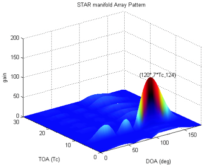
$N = 3, \underline{w} = \underline{h}(120^{\circ}, 7T_c)$



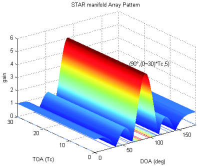
$N = 4, \underline{w} = \underline{1}_{2N\mathcal{N}_c}$



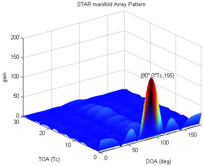
$N = 4, \underline{w} = \underline{h}(90^\circ, 0T_c)$



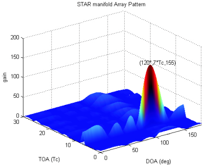
$N = 4, \underline{w} = \underline{h}(120^\circ, 7T_c)$



$N = 5, \underline{w} = \underline{1}_{2N\mathcal{N}_c}$

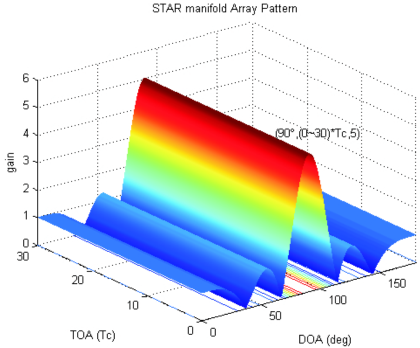


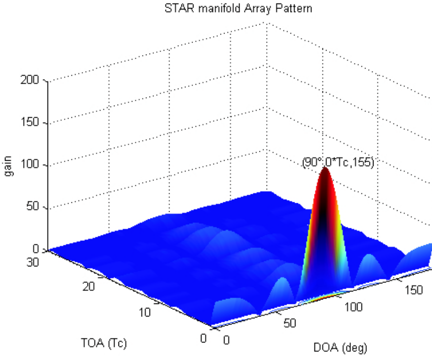
$N = 5, \underline{w} = \underline{h}(90^\circ, 0T_c)$



$N = 5, \underline{w} = \underline{h}(120^\circ, 7T_c)$

Example: Space-only & Spatiotemporal Gain Patterns





Spatiotemporal Beamformers

- If a single-user Rx (SU-Rx) is used then we only need to estimate the channel parameters of the i-th user only (with reference to the last figure, these are provided at the output of "Processor-2". Then, the STAR manifold matrix of the i-th user can be formed in the block "Processor-3" as follows

$$\mathbb{H}_i = \left[\underline{h}_{i1}, \quad \underline{h}_{i2}, \quad ..., \quad \underline{h}_{iL_p}\right] \in \mathcal{C}^{2N\mathcal{N}c \times L_p} \tag{11}$$

  where L_p is the number of multipaths.

- If a multi-user Rx (MU-Rx) is used then the channel estimator ("Processor-2") should provide estimates for all users and thus Equ. 11 should be formed in the block "Processor-3" for every i (i.e. $\forall i$).

- Examples of spatiotemporal weight vectors to receive the multipath signals from the *i*-th user:
  - spatiotemporal-RAKE (SU):

$$\underline{w}_i = \mathbb{H}_i \underline{\beta}_i \tag{12}$$

  - spatiotemporal-subspace Rx (SU)

$$\underline{w}_i = \text{constant} \times \mathbb{P}_n \mathbb{H}_i \left(\mathbb{H}_i^H \mathbb{P}_n \mathbb{H}_i \right)^{-1} \underline{\beta}_i . \tag{13}$$

where a scalar constant is used as a normalising factor such that $\|\underline{w}_i\| = 1$.
and $\mathbb{P}_\text{n}$ is the projection operator associated with the "noise subspace" of $\mathbb{R}_{xx} = \mathcal{E}\left\{ \underline{x}[n] . \underline{x}[n]^H \right\}$

Spatiotemporal Capacity

- **SISO capacity** :

$$C = B\log_2(1 + \mathrm{SNIR}_{out}) \quad \text{bits/sec}$$

- **MIMO Capacity** :

$$C = B\log_2\left(\frac{\det(\mathbb{R}_{xx})}{\det(\mathbb{R}_{nn})}\right) \quad \text{bits/sec}$$

- If **bandwidth** $\longrightarrow \infty$ then $C = ?$

psd. associated with all other users.

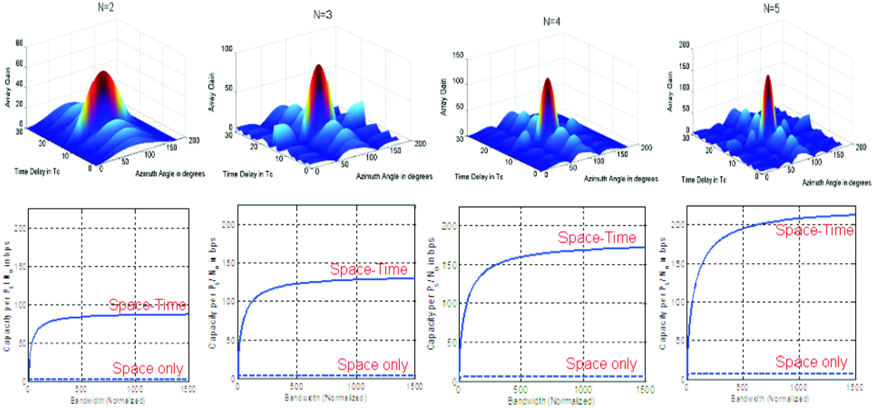
$$\text{SISO} \quad : \quad \lim_{B\to\infty} C = 1.44\frac{P_s}{N_0 + N_J}$$

beamforming nulls

$$\text{space-only SIMO} \quad : \quad \lim_{B\to\infty} C = N \times 1.44\frac{P_s}{N_0 + \underset{0}{N_J \downarrow}}$$

$$\text{spatiotemporal-SIMO} \quad : \quad \lim_{B\to\infty} C = N \times N_{ext} \times 1.44\frac{P_s}{N_0 + \underset{0}{N_J \downarrow}}$$

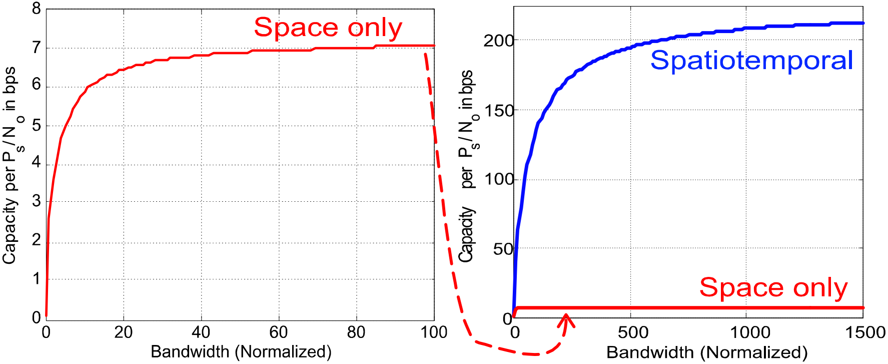
- Capacity gain of arrayed-CDMA-Rx employed joint space-time (spatiotemporal) processing:



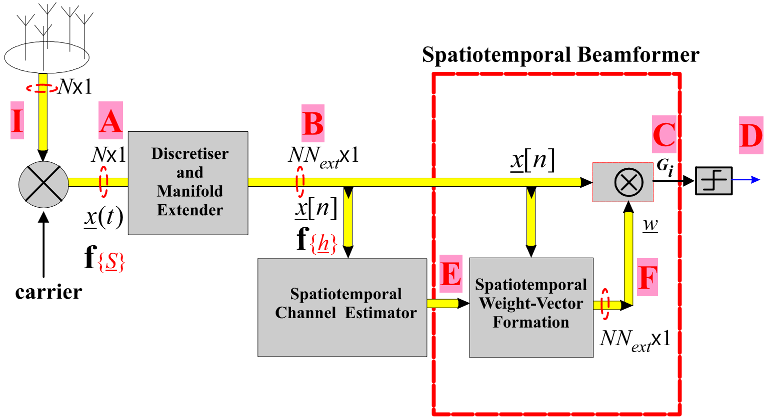
$$\lim_{B\to\infty} C = N\mathcal{N}_c \times 1.44 \frac{P_s}{N_0 + N_j \downarrow}$$

Space and Spatiotemporal Capacity Curves

$N = 5$ antennas



Example-1: Multipaths



- at point $\boxed{A}$: $\underline{x}(t) = \text{function}\{\underline{S}_{ij}\} + \underline{n}(t)$
- at point $\boxed{B}$: $\underline{x}[n] = \text{function}\{\underline{h}_{ij}\} + \underline{n}[n]$

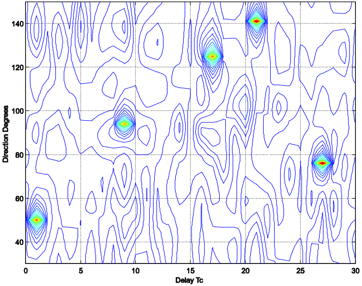
- 3 users, 5 paths per user, 1st user=desired

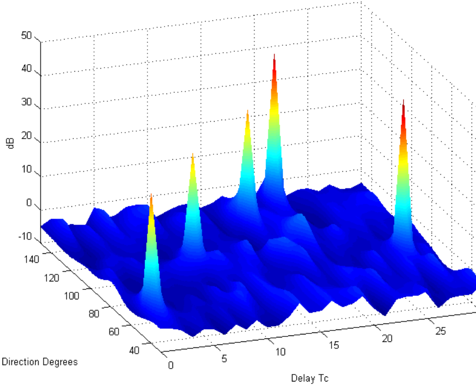
User 1 (Desired)	Path 1	Path 2	Path 3	Path 4	Path 5
Path Delay (T_c)	1	9	17	21	27
Path Direction (^{o})	50	94	125	141	76
Path Coefficient	-0.10 + 0.26**j**	-0.01 - 0.24**j**	-0.31 - 0.02**j**	-0.31 - 0.02**j**	0.42 - 0.35**j**

User 2 (Interfer)	Path 1	Path 2	Path 3	Path 4	Path 5
Path Delay (T_c)	4	8	17	26	27
Path Direction (^{o})	92	35	149	67	61
Path Coefficient	-0.20 + 0.56**j**	-0.41 - 0.74**j**	-0.39 - 0.92**j**	-0.91 - 0.12**j**	0.76 - 0.00**j**

User 3 (Interfer)	Path 1	Path 2	Path 3	Path 4	Path 5
Path Delay (T_c)	2	13	19	25	27
Path Direction (^{o})	103	84	80	79	116
Path Coefficient	-0.15 + 0.27**j**	-0.71 - 0.24**j**	-0.11 - 0.01**j**	-0.21 - 0.05**j**	0.45 - 0.55**j**

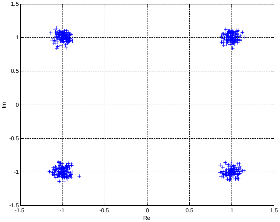
- Surface and contour plots of the cost function (Equ 8) shows that all 5 path delays and directions are correctly estimated



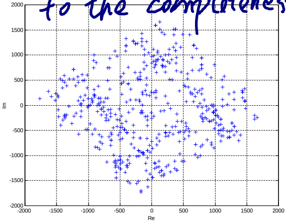


Constellation Diagram (Decision Variables):

STAR MU receiver is sensitive to the completeness of info.

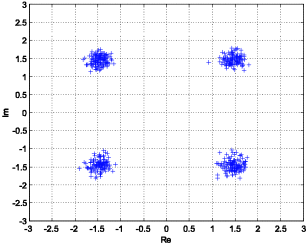


ST Decorrel. MU Rx

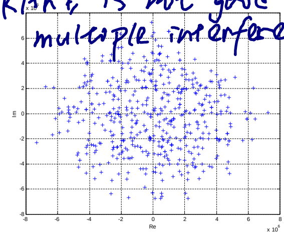


ST Decorrel. MU Rx (Incomp)

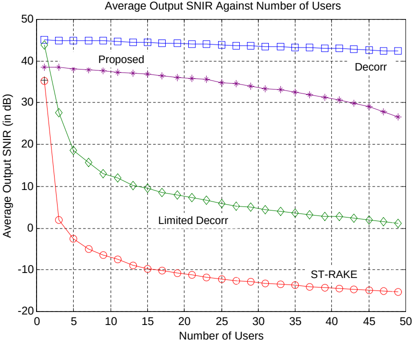
RAKE is not good for multiple interferences.



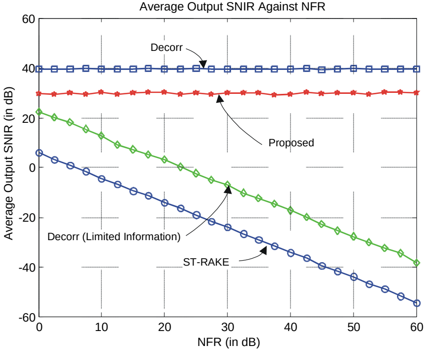
STAR manifold Rx



ST-RAKE SU Rx

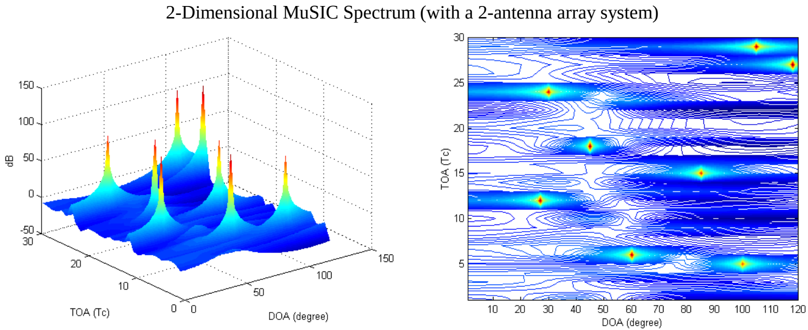


$\mathrm{SNIR}_{out}=\mathrm{f}\{M\}$



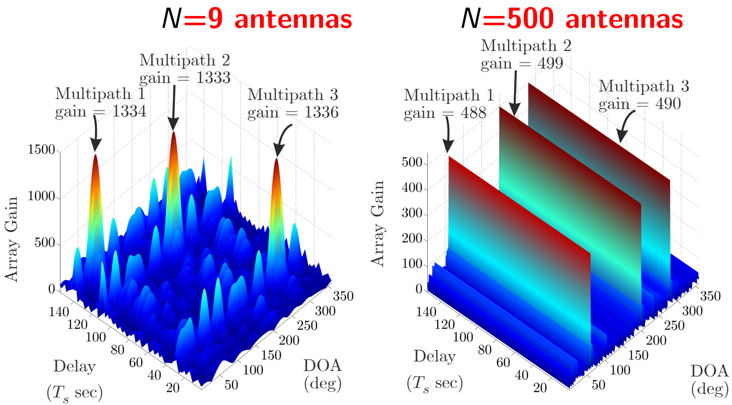
'Near-Far' Resistance

- Two antennas= good for "handsets"
- Example Desired user's parameters = 8 paths with (TOA in T_c, DOA in degrees) as follows:
  - $(5, 100^\circ), (6, 60^\circ), (12, 27^\circ), (15, 85^\circ),$
    $(18, 45^\circ), (24, 30^\circ), (27, 118^\circ), (29, 105^\circ)$
  - The desired user's STAR MUSIC-type spectrum (and contour diagram) for an array of $N = 2$ antennas (good for a handset) operating in the presence of three CDMA users is shown below:



Example-2: Spatiotemporal Beamformer versus maMI (parametric)

- see IEEE Transactions on Wireless Comms: "*Spatiotemporal-MIMO Channel Estimator and Beamformer for 5G*" (very recently published)
- Rx Antenna arrays
  - Circular Array of N=**9** antennas: **Spatiotemporal beamformer** (16x9).
  - Circular Array of N=**500** antennas: **Massive MIMO** (maMI, 16x500)
- **4 co-channel users** with **3 paths per user** in a frequency selective channel
- the spatiotemporal manifold incorporates the following system parameters: 5 subcarriers and a pn-code of length 15.



(a) Beampattern of a Doppler-STAR-subspace receiver consisting of 9 antenna elements.

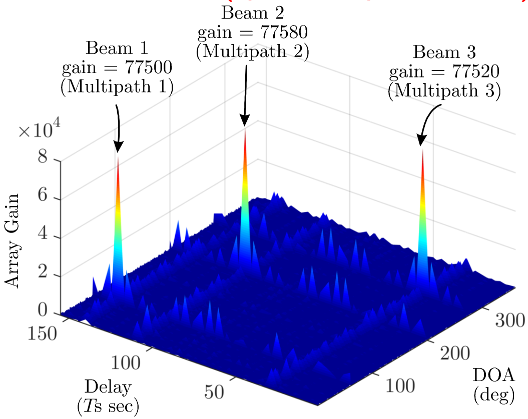
(b) Beampattern of a massive MIMO subspace receiver consisting of 500 antenna elements.

- The **9-antenna** spatiotemporal beamformer provides
  - higher gain and spatiotemporal selectivity
  - better performance ($\approx$ 15dB, see paper)

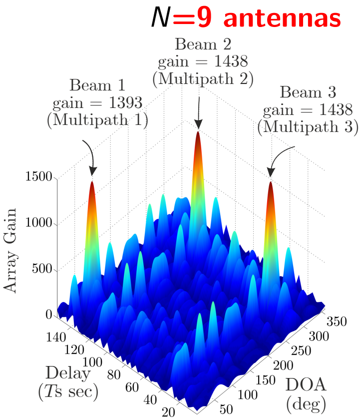
than a traditional **500-antenna** MIMO system

Example-2: Spatiotemporal Beamformer (cont.)

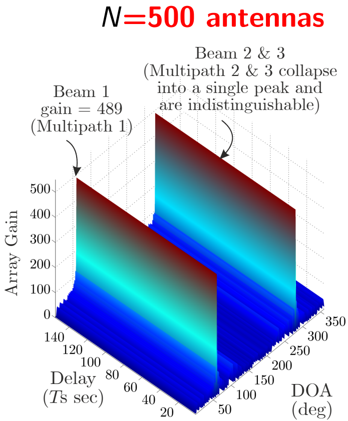
N=500 antennas (spatiotemporal maMI)



Example-2: Spatiotemporal Beamformer (Co-directional Signals)

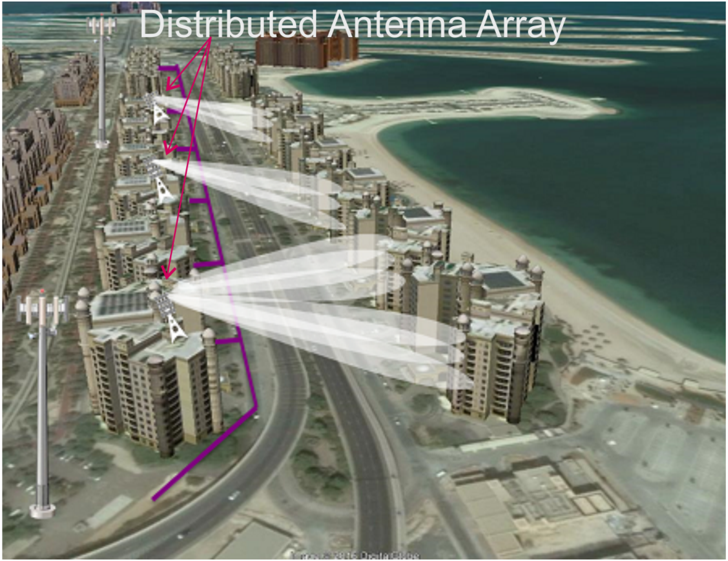


(a) Beampattern of a Doppler-STAR-subspace receiver consisting of 9 antenna elements.



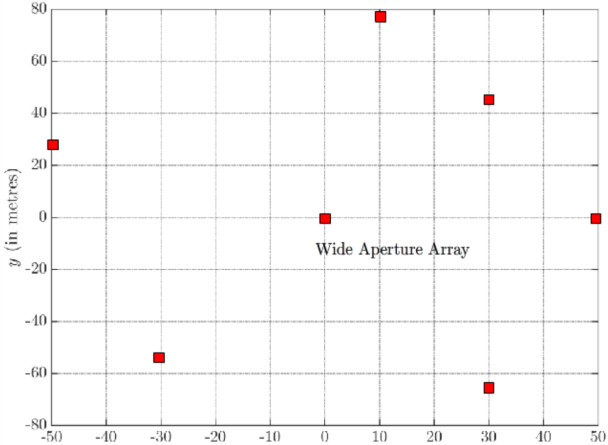
(b) Beampattern of a massive MIMO subspace receiver consisting of 500 antenna elements.

Distributed Antenna Arrays (or Large Aperture Arrays)



Introduction

- Classification:
  - small aperture arrays
  - large/wide aperture or distributed arrays (many applications,e.g. repetitive localisation for trajectory tracking of mobile signals)

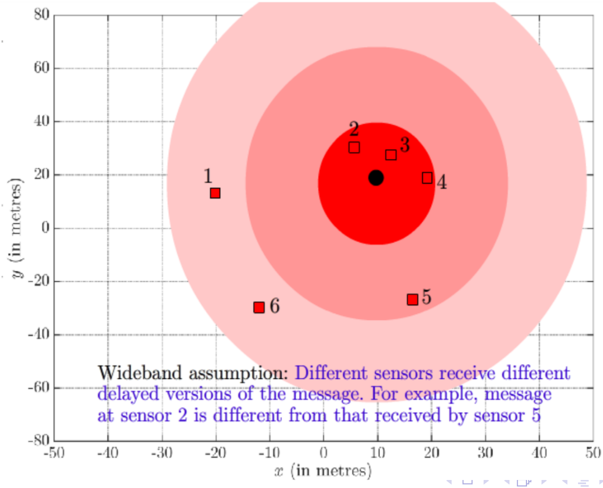


Wide Band Assumption (WB-assumption): Definition

- If the transmitted wavefront changes when travel across the sensors of the array
  $\Rightarrow$ different sensors see different parts of the transmitted signal
  $=$ this is defined as the "wideband-assumption" (WB-assumption).
- this should not be confused with the term "wideband signals".
- If the array elements are distributed in space with large inter-sensor spacings, the WB-assumption is essential.

Wideband vs Narrowband assumption

- **WB-assumption**: It is a function of the **array geometry** , **source location** and **signal bandwidth**



WideBand Assumption Signal Model

- NB-assumption and WB-assumption for M sources:

$$\text{NB-assumption:} \qquad \underline{x}(t) = \sum_{i=1}^{M} \underline{S}_i m_i(t) + \underline{n}(t) \tag{14}$$

$$\text{WB-assumption:} \qquad \underline{x}(t) = \sum_{i=1}^{M} \underline{S}_i \odot \underline{\mathrm{m}}_i(t) + \underline{n}(t), \tag{15}$$

where, the "spherical wave manifold vector" is given by

$$\underline{S}_i = \underline{S}(\theta_i, \rho_i, \text{array geometry, carrier freq})$$

- Covariance Matrix
  - NB-assumption:

$$\mathbb{R}_{xx} = \sum_{i=1}^{M} P_i \underline{S}_i \underline{S}_i^H + \mathbb{R}_{nn} \tag{16}$$

  - WB-assumption:

$$\mathbb{R}_{xx} = \sum_{i=1}^{M} \underline{S}_i \underline{S}_i^H \odot \mathbb{R}_{\underline{\mathrm{m}}_i \underline{\mathrm{m}}_i} + \mathbb{R}_{nn} \tag{17}$$

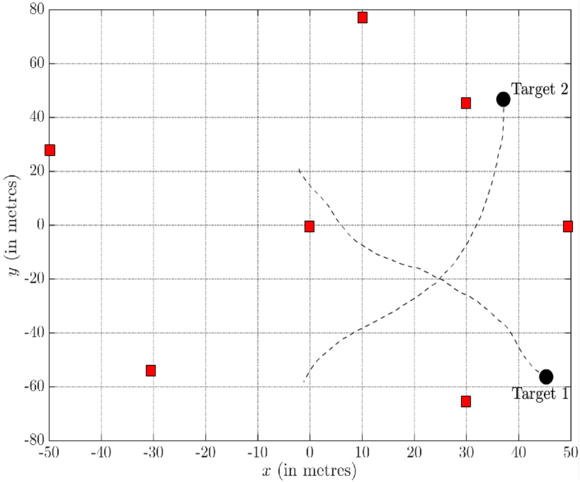
where

$$\mathbb{R}_{\underline{\mathrm{m}}_i \underline{\mathrm{m}}_i} = \mathcal{E}\left\{ \underline{\mathrm{m}}_i(t)\, \underline{\mathrm{m}}_i(t)^H \right\} \tag{18}$$

Example: Spatiotemporal Multisource Tracking

- see IEEE Trans on Aerospace and Electronic Systems, 2017 "*Multi-source Spatiotemporal Tracking using Sparse Large Aperture Arrays*", pp.837-853
- In this work a new spatiotemporal-state-space model is presented
- This model incorporates
  - both the WB and NB assumptions:
  - the geometry of an array of sensors
    - ★ array with sensors distributed in space,
    - ★ under the wideband assumption,
  - the targets/sources parameters (kinematics of the targets):
    - ★ ranges,
    - ★ directions,
    - ★ velocities and associated Doppler effects.

Example (cont.)



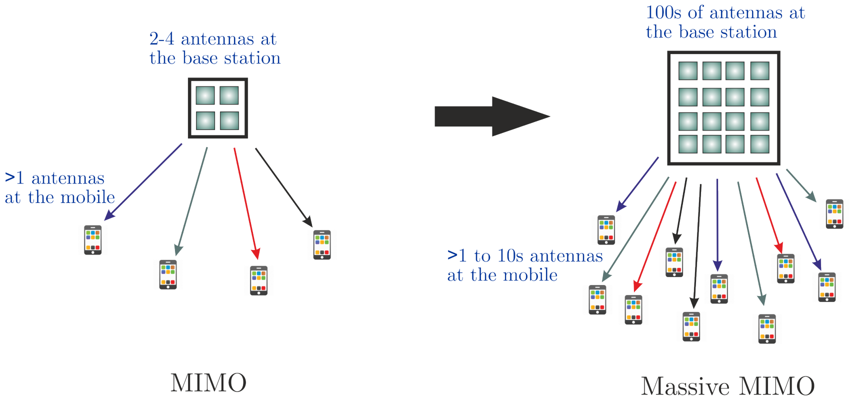

MASSIVE MIMO

Massive MIMO: Introduction

- **MIMO** : The more antennas N the transmitter/receiver is equipped with, the more the possible signal paths and the better the performance in terms of data rate and link reliability.
- The price to pay is
  - increased complexity of the hardware (number of RF amplifier frontends) and
  - the complexity and **energy consumption** of the signal processing at both ends.

Massive MIMO: What and Why?

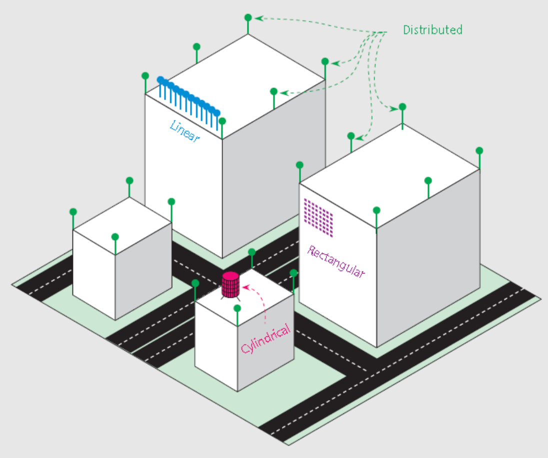
- Massive MIMO (also known as Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO and Full-Dimension MIMO)
- **Massive MIMO** = Employing 100s of antennas at the base station.

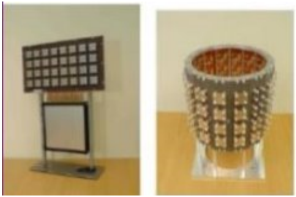


- **maMI** : makes a clean break with current practice through the use of a **very large number of antennas** N (e.g., hundreds or thousands) that are operated fully coherently and adaptively.
  - Extra antennas
    $\Downarrow$
    focusing the transmission and reception of signal energy into ever-smaller regions of space
    $\Downarrow$
    huge improvements in throughput and energy efficiency
  - MaMI was originally **envisioned** for **time division duplex (TDD)** operation (channel estimation is carried out only on the uplink and the estimated parameters are used in the downlink),
  - MaMI can **potentially be applied** also in **frequency division duplex (FDD)** operation (channel estimation can be carried out on both uplink and downlink).

- Other benefits of massive MIMO include:
  - the extensive use of inexpensive low-power components,
  - reduced latency,
  - simplification of the media access control (MAC) layer, and
  - robustness to interference and intentional jamming.
- While massive MIMO renders many traditional research problems irrelevant, it uncovers entirely new problems that urgently need attention; for example,
  - the challenge of making many **low-cost low-precision components** to work effectively together,
  - the need for new **channel estimation** approaches,
  - **reducing internal power consumption** to achieve total energy efficiency reductions

maMI BS Antenna Geometries





Massive MIMO, Macro-cells

Summary of Main Advantages and Challenges

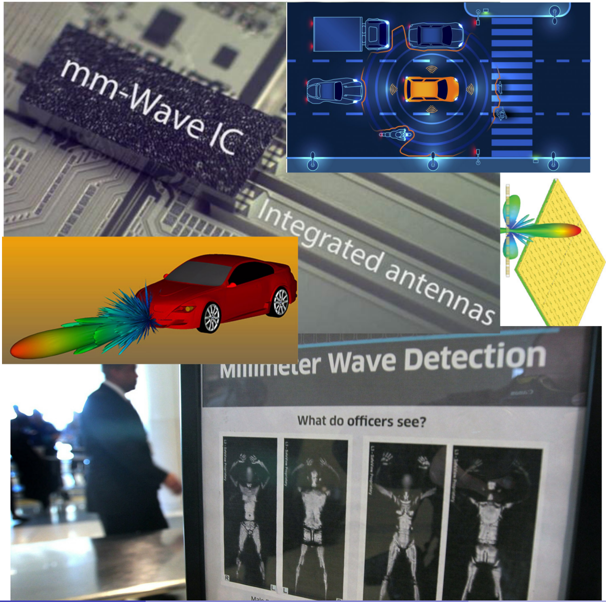
maMI Advantages

- Increased **data rate** .
- Significant **reduction in air-latency** .
- Simplifies the multiple-access layer.
- Improved **energy efficiency** .
- Improved **interference suppression** .

maMI Challenges

- Handling **huge amounts** of data for baseband signal processing.
- **Low cost RF chains** required.
- Efficient **calibration and synchronisation** across multiple RF chains required.
- Internal **power consumption** constraints.
- **Channel estimation** is challenging utilising conventional non-parametric models.

mmWave Wireless Comms

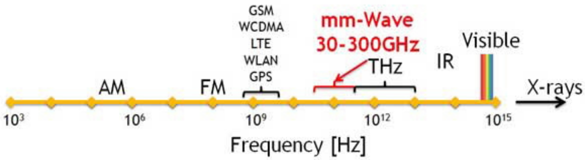


mmWave Communications: Introduction

- **mmWave** : milimeter wave or milimeter band
- also known by the ITU (International Telecommunications Union) as **Extermely High Frequency (EHF)**
- they have high atmospheric attenuation (waves are absorbed by gases in the atmosphere, e.g. rain and humidity impact performance)
  $\Downarrow$
  strength$=\downarrow$
  $\Downarrow$
  range$=\downarrow$.
  Thus, due to its short range (about 1km) mmWaves travel by line of sight and can be blocked by objects (e.g. trees, buildings, etc)
- mmWave can be used for **high-speed** (up to 10Gbps) wireless broadband communications.

mmWave Spectrum

- Spectrum: 30GHz-300GHz ⇒short wavelegths from 10mm to 1mm!



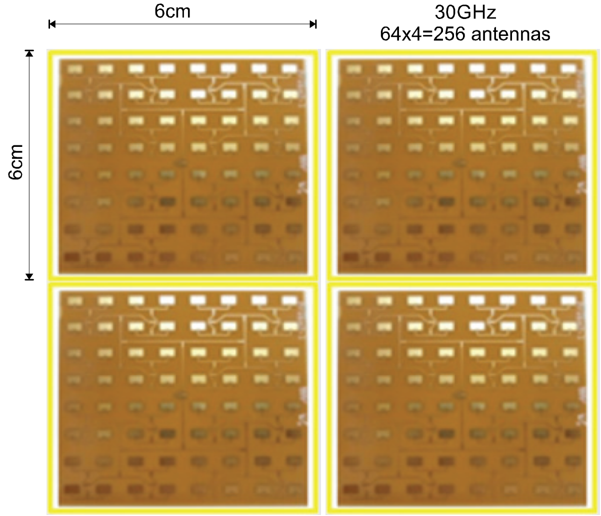
- **un-utilised spectrum:** 30-60GHz. For instance,
  - 60GHz can be used for short range data links
  - the IEEE WiFi standard **802.11ad** run on 60GHz mmWave band
- **licenced spectrum** (from FCC):
  - 71GHz-76GHz,
  - 81GHz-86GHz and
  - 92GHz-95GHz

for point-to-point high bandwidth communication links

mmWave Communications versus LTE 6GHz

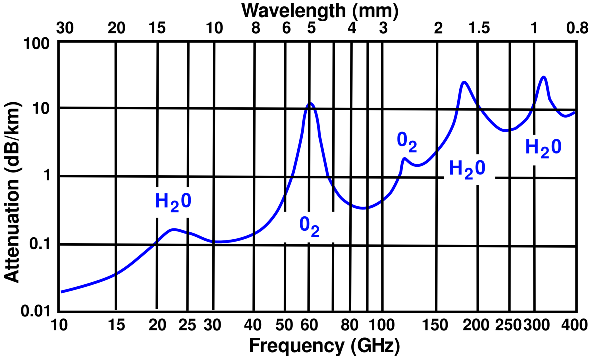
	Sub 6GHz	MmWave
bandwidth	1-160MHz	100MHz-2GHz
role of antennas	multiplexing & diversity	array gain & multiplexing
exploiting channel	limited feedback	directional beamforming
antennas @ BS	1 to 8	32 to 256
antennas @ UE	1 or 2	1 to 32
scattering	rich	sparse
urban coverage	via diffraction	via reflection
penetration loss	low	high
large-scale fading	distant dependent + shadowing	distant dependent + blockage

A Planar Array Geometry of 256 antennas at 30GHz



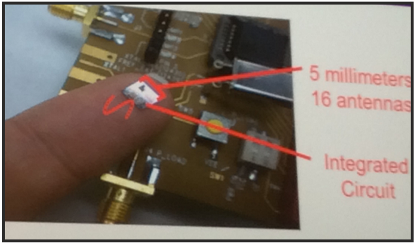
mmWave MIMO: Main Characteristics

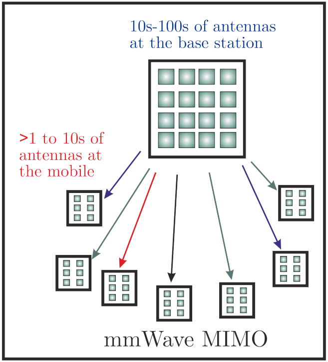
- **Huge propagation losses** : Rain attentuation and atmospheric and molecular absorption is very high at these frequencies. This limits the range of mmWave communications and mandates the requirement of algorithms that are powerful enough to combat these losses.



mmWave MIMO: Main Characteristics

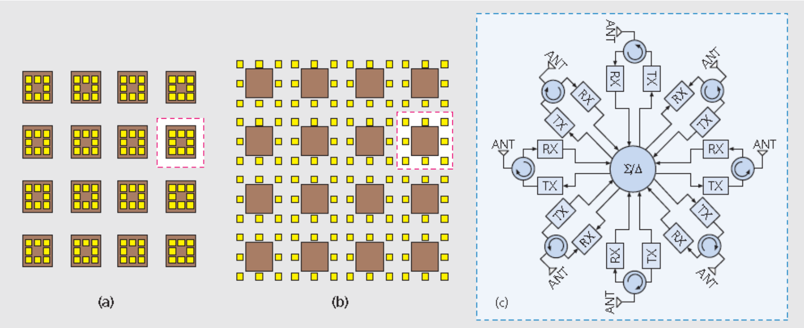
- **Requires Highly directional beams** : With current technologies, the size of the antenna element shrinks dramatically at these frequencies. This makes it possible to have a very large number of antenna elements on the Tx and Rx and, thus, employ powerful beamforming algorithms at the Tx and Rx to obtain accurate spatial selectivity.





60GHz Antenna Array Chipset (Qualcomm)

Chipsets of Antenna Arrays with 8 Elements



(a) 4x4 RF chips (brown squares), each with 8 antennas (yellow squares)

(b) possible distribution of 4x4 RF chips, each with 8 antennas mounted nearby on a circuit board on a different substrate

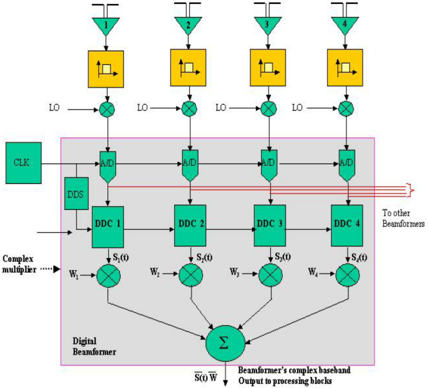
(c) clock diagram for a single chip, including Tx and Rx chains, sharing antennas around the chip

Digital mmWave Beamformer

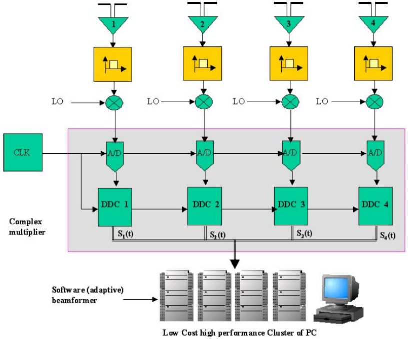
- In a digital beamformer, each antenna element has its own corresponding baseband port which offers the largest flexibility.
- However, ADCs and DACs operating at multi-GHz sampling rates are very power consuming; a full digital beamformer with several hundred antenna elements is very power hungry and complex.
- Therefore early mmWave communication systems are expected to use analog or hybrid beamforming architectures.

Digital mmWave Beamformers Implementation

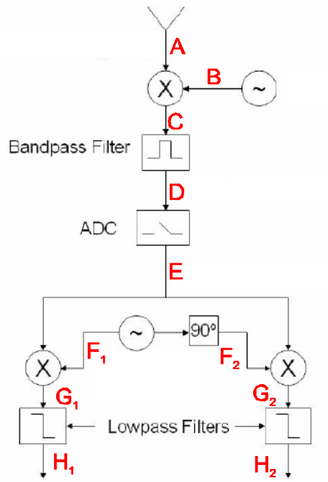
Digital Beamformer



Digital BF PC-based



Single Branch of a Digital Beamformer



$\boxed{\text{point-A}}$=k-th element

$$= x_k(t)\cos\left(2\pi F_{RF}\left(t-\frac{\underline{r}_k^T\underline{k}_i}{c}\right)\right)$$
$$= x_k(t)\cos\left(2\pi F_{RF}t-\psi_k\right)$$

where $\psi_k \triangleq 2\pi F_{RF}\frac{\underline{r}_k^T\underline{k}_i}{c}$

Note: $F_{RF}=F_c$ =carrier frequency

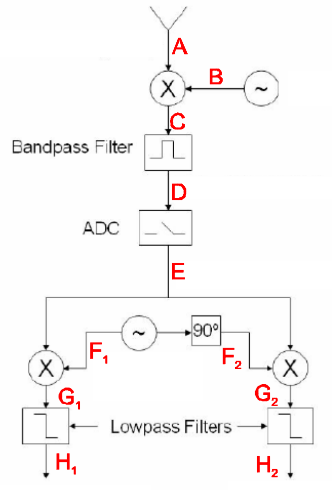
$\boxed{\text{point-B}} = 2\cos(2\pi F_{LO}t)$

where $F_{LO}=F_{RF}-F_{IF}$

$\boxed{\text{point-C}} = \boxed{\text{point-A}} \times \boxed{\text{point-B}} = 2x_k(t)\cos\left(2\pi F_{RF}t-\psi_k\right)\cos(2\pi F_{LO}t)$

$= x_k(t)\cos\left(2\pi\left(F_{RF}+F_{LO}\right)t-\psi_k\right)+x_k(t)\cos\left(2\pi\left(F_{RF}\text{-}F_{LO}\right)t-\psi_k\right)$

Single Branch of a Digital Beamformer



$$\boxed{\text{point-D}} = x_k(t)\cos\left(2\pi(\underbrace{F_{RF}-F_{LO}}_{\triangleq F_{IF}})t-\psi_k\right)$$

$$\boxed{\text{point-E}} = x_k(t_\ell)\cos\left(2\pi F_{IF}t_\ell-\psi_k\right)$$

$$\boxed{\text{point-F1}} = 2\cos\left(2\pi F_{DLO}t_\ell\right)$$

Note: $F_{DLO} = F_{IF} =$intermediate/digital-LO frequ.

$$\boxed{\text{point-G1}} = x_k(t_\ell)\cos\left(2\pi(F_{IF}+F_{DLO})t_\ell-\psi_k\right) + x_k(t_\ell)\cos\psi_k$$

$$\boxed{\text{point-H1}} = x_k(t_\ell)\cos(\psi_k)$$

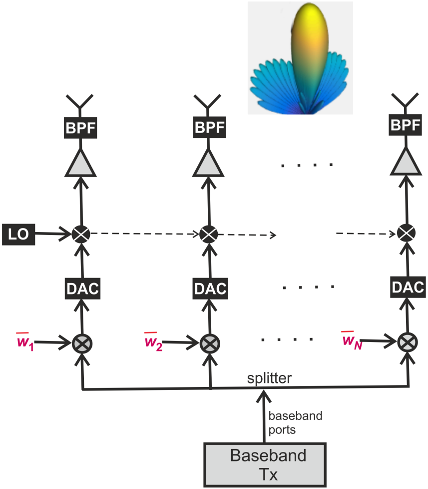
$$\boxed{\text{point-F2}} = 2\sin\left(2\pi F_{DLO}t_\ell\right)$$

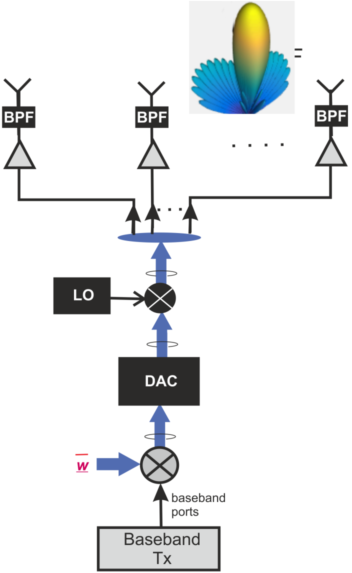
$$\boxed{\text{point-G2}} = x_k(t_\ell)\sin\left(2\pi(F_{IF}+F_{DLO})t_\ell-\psi_k\right) + x_k(t_\ell)\sin\psi_k$$

$$\boxed{\text{point-H2}} = x_k(t_\ell)\sin\psi_k$$

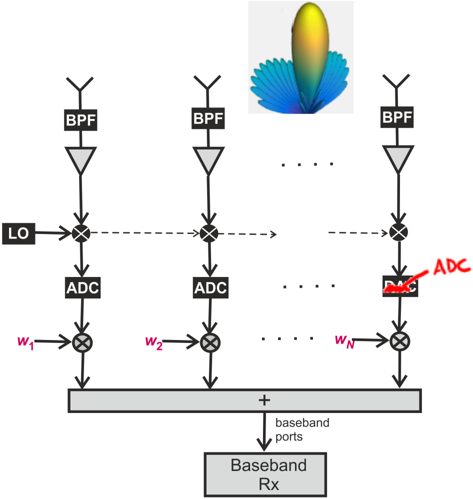
$$\text{o/p} = x_k(t_\ell)\cos\psi_k + jx_k(t_\ell)\sin\psi_k = x_k(t_\ell)\underbrace{\exp\left(j\frac{2\pi F_{RF}}{c}\underline{r}_k^T\underline{k}_i\right)}_{k^{\text{th}}\text{ element of manifold vec.}}$$

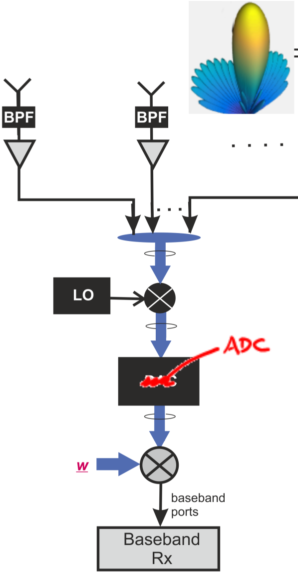
Digital Tx-Beamforming





Digital Rx-Beamforming

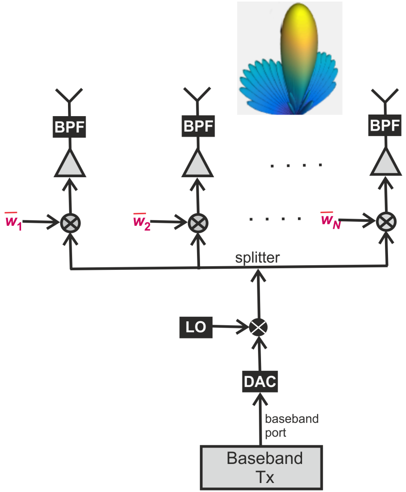


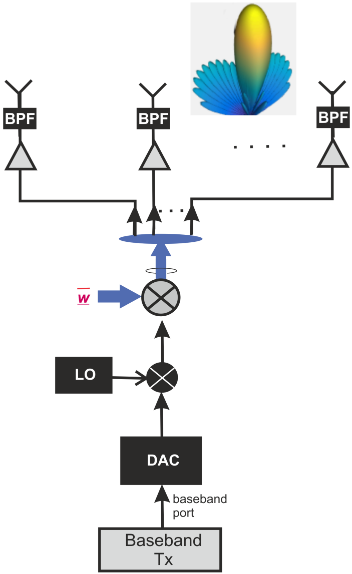


Analogue mmWave Beamformers

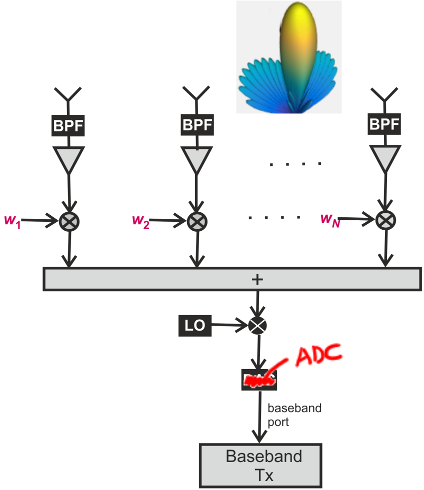
- In analogue beamforming, **one baseband port** feeds an analogue beamforming network where the beamforming weights are applied either directly on the analog baseband components, at some intermediate frequency, or at RF. For example, an RF beamforming network may consist of several phase shifters, one per antenna element, and optionally also variable gain amplifiers.
- In any case, an analogue beamforming network typically generates physical beams but cannot generate a complex beam pattern. Especially in a multi-user environment this can lead to interference, if pure beam separation is not sufficient.

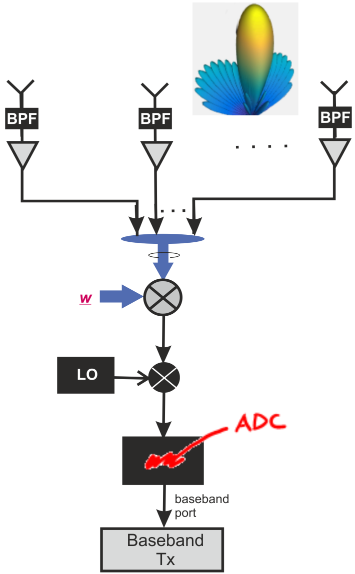
Analogue Tx-Beamforming



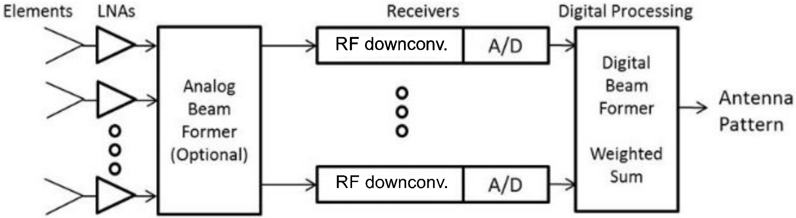


Analogue Rx-Beamforming

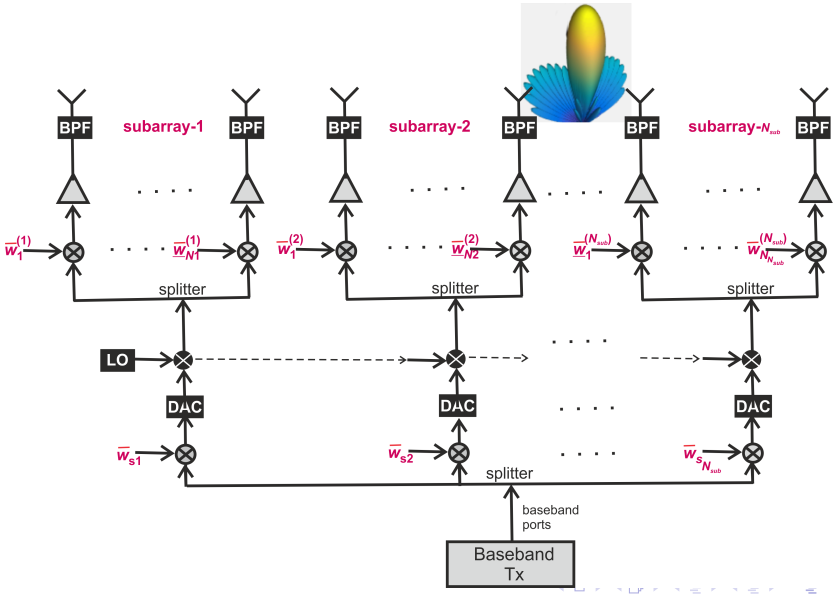




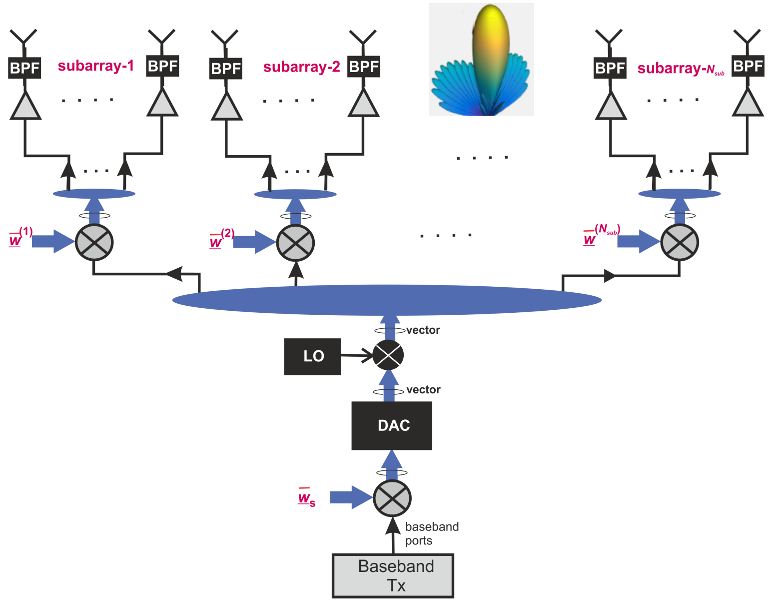
- **Hybrid beamforming** , is a compromise between Digital and Analogue Beamformers where a digital beamformer operating on a few baseband ports is followed by an analog beamforming network.
- This architecture enables a compromise with respect to both complexity and flexibility between analogue and full digital beamformer



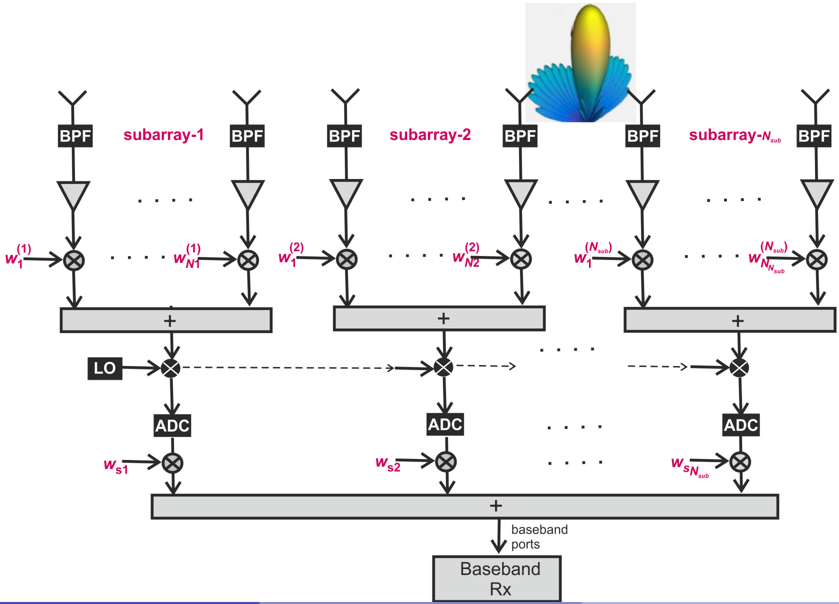
Hybrid Tx-Beamforming



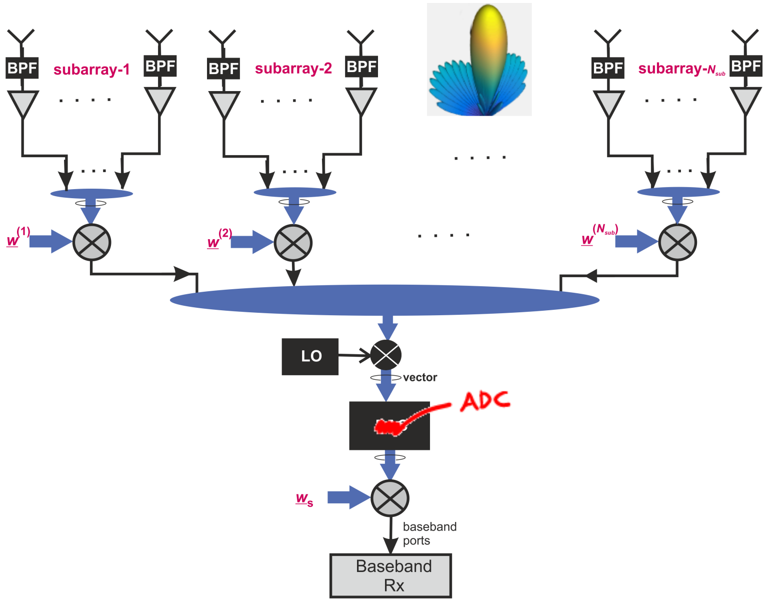
Hybrid Tx-Beamforming (vector representation)



Hybrid Rx-Beamforming



Hybrid Rx-Beamforming (vector representation)



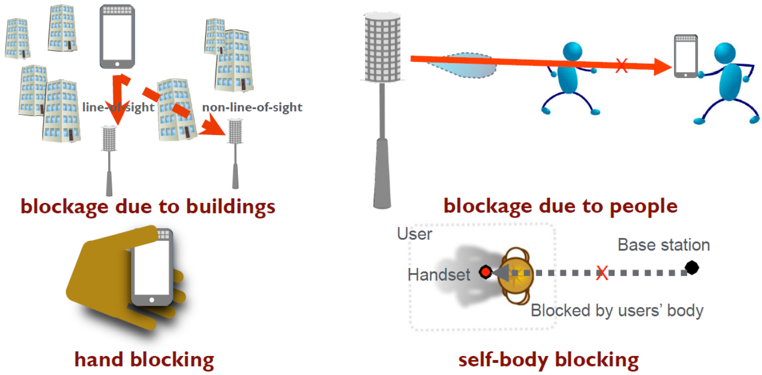
Some Comments

- A beamforming receiver provides spatial selectivity (i.e. **high gain reception of signals in desired directions** while **suppressing signals in other directions**).
- Each individual antenna element, however, does not provide much spatial selectivity. For a digital beamforming receiver this means that each signal path, extending from respective antenna element all the way to the baseband port, will have to accommodate desired as well as undesired signals.
- Thus, to handle strong undesired signals, requirements on **dynamic range will be high for all blocks** in the signal path and that will have a corresponding **impact on power consumption**. In an analog beamformer, however, the beamforming may be carried out already at RF and thus all subsequent blocks will need less dynamic range compared to the digital beamforming receiver.

Digital BF	Hybrid BF	Analogue BF
TX/RX weights at baseband (i.e. digital)	TX/Rx weights at both RF (analogue) and baseband (digital)	Tx/Rx weights at RF to form beams
Each antenna element (or antenna port) has a transceiver unit (i.e. overall, high number of transceiver units)	Each RF-beam has a transceiver unit (i.e. moderate number of transceivers)	One transceiver unit and one RF-beam
good for frequency selective channels (one beam per path)	conbination of digital (baseband) and analogue (RF) BF.	good for a frequency flat channel
best for capacity and flexibility (high power consumption and cost - especially if BW=↑)	optim. for both coverage and capacity	best for coverage than power consumption and cost

mmWave MIMO: Main Characteristics

- **Sensitivity to Blockage** : Due to the small wavelength, the links in the 60 GHz band are very sensitive to blockage. For instance, blockage by a human causes a 20-30 dB dip in the link budget.



mmWave MIMO: Main Advantages and Challenges

Advantages

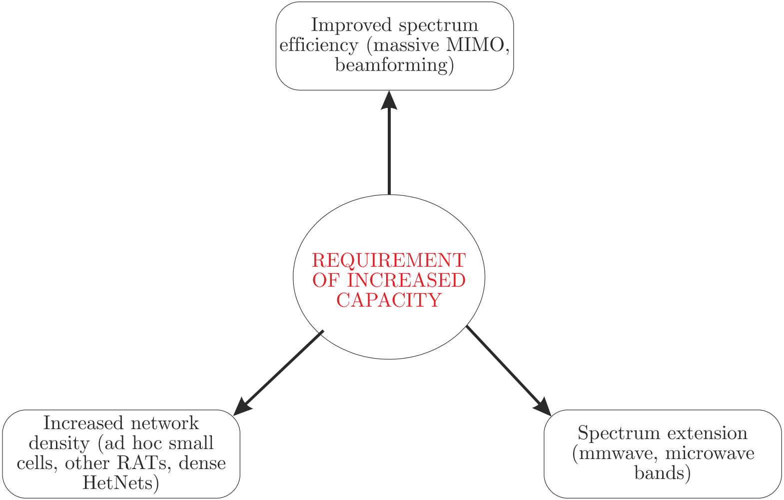
- Possible to achieve very **high data rates** .
- **Highly directional beams** may be constructed leading to superior interference suppression.
- Relieves the **demand for spectrum** .

Challenges

- The channel presents very high level of fading and **penetration loss** – to the extent that rain can completely cut off a network signal!
- Very little is known about the channel at these frequencies.
- Handling huge amounts of data for baseband signal processing.
- **Low cost RF chains** required - analog and hybrid beamforming needs to be explored.

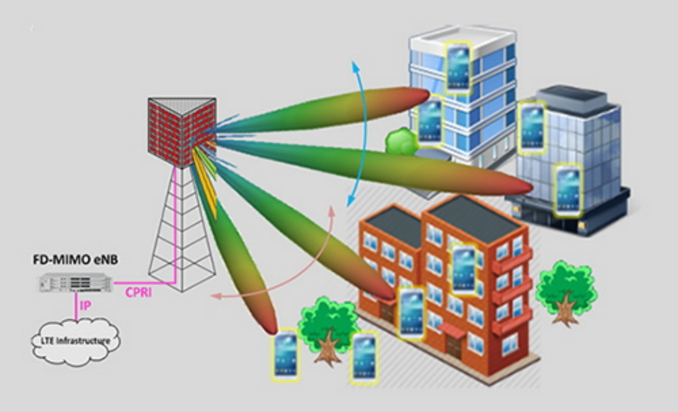

Millimeter Waves
Small Cell
Massive MIMO
5G
TM
Beamforming
Full Duplex

High Capacity Requirements: Candidate Technologies

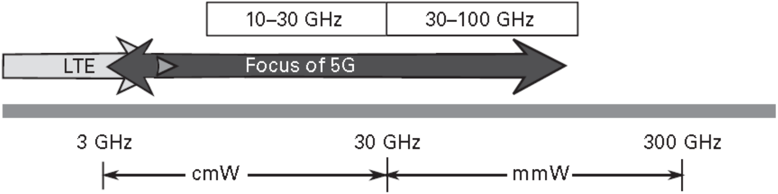


1. Improve Spectrum Efficiency:

- A very large antenna array at each Base Station (BS) serving simultaneoulsy a large number of co-channel users (massive MIMO), or
- A spatiotemporal array MIMO, or
- A spatiotemporal array massive MIMO

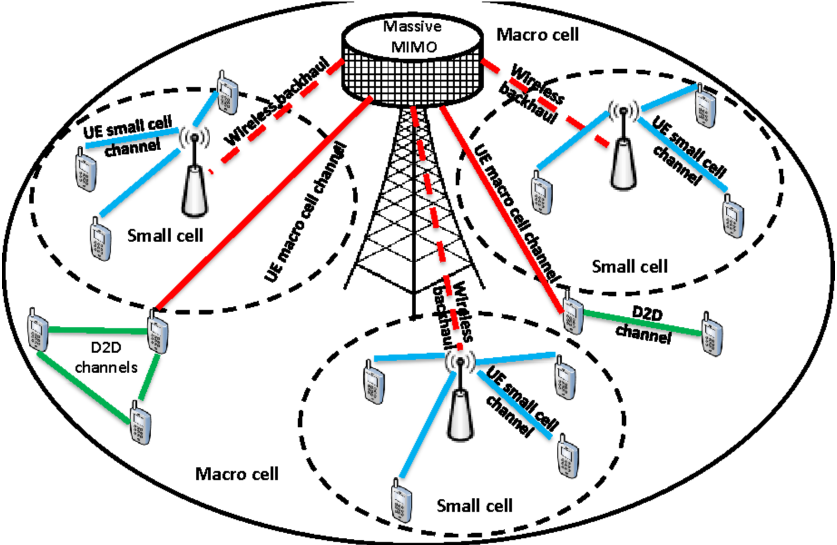


2. Spectrum Extension (up to 100GHz)

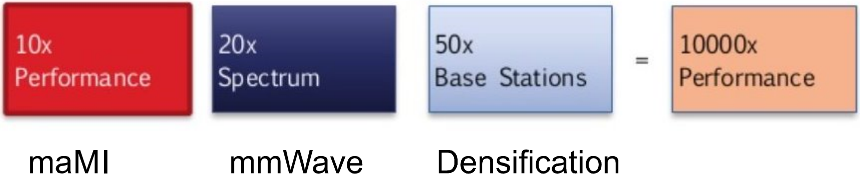


3. Increase Network Density

- Many BSs and many cells of different size

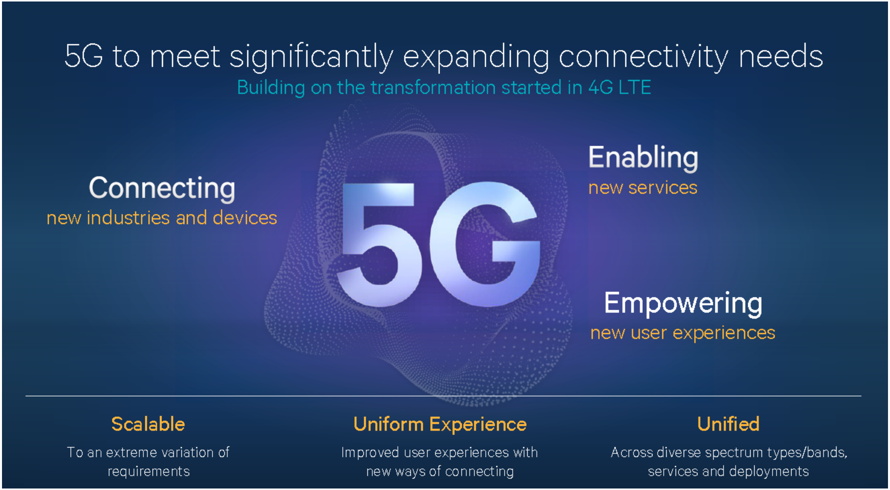


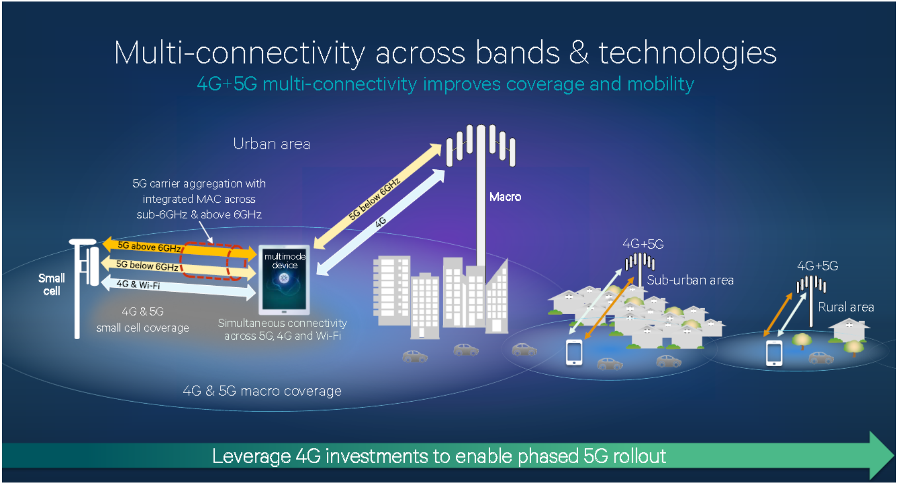
4. Overall Performance (Capacity)



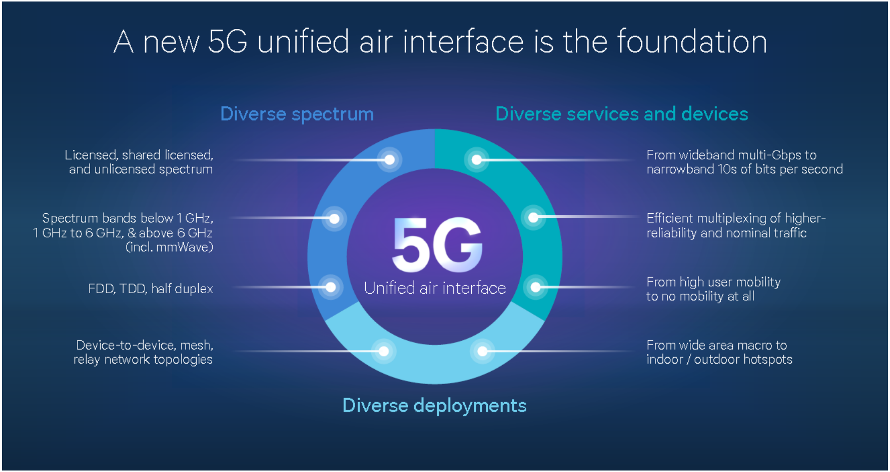
- Note: with a spatiotemporal array massive MIMO $\Rightarrow\Downarrow$

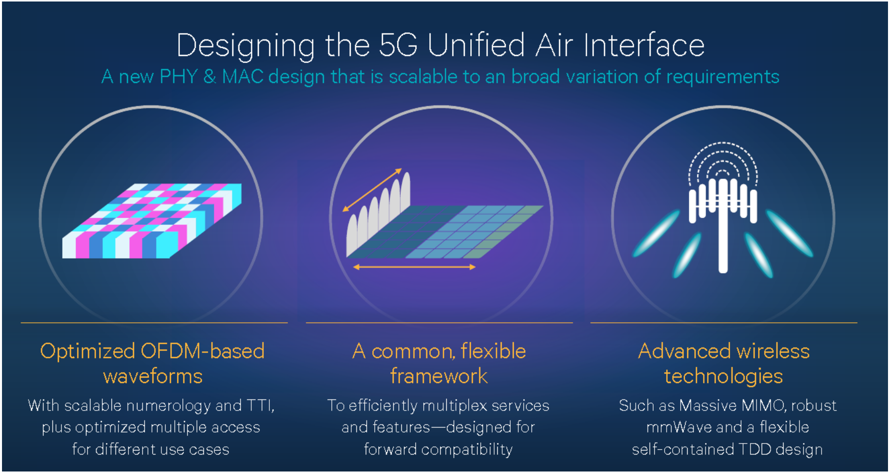
$$\text{Overall} >> 10000 \times \textit{Performance}$$

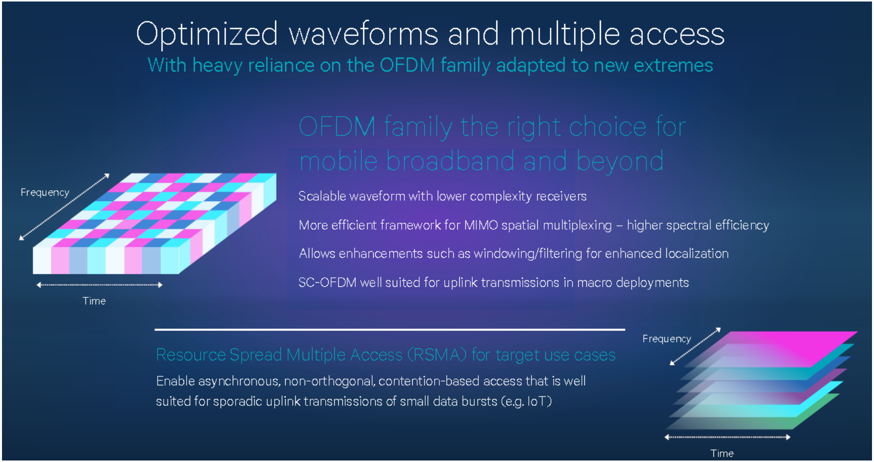

5G to meet significantly expanding connectivity needs
Building on the transformation started in 4G LTE
Connecting
new industries and devices
5G
Enabling
new services
Empowering
new user experiences
Scalable
To an extreme variation of requirements
Uniform Experience
Improved user experiences with new ways of connecting
Unified
Across diverse spectrum types/bands, services and deployments


Multi-connectivity across bands & technologies
4G+5G multi-connectivity improves coverage and mobility
Urban area
5G carrier aggregation with integrated MAC across sub-6GHz & above 6GHz
5G above 6GHz
5G below 6GHz
4G & Wi-Fi
Small cell
multimode device
5G below 6GHz
4G
Macro
4G & 5G small cell coverage
Simultaneous connectivity across 5G, 4G and Wi-Fi
4G+5G
Sub-urban area
4G+5G
Rural area
4G & 5G macro coverage
Leverage 4G investments to enable phased 5G rollout


Diverse spectrum types and bands
From narrowband to ultra-wideband, TDD & FDD
Licensed Spectrum
Cleared spectrum
EXCLUSIVE USE
Shared Licensed Spectrum
Complementary licensing
SHARED EXCLUSIVE USE
Unlicensed Spectrum
Multiple technologies
SHARED USE
Below 1 GHz: longer range, massive number of things
Below 6 GHz: mobile broadband, higher reliability services
Above 6 GHz including mmWave: for both access and backhaul, shorter range


A new 5G unified air interface is the foundation
Diverse spectrum
Diverse services and devices
Licensed, shared licensed, and unlicensed spectrum
Spectrum bands below 1 GHz, 1 GHz to 6 GHz, & above 6 GHz (incl. mmWave)
FDD, TDD, half duplex
Device-to-device, mesh, relay network topologies
5G
Unified air interface
From wideband multi-Gbps to narrowband 10s of bits per second
Efficient multiplexing of higher-reliability and nominal traffic
From high user mobility to no mobility at all
From wide area macro to indoor / outdoor hotspots
Diverse deployments


Designing the 5G Unified Air Interface
A new PHY & MAC design that is scalable to an broad variation of requirements
Optimized OFDM-based waveforms
With scalable numerology and TTI, plus optimized multiple access for different use cases
A common, flexible framework
To efficiently multiplex services and features—designed for forward compatibility
Advanced wireless technologies
Such as Massive MIMO, robust mmWave and a flexible self-contained TDD design


Optimized waveforms and multiple access
With heavy reliance on the OFDM family adapted to new extremes
OFDM family the right choice for mobile broadband and beyond
Frequency
Time
Scalable waveform with lower complexity receivers
More efficient framework for MIMO spatial multiplexing – higher spectral efficiency
Allows enhancements such as windowing/filtering for enhanced localization
SC-OFDM well suited for uplink transmissions in macro deployments
Resource Spread Multiple Access (RSMA) for target use cases
Enable asynchronous, non-orthogonal, contention-based access that is well suited for sporadic uplink transmissions of small data bursts (e.g. IoT)
Frequency
Time

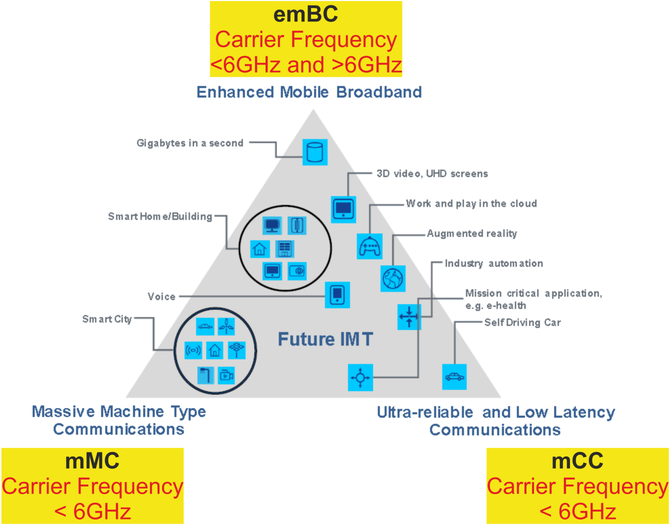
"New Radio"

- 3GPP named 5G as "**New Radio**" (NR)

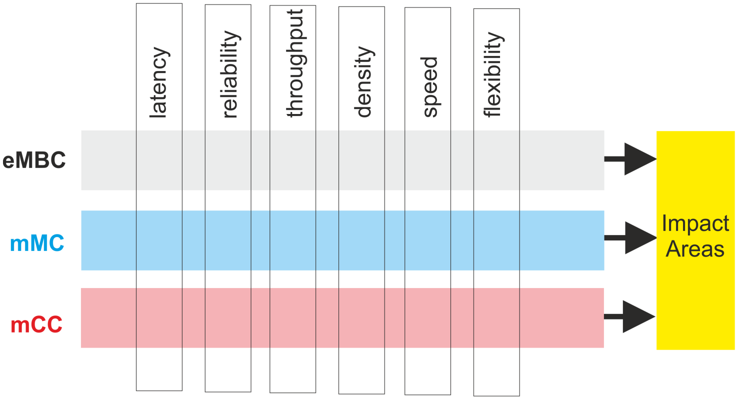
- NR supports **OFDM-family** with
  - **subcarrier spacing** : 15×2^m kHz (Note: In LTE-4G this is 15kHz)
    - ★ $m = 0$ or positive integers: $15, 30, 60, 120, 240, 480$ kHz
    - ★ m are negative integers: 3.75, 7.5 kHz
  - **Frame length** : no frame length (Note: In LTE-4G this is 10ms)
  - **Subframe length** : 1ms (Note: In LTE-4G this is 1ms)
  - **slot length** :
    - ★ subcarrier spacing ≤ 60 kHz: 7 or 14 OFDM symbols per slot
    - ★ subcarrier spacing > 60 kHz: 14 OFDM symbols per slot
    - ★ Note: In LTE-4G this is 7 OFMA symbols

- NR supports **three broad 5G communication families**
  - **Enhanced Mobile Broadband communications (emBC)** – i.e. mobile communication links of very high bandwidth (broadband) thus delivering very high speeds per user (multi Gbits/sec). For instance, mobile users with UHD screens need this family of communication links.
  - **Massive Machine Communications (mMC)** , - i.e. simultaneous comm links to potentially millions of machines (e.g. smart cities).
  - **Mission Critical Communications (mCC)** – i.e. communication links of high reliability and low latency (e.g. comm links for self-driving cars or aerospace industry)
- NR supports **spectrum** below and above 6GHz (this could be licensed or unlicenced)

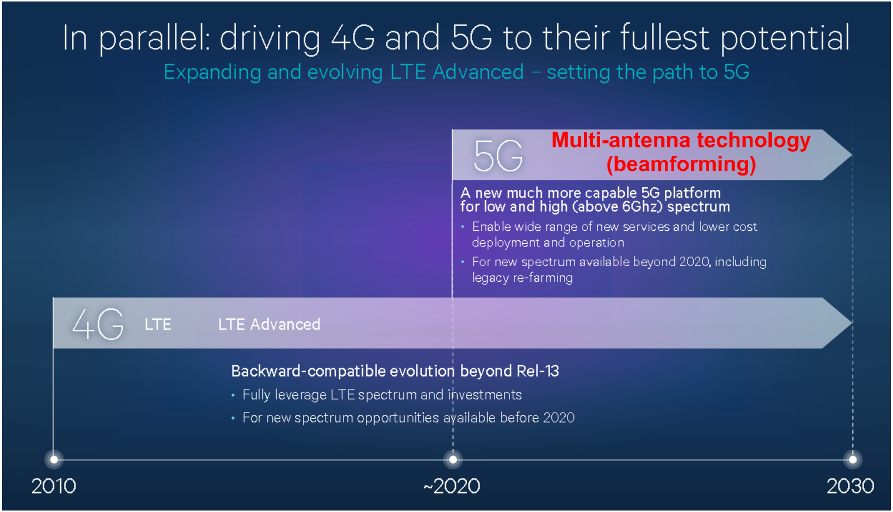
Triangle Diagram



Three broad 5G Communication Families



Multi-Antenna Technology (Beamforming)



Note-1: Some Current Matlab Useful Toolboxes

- Phased Array System Toolbox
- Antenna Toolbox
- RF Blockset
- RF Toolbox
- Communications Systems Toolbox
- Golbal Optimisation Toolbox

Note-2: Typical Array Design Elements

- Array geometry
- Array aperture
- Lattice structure of the elements and element tapering
- array ambiguities
- array uncertainties (geometrical and electrical, including mutual coupling)

An Imaginary Illustration

- The figure below shows an imaginary illustration of the future handheld mobile set with a Monolithic Microwave Integrated Circuit (MMIC) antenna array [Since 1995 this slide concludes my Lectures].