E401: Advanced Communication Theory

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Multi-Antenna Wireless Communications

Spatiotemporal Wireless Communications,
Massive MIMO,
mmWave,
Distributed Antenna Array,
5G.

Table of Contents

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.
    N.B.:This means that the number of sources/signals $M > N$
  - multipath effects in frequency selective channels.

- **Solutions** :
  1. to employ **massive MIMO** ,
     - ★ That is, if $M > N$ then we can increase N so that $M < N$, i.e. we add more hardware (HW) but also we increase the computational complexity.
  2. to employ statiotemporal algorithms (manifold extenders)
     - ★ That is, if $M > N$ then we can keep N fix but we can use sophisticated algorithms to increase the observation space from N to $N.N_{ext}$ - so that $M < N.N_{ext}$,
       i.e. only computational complexity is increased
  3. to employ both massive MIMO and manifold extenders

Solution-1

- $\geq$**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.
  - There are two cases:
    - *Non-parametric* massive: The antennas are not working together but are independent units. This is a problematic approach (N=$\uparrow$ $\Rightarrow$number-of-unknowns=$\uparrow$)
    - *Parametric* massive: based on array processing (antennas are working together as a single unit. This is a good approach (N=$\uparrow$ $\Rightarrow$number-of-unknowns$\neq\uparrow$).

Solution-2

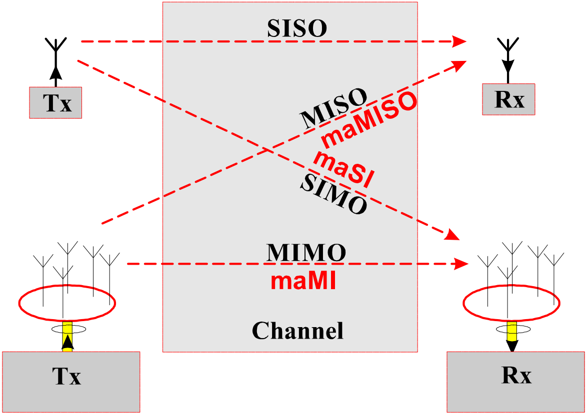
- **Solution:** use array processing in conjunction with
  - spatiotemporal algorithms. or
  - "virtual" arrays, or
  - both spatiotemporal algorithms and "virtual" arrays.

  In this case we keep the number of antennas N fixed but we extend the "array manifold" to
  - spatiotemporal manifolds,
  - virtual array manifolds or
  - virtual-spatiotemporal manifolds

Solution-3

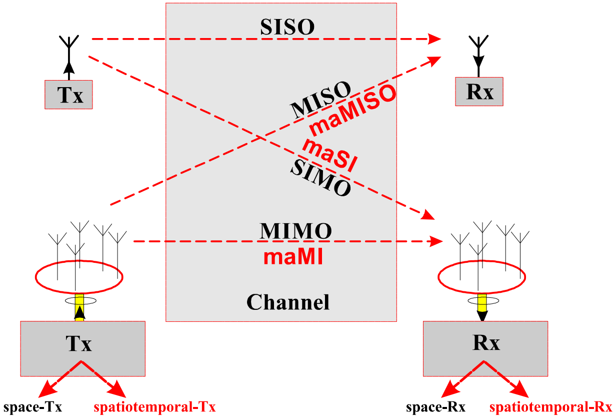
- **Solution:** we increase the number of antennas N and, at the same time, we extend the array manifold (both Solutions 1 and 2)

- **Solution-1:**



- massive SIMO Rx and massive MIMO Rx: $M < N$
- Remember:
  - ★ M = number of users/sources/signals/transmitters,
  - ★ N = number of Rx antennas

- **Solutions 2 and 3:**



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


MASSIVE MIMO

Massive MIMO: Introduction

Massive MIMO also known as Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO and Full-Dimension MIMO

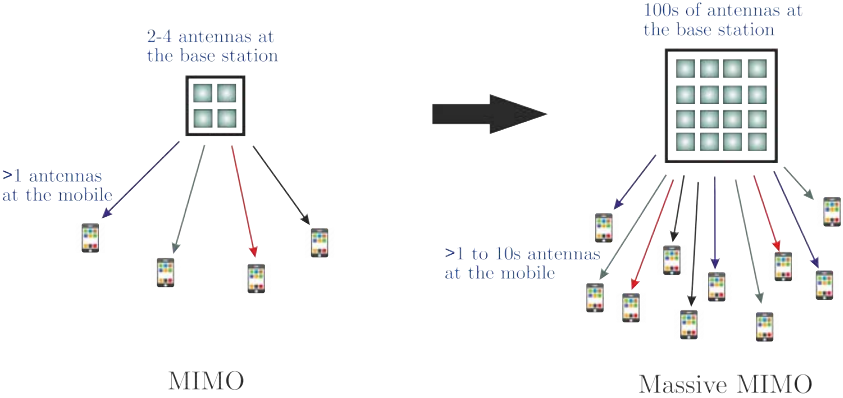
Definition (MIMO and maMI)

- MIMO (multiple input, multiple output) is an antenna array technology for wireless systems (e.g. wireless comms or radar) where antenna arrays are used at both the transmitter (source) and receiver (destination).

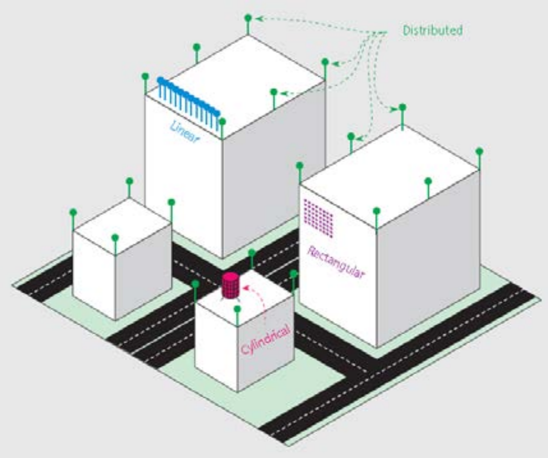
  However, there is no a clear definition when a MIMO system is defined as "massive MIMO" (maMI)

- some say:

Massive MIMO = Employing 100s of antennas at the base station.



maMI BS Antenna Geometries



Example of Massive MIMO: Macro-cells

Massive MIMO: What and Why?

- **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

  $\Downarrow$

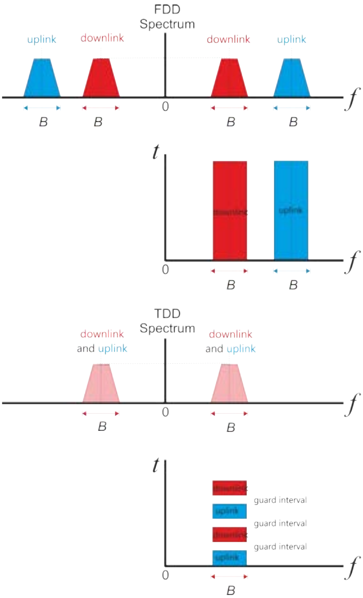
  focusing the transmission and reception of signal energy into ever-smaller regions of space

  $\Downarrow$

  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).



- The more antennas N the transmitter/receiver is equipped with,
  - the more the possible signal paths/users/sources/Tx (M) can be
    - ★ detected,
    - ★ resolved and
    - ★ their parameters can be estimated

    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 antennas, number of RF-chains, etc) and
  - the complexity (longer vectors and bigger matrices to handle) and **energy consumption** of the signal processing at both ends.

Summary of Main Advantages and Challenges

Main Advantages/Benefits

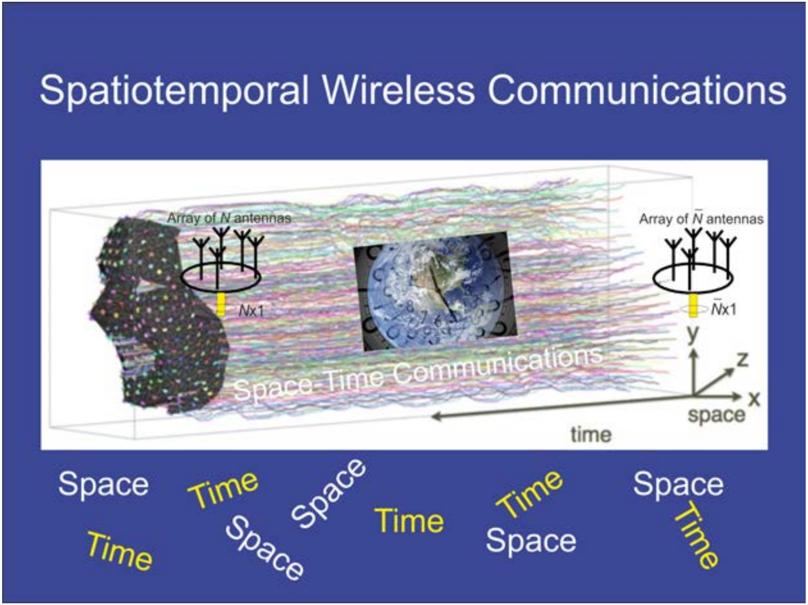
- Increased **data rate** .
- Significant **reduction in air-latency** .
- Simplifies the **MAC** (media access control) layer.
- Improved **energy efficiency** .
- Improved **interference suppression** (**robustness** to interference and intentional jamming)

- While massive MIMO renders many traditional research problems irrelevant, it uncovers entirely new problems that urgently need

Summary of Main Advantages and Challenges

Main Challenges

- Hardware complexity $=\uparrow$ $\therefore$ **Low cost RF chains** required.
  - This will lead to the extensive use of **inexpensive** low-power components,
  - The challenge of making many **low-cost low-precision components** to work effectively together,
- Computational complexity$=\uparrow$.
  - Handling **huge amounts** of data for baseband signal processing.
- Efficient **calibration & synchronisation** across multiple RF-chains required.
- Internal **power consumption** constraints.
  - **reducing internal power consumption** to achieve total energy efficiency reductions
- **Channel estimation** is challenging utilising conventional non-parametric models.
  - need for new **channel estimation** approaches


Spatiotemporal Wireless Communications
Array of N antennas
Nx1
Array of $\bar{N}$ antennas
$\bar{N}$x1
Space-Time Communications
y
z
x
space
time
Space
Time
Time
Space
Space
Time
Time
Space
Space
Time

Spatiotemporal Communications

- Spatiotemporal (Space-Time) Communications can be employed in **TDMA/FDMA, CDMA, OFDMA and NR** type systems

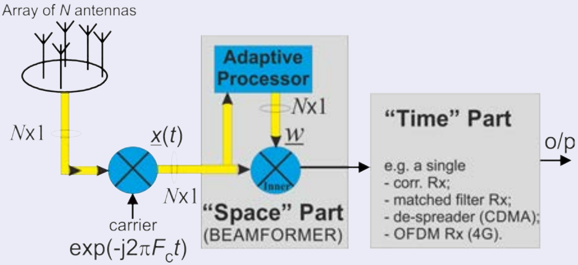
- N.B.:
  - In **TDMA/FDMA** the signal is not spread and only few (mainly one or two - i.e. $M < N$) strong cochannel interferences (CCI) are present when the system employs channel reuse between cells.
    The array can be used to null (remove/reduce) these few interferences
  - In **CDMA** all active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

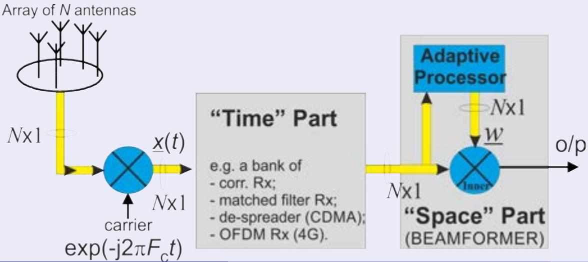
1. Decoupled Space and Time Rxs.
   $\exists$ two main Rx architectures
   1. **"Space"** and then **"Time"**
   2. **"Time"** and then **"Space"**
2. STAR-Rx's (SPATIOTEMPORAL ARRAY manifold Rx), where the time and space are integrated.
   $\exists$ one generic STAR-Rx architecture[a]

[a] N.B.: STAR should not to be confused with STAP (space-time adaptive processing)

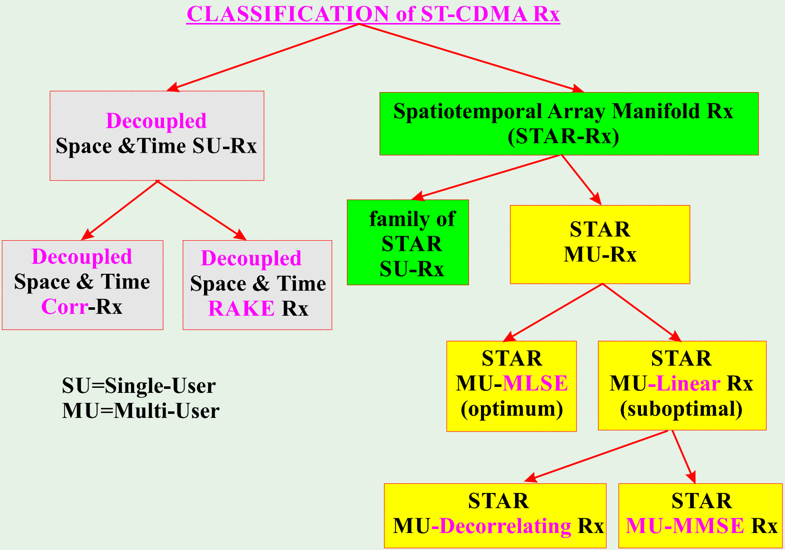
Definition ("Space" and then "Time")



Definition ("Time" and then "Space")

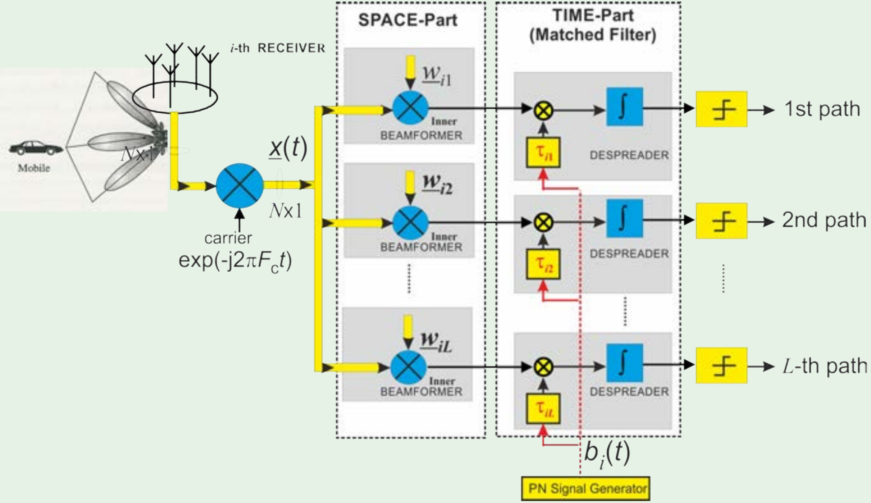


Example (ST-CDMA Rx Classification)



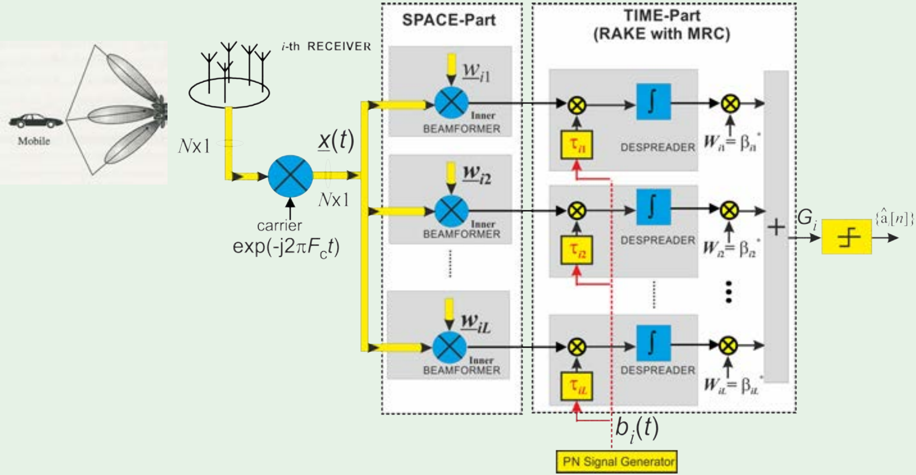
SU=Single-User
MU=Multi-User

Example (Decoupled Space & Time CDMA Receiver)



- N.B.: each path is received/isolated individually (i.e. no diversity)

Example (Decoupled Space & Time RAKE CDMA Receiver)



- N.B.: Multipath diversity (all multipaths are separated and combined)

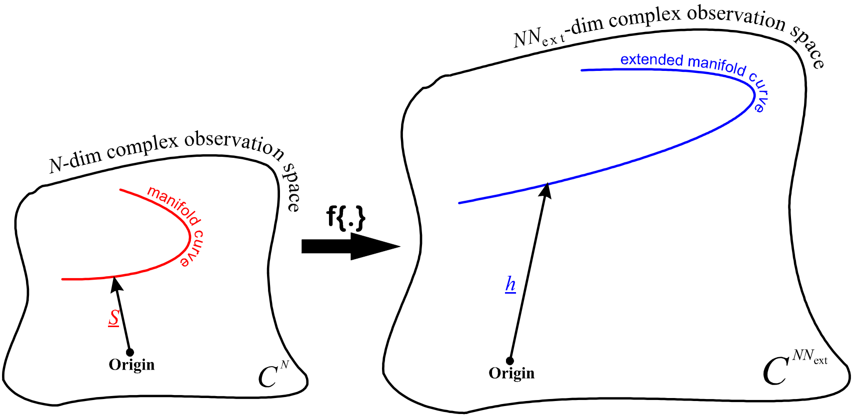
Spatiotemporal Manifolds (Extended Manifolds)

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

- For instance

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



Extension of the spatial manifold to the extended manifold

"Functions of Array Manifolds", *IEEE Transactions on Signal Processing*, Vol 59, Issue 7, p.3272-3287, 2011

- Extended array manifold vectors can be re-expressed as a function of spatial manifold vector $\underline{S}$.

Examples

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

$$\underline{h} = \underline{S} \otimes \underline{A} \tag{2}$$

$$\underline{h} = (\underline{S} \otimes \underline{A}) \odot \underline{B} \tag{3}$$

where $\underline{h}$, $\underline{S}$, $\underline{A}$, $\underline{B}$, $\mathbb{A}$ are functions of the parameters of interest

Definition

- spatiotemporal manifold: $\mathcal{H} \triangleq$ locus of all vectors $\underline{h}$

- Advantages:
  - No need to perform the same analysis multiple times but to express the analysis as a function of the "spatial" manifolds
  - Easier to evaluate the effect of changing the system architecture

Examples

- Extensions of the array manifold for use in modern digital communications
  - Basic STAR manifold
$$\underline{h}^{\text{STAR}} = \underline{S} \otimes \mathbb{J}^{\ell} \underline{c} \tag{4}$$
  - Polar-STAR manifold
$$\underline{h}^{\text{POL-STAR}} = \underline{S} \otimes \underline{\mathrm{q}} \otimes \mathbb{J}^{\ell} \underline{c} \tag{5}$$
  - Doppler-STAR manifold
$$\underline{h}^{\text{DOP-STAR}} = \underline{S} \otimes \left(\mathbb{J}^{\ell} \underline{c} \odot \underline{\mathcal{F}}_D \right) \tag{6}$$
  - Multicarrier-STAR manifold
$$\underline{h}^{\text{MC-STAR}} = \underline{S} \otimes \mathbb{J}^{\ell} \underline{\alpha} \left[\ell, F_k \right] \tag{7}$$
- MIMO: the above extended manifolds but also include the Tx-array properties
  - e.g. virtual-STAR
$$\underline{h}^{\text{virtual-STAR}} = \underline{S} \otimes \overline{\underline{S}}^{*} \otimes \mathbb{J}^{\ell} \underline{c} \tag{8}$$

where ℓ =delay, $\underline{\mathrm{q}}$ =polarisation parameters, F_k =subcarrier, $\underline{c}$ = PN-code, $\overline{\underline{S}}$ =Tx manifold vector.

The "Shifting Matrix"

- The matrix $\mathbb{J}$ is known as a **shifting matrix** (a $N_{ext} \times N_{ext}$ matrix) defined as follows

$$\mathbb{J} \triangleq \mathbb{J}_{N_{ext}} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} = \begin{bmatrix} \underline{0}^T_{N_{ext}-1} & 0 \\ \mathbb{I}_{N_{ext}-1} & \underline{0}_{N_{ext}-1} \end{bmatrix} \tag{9}$$

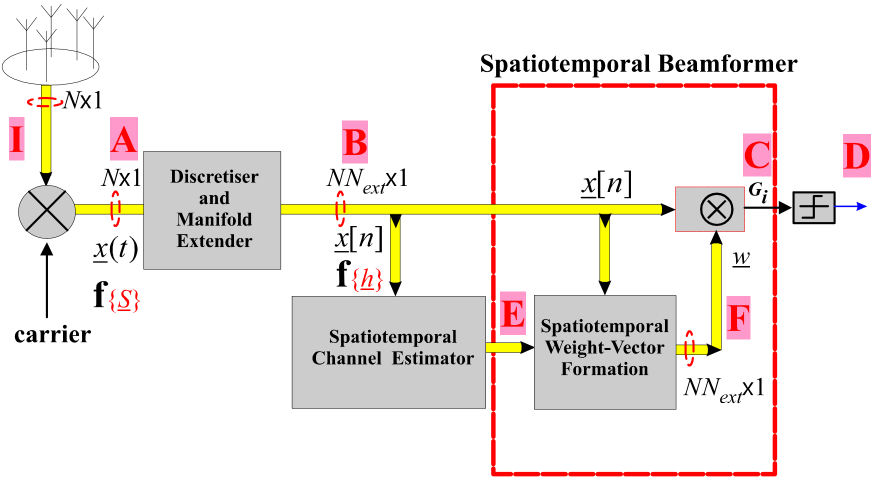
  having the property that every time the matrix $\mathbb{J}$ (or $\mathbb{J}^T$) operates on a column vector it down-shifts (or up-shifts) the elements of the vector by one.

- N.B.: $\mathbb{J}^{\ell}\underline{x}$ 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.

Examples

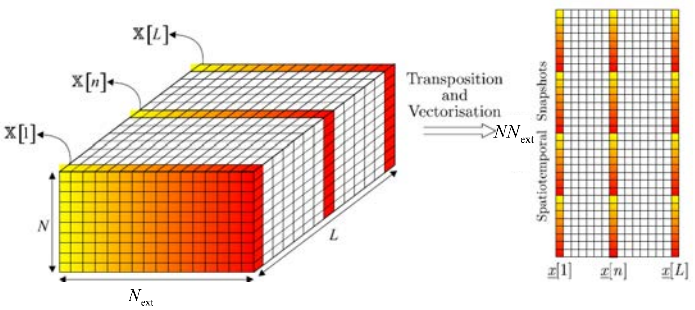
$$\underline{x}=\begin{bmatrix} x_1\\ x_2\\ x_3\\ \vdots\\ x_K \end{bmatrix};\quad \mathbb{J}^{3}\underline{x}=\begin{bmatrix} 0\\ 0\\ 0\\ x_1\\ x_2\\ \vdots\\ x_{K-3} \end{bmatrix};\quad \left(\mathbb{J}^{T}\right)^{2}\underline{x}=\begin{bmatrix} x_3\\ x_4\\ \vdots\\ x_K\\ 0\\ 0 \end{bmatrix} \tag{10}$$

A Generic Spatiotemporal Rx Architecture



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

3D-data Cube



3D-data Cube

Vectorisation of 3D-data Cube

$$
\begin{aligned}
\underline{x}[n] &= \mathrm{vec}\left\{\mathbb{X}[n]^T\right\} & (11)\\
&= \mathrm{function}\{\underline{h}\} + \underline{\mathrm{n}}[n] & (12)
\end{aligned}
$$

Example (A Representative Rx: STAR Manifold Rx)

- Let us focus on an extended manifold which is:
  $\underline{S}(\theta, \phi, F_c, c, \underline{r}_x, \underline{r}_y, \underline{r}_z,$
  pseudorandom sequ, *delay*$)$.
  $\Downarrow$
  $\underline{h} =$ basic STAR$= \underline{S} \otimes \mathbb{J}^{\ell} \underline{c}$ (see Equation 4)
- The above is suitable for many antenna array systems, including CDMA systems.
- For the j^{th} path of the i^{th} user the **array manifold vector** is

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

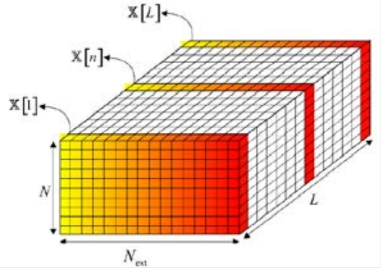
where $[\underline{r}_1, \underline{r}_2, \ldots, \underline{r}_N]$ represents the array geometry and $\underline{\mathrm{k}}(\theta_{ij}, \phi_{ij})$ is the wavenumber vector.
In this case, the extended manifold is

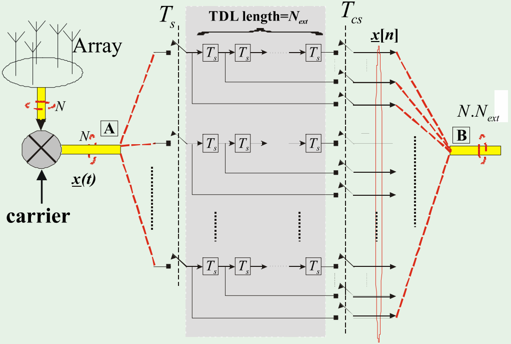
$$\underline{h}_{ij} \triangleq \underline{S}_{ij} \otimes \mathbb{J}^{l_{ij}} \underline{\mathfrak{c}}_i \in \mathcal{C}^{NN_{ext} \times 1} \tag{13}$$

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

Example (cont.)

- **To achieve this extension,** the array received signal vector $\underline{x}(t) \in \mathcal{C}^{N \times 1}$ is transformed to a discretised signal $\underline{x}[n] \in \mathcal{C}^{NN_{ext} \times 1}$
- $N_{ext} = 2 \times q \times \mathcal{N}_c$, where: $\mathcal{N}_c$=code period; q =oversampling factor.

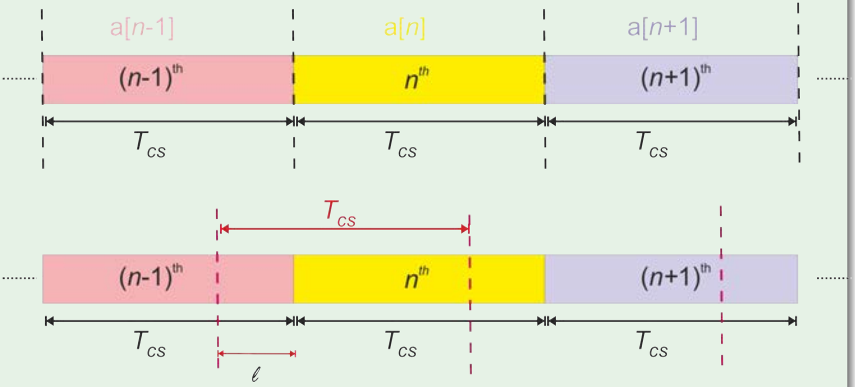




- Note-1: $T_s = \frac{T_c}{q}$. If $q = 1$ then the array received signal vector $\underline{x}(t)$ is discretised by a chip rate sampler, i.e. $T_s = T_c$.
- Note-2: The parameter ℓ is the discrete delay: $\ell = \left\lceil \frac{\tau}{T_s} \right\rceil \bmod \mathcal{N}_c$.

Example (cont.)

- The discrete samples are then passed through a "manifold extender" (in this example: $q = 1$ and this is a tapped-delay line of length[a] 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.



[a]this may may also of length $\mathcal{N}_c$ to reduce the ISI (Inter-Symbol Interference)

Example (cont.)

- 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,

$$\text{i.e. } \underline{x}[n] = \left[\underline{x}_1[n]^T, \underline{x}_2[n]^T, \ldots, \underline{x}_N[n]^T\right]^T \in \mathcal{C}^{2\mathcal{N}_c N\times 1} \quad (14)$$

$$= \text{vec}(\mathbb{X}[n]^T) \quad (15)$$

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

$$\mathbb{R}_{xx} = \mathcal{E}\left\{\underline{x}[n]\,.\underline{x}[n]^H\right\} \in \mathcal{C}^{2\mathcal{N}_c N\times 2\mathcal{N}_c N} \quad (16)$$

- Note that the whole theory presented in the previous TOPIC "Array Receivers for SIMO and MIMO", can be applied directly here using the above $\mathbb{R}_{xx}$

Example (cont.)

- For M users (assuming the 1st to be the desired user) and a frequency selective channel of K_i paths for the i-th user, the vector $\underline{x}[n] \in C^{NN_{ext}\times 1}$ can be expressed as follows:

$$\underline{x}[n] = \sum_{i=1}^{M}[\mathbb{H}_{i,\text{prev}}\underline{\beta}_i,\ \mathbb{H}_i\underline{\beta}_i,\ \mathbb{H}_{i,\text{next}}\underline{\beta}_i]\begin{bmatrix} a_i[n-1] \\ a_i[n] \\ a_i[n+1]\end{bmatrix} + \underline{n}[n] \quad (17)$$

$$\underline{x}[n] = \mathbb{H}_1\underline{m}_1[n] + \underline{I}_{ISI}[n] + \underline{I}_{MAI}[n] + \underline{n}[n] \quad (18)$$

where

$$\mathbb{H}_1 = \left[\underline{h}_{11},\ \ \underline{h}_{12},\ \ \ldots,\ \ \underline{h}_{1K_1}\right] \quad (19)$$

$$\underline{I}_{ISI}[n] = \left(\mathbb{I}_N \otimes \left(\mathbb{J}^T\right)^{N_c}\right)\mathbb{H}_1\underline{m}_1[n\text{-}1] + \left(\mathbb{I}_N \otimes \mathbb{J}^{N_c}\right)\mathbb{H}_1\underline{m}_1[n\text{+}1] \quad (20)$$

$$\underline{m}_1[n] = \begin{cases} a[n].\underline{\beta}_1 & \text{for slow fading} \\ a[n].\underline{\beta}_1[n] & \text{for fast fading}\end{cases} \in C^{K_1\times 1} \quad (21)$$

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 (n-th interval):

$$\xi(\theta, \ell) = \frac{1}{\underline{h}(\theta, \ell)^H \mathbb{P}_{\mathrm{n}} \, \underline{h}(\theta, \ell)} \tag{22}$$

- In Equation 22 the matrix $\mathbb{P}_{\mathrm{n}}$ is the projection operator associated with the "noise subspace" of

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

i.e. this projection operator should be estimated from the 2nd order statistics (i.e. $\mathbb{R}_{xx}$) of the $\underline{x}[n] \in C^{NN_{ext} \times 1}$ given by Equation 18.

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.

The Reception Problem

Definition (**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

$$\text{if } (\theta,\ell) \longmapsto \underline{h}(\theta,\ell) \text{ then } g(\theta,\ell) = \underline{w}^H \underline{h}(\theta,\ell) \tag{23}$$

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

$$\text{with } \ell \triangleq \left\lceil \frac{\tau}{T_s} \right\rceil \operatorname{mod} \mathcal{N}_c \tag{24}$$

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

- N.B.: default pattern $(q=1)$:
  - 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. $\underline{w} = \underline{h}(90°, 0T_c)$, (i.e. no weights)

Example: Space & Spatiotemporal Gain Patterns

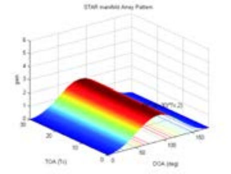
- Consider a Uniform Linear Array of N elements using a PN-code of length $\mathcal{N}_c = 31$. $T_s = T_c$

  Examples of the STAR array pattern for

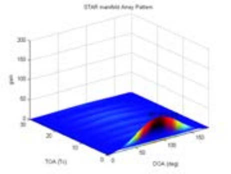
  - delays: 0 and $7T_c$
  - directions: 90° and 120°

  and $N = 2, 3, 4, 5$ are given below:

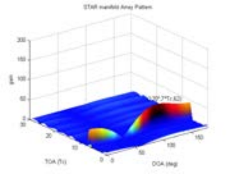
Example ($N = 2$)



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

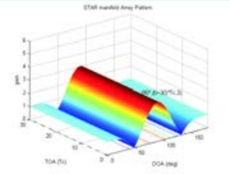


$\underline{w} = \underline{h}(90^\circ, 0T_c)$

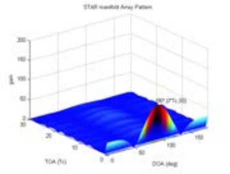


$\underline{w} = \underline{h}(120^\circ, 7T_c)$

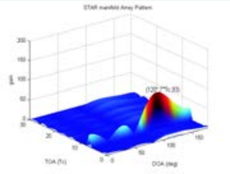
Example ($N = 3$)



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

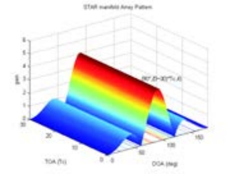


$\underline{w} = \underline{h}(90^\circ, 0T_c)$

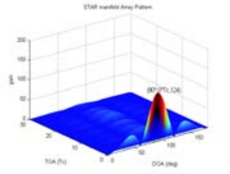


$\underline{w} = \underline{h}(120^\circ, 7T_c)$

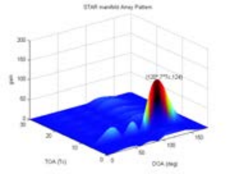
Example ($N = 4$)



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

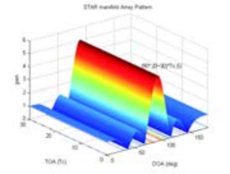


$\underline{w} = \underline{h}(90°, 0T_c)$

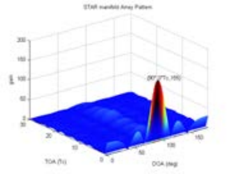


$\underline{w} = \underline{h}(120°, 7T_c)$

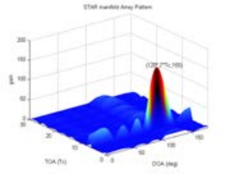
Example ($N = 5$)



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

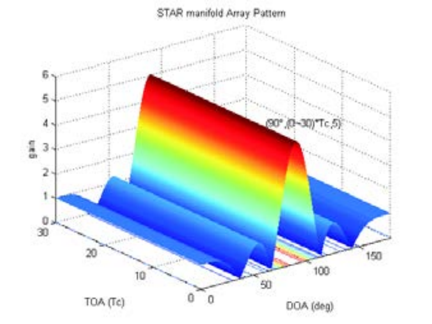


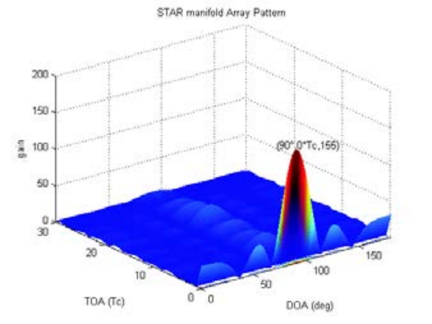
$\underline{w} = \underline{h}(90°, 0T_c)$



$\underline{w} = \underline{h}(120°, 7T_c)$

Example (focusing on the pattern for $N = 5$)





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

$$\mathbb{H}_i = \left[\underline{h}_{i1}, \quad \underline{h}_{i2}, \quad ..., \quad \underline{h}_{iL_p}\right] \in C^{2N\mathcal{N}c \times L_p} \tag{25}$$

  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. 25 should be formed in the block "Processor-3" for every i (i.e. $\forall i$).

- The concept of "spatiotemporal (STAR) weight vectors" can be extended to other receivers too.
- The following two receivers may be used to receive the multipath signals (multipath diversity) of the i-th user.

STAR-RAKE (SU)

$$\underline{w}_i = \mathbb{H}_i \underline{\beta}_i \tag{26}$$

STAR-Subspace (SU)

$$\underline{w}_i = \text{constant} \times \mathbb{P}_n \mathbb{H}_i \left(\mathbb{H}_i^H \mathbb{P}_n \mathbb{H}_i\right)^{-1} \underline{\beta}_i . \tag{27}$$

- where
  - a scalar constant is used as a normalising factor such that $\|\underline{w}_i\| = 1$, and
  - $\mathbb{P}_{\mathrm{n}}$ 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** :

$$C = B\log_2(1 + \mathrm{SNIR}_{out}) \quad \text{bits/sec} \tag{28}$$

- **MIMO Capacity** :

$$C = B\log_2\left(\frac{\det(\mathbb{R}_{xx})}{\det(\mathbb{R}_{nn})}\right) \quad \text{bits/sec} \tag{29}$$

or,equivalently,

$$C = B\log_2\left(\det\left(\mathbb{I}_N + \frac{1}{\sigma_n^2}\mathbb{S}\mathbb{R}_{mm}\mathbb{S}^H\right)\right) \quad \text{bits/sec} \tag{30}$$

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

$$\text{SISO} \quad : \quad \lim_{B\to\infty} C = 1.44 \frac{P_s}{N_0 + N_J} \tag{31}$$

$$\text{space SIMO} \quad : \quad \lim_{B\to\infty} C = N \times 1.44 \frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{32}$$

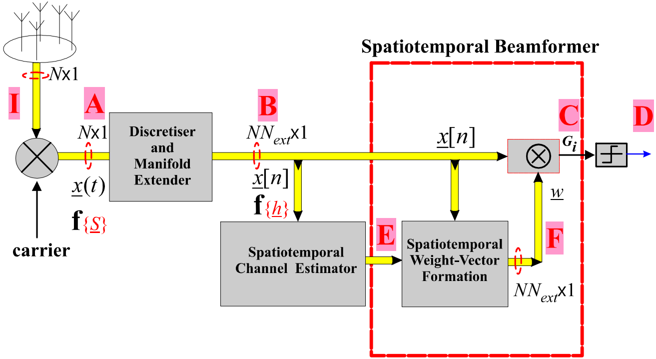
$$\text{MIMO - virtual SIMO} \quad : \quad \lim_{B\to\infty} C = \overline{N} \times N \times 1.44 \frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{33}$$

$$\text{spatiotemporal-SIMO} \quad : \quad \lim_{B\to\infty} C = N \times N_{ext} \times 1.44 \frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{34}$$

$$\text{virtual-spatiotemporal-SIMO} \quad : \quad \lim_{B\to\infty} C = \overline{N} \times N \times N_{ext} \times 1.44 \frac{P_s}{N_0 + \underset{0}{N_J \downarrow}} \tag{35}$$

Spatiotemporal Representative Examples

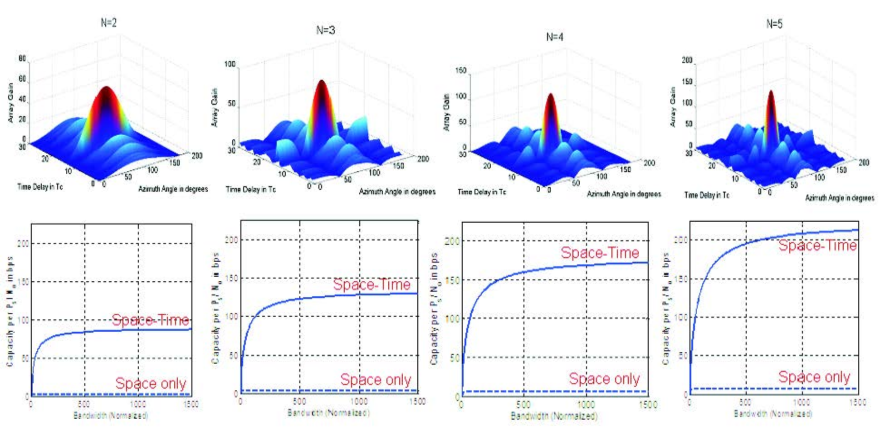
The following examples are based on the following generic ST-Rx architecture and references



"STAR Channel Estimation in DS-CDMA Communication Systems", IEE Proc.-Commun., Vol. 151, No. 4, August 2004.

"Spatiotemporal-MIMO Channel Estimator and Beamformer for 5G", IEEE Trans. on Wireless Comms, Vol. 15, No. 12, December 2016.

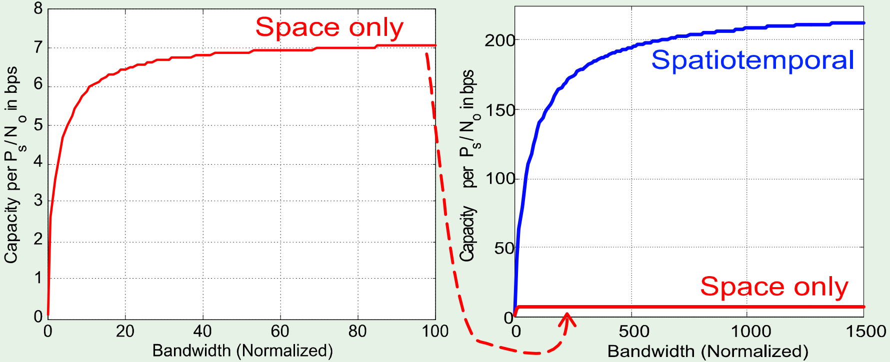
Examples (1. ST-Array Pattern and ST-Capacity)



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

Examples (1. cont.)

- $N = 5$ antennas



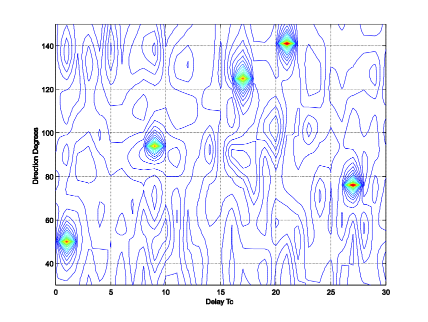
Examples (2. Spatiotemporal Channel Estimation)

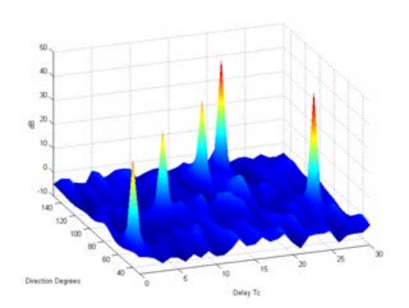
- 3 users, 5 paths per user, 1st user=desired

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**

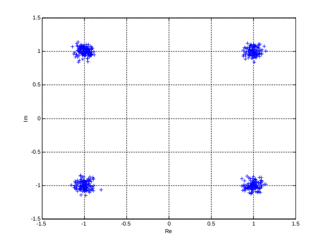
Examples (2. cont.)

- Surface and contour plots of the cost function (Equ 22) shows that all 5 path delays and directions are correctly estimated

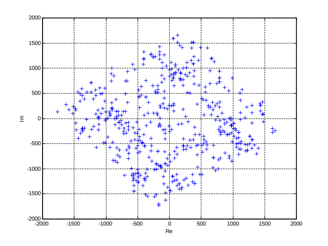




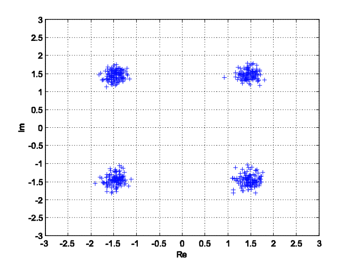
Examples (3. Constellation Diagram (Decision Variables))



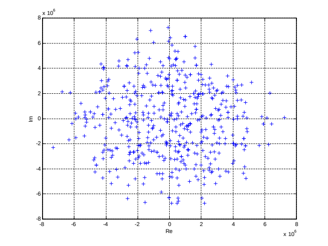
ST Decorrel. MU Rx



ST Decorrel. MU Rx (Incomp)

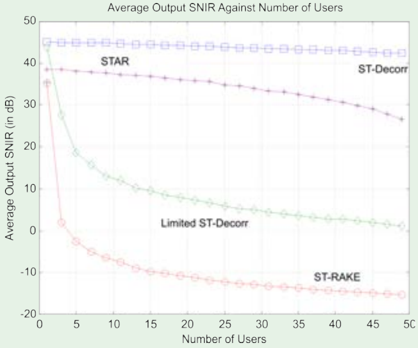


STAR manifold Rx

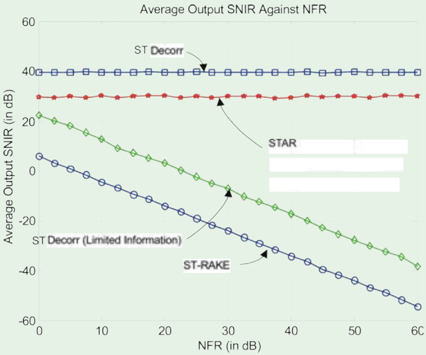


ST-RAKE Rx

Examples (4. SNIR output)



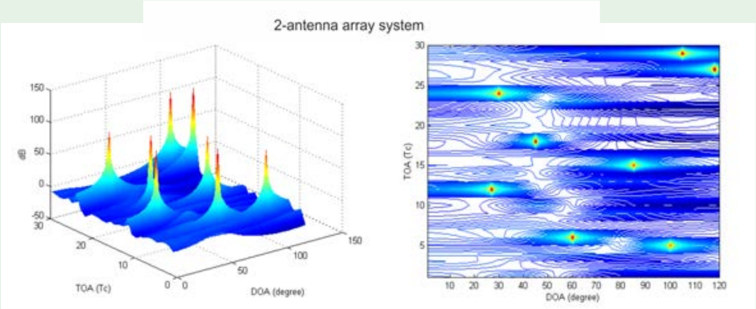
$\text{SNIR}_{out} = f\{M\}$



'Near-Far' Resistance

Examples (5. $M > N = 2$: good for "handsets")

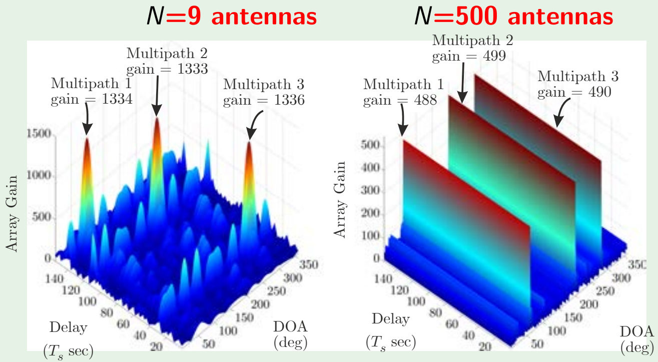
- Desired user's parameters = 8 paths with (TOA in T_c, DOA in degrees) as follows:
  - $(5, 100°), (6, 60°), (12, 27°), (15, 85°),$
  - $(18, 45°), (24, 30°), (27, 118°), (29, 105°)$
- The desired user's STAR Subspace-type spectrum (and contour diagram) for an array of $N = 2$ antennas, operating in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



Examples (6. Spatiotemporal Beamformer versus maMI (parametric))

- see reference [2], page-49
- 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.

Examples (6. cont.)



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

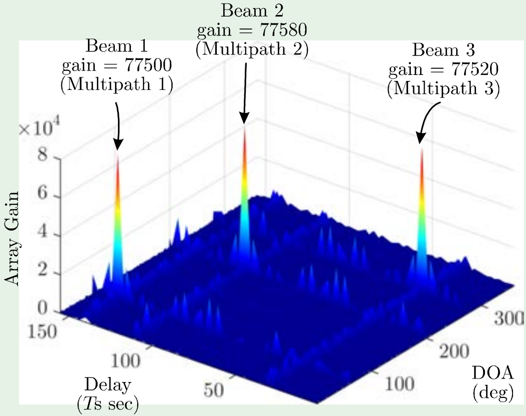
(b) Beampattern of a massive MIMO subspace receiver consisting of 500 antenna elements.

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

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

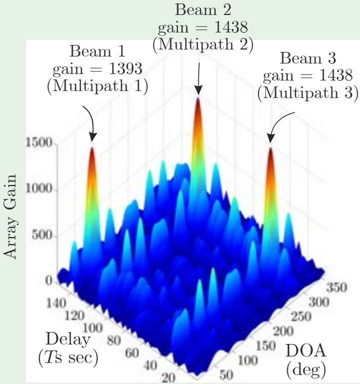
Examples (6. cont.)

N=500 antennas (spatiotemporal maMI)

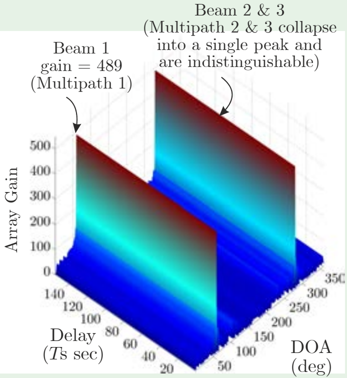


Examples (6. cont.)

N=9 antennas **N=500 antennas**

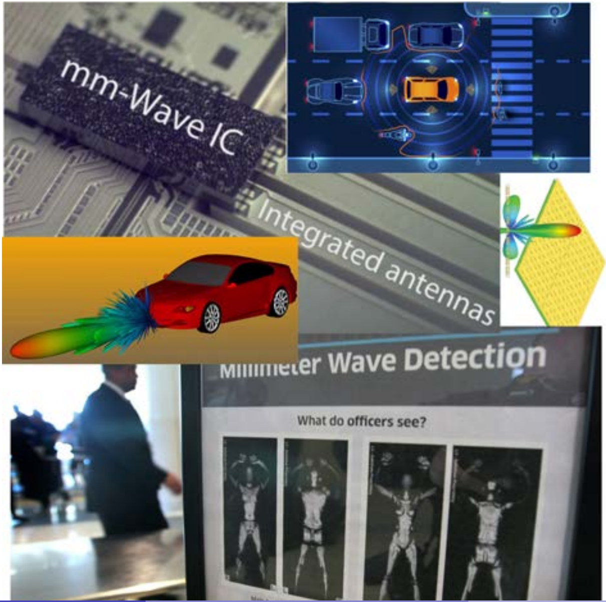


(a) Beampattern of a Doppler-STAR-subspace receiver consisting of 9 antenna elements.



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

mmWave Wireless Comms

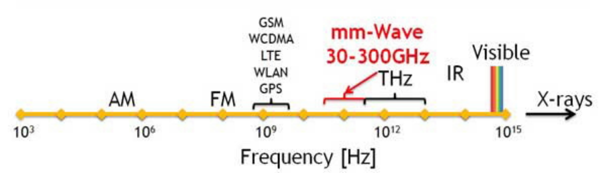


mmWave Communications: Introduction

- **mmWave** : milimeter wave or milimeter band
- also known by the ITU (International Telecommunications Union) as **Extermely High Frequency (EHF)** band.

Definition (mmWave)

- mmWave$\triangleq$Spectrum 30GHz-300GHz $\Leftrightarrow$short wavelegths from 10mm to 1mm!



mmWave Spectrum Utilisation

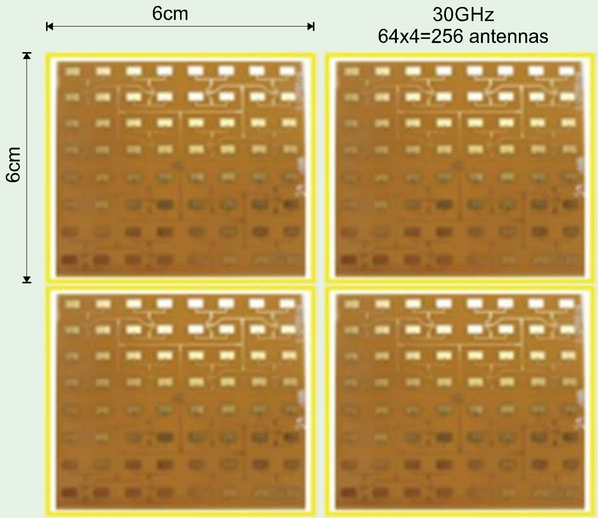
- **un-utilised spectrum:** 30-60GHz. For instance,
  - 60GHz can be used for short range data links
  - the IEEE WiFi standard **802.11ad** run on 60GHz mmWave band
- **licenced spectrum** (from FCC):
  - 71GHz-76GHz,
  - 81GHz-86GHz and
  - 92GHz-95GHz

  for point-to-point high bandwidth communication links
- mmWave can be used for **high-speed** (up to 10Gbps) wireless broadband communications.

mmWave Communications versus LTE 6GHz

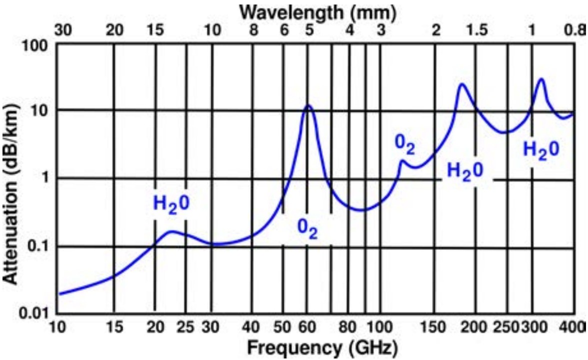
	Sub 6GHz	MmWave
bandwidth	1-160MHz	100MHz-2GHz
role of antennas	multiplexing & diversity	array gain & multiplexing
exploiting channel	limited feedback	directional beamforming
antennas @ BS	1 to 8	32 to 256
antennas @ UE	1 or 2	1 to 32
scattering	rich	sparse
urban coverage	via diffraction	via reflection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

Example (A Planar Array Geometry of 256 antennas at 30GHz)



mmWave MIMO: Main Characteristics

1. Very high atmospheric attenuation
    - Rain attenuation (rain and humidity impact performance)
    - Atmospheric and molecular absorption (but only at certain frequencies)



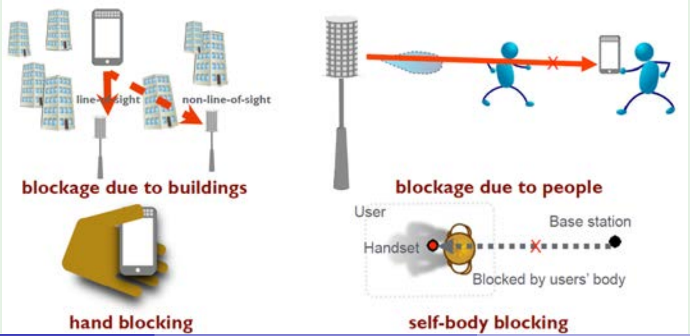
This implies **Huge propagation losses** $\Rightarrow$ strength$=\downarrow\Rightarrow$range$=\downarrow$
i.e. limit the range of mmWave comms and mandate the requirement of algorithms that are powerful enough to combat these losses.

2. Very high path loss (free-space Friis attenuation ↑ with frequency). Thus, due to very small wavelength (milimeter) we observe:
   - blockage (e.g. by objects such trees, buildings, etc.
   - diffractions.

   This implies **Sensitivity to Blockage,** i.e due to the small wavelength, the links in the 60 GHz band are very sensitive to blockage.

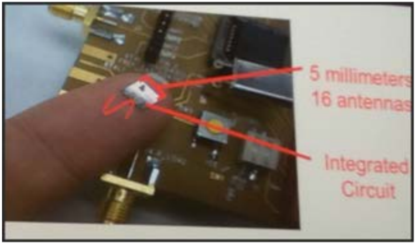
Examples

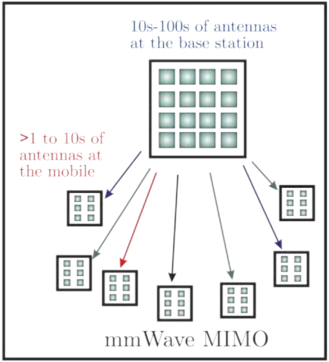
- blockage by a human causes a 20-30 dB dip in the link budget.



3. Solution to very high atmospheric attenuation and path loss:

   - **Highly directional beams.** With current technologies, the size of the antenna element shrinks dramatically at these frequencies. This makes it possible to have a massive antenna array on the Tx and Rx and, thus, employ powerful beamforming algorithms at the Tx and Rx to obtain accurate and highly directional beams.

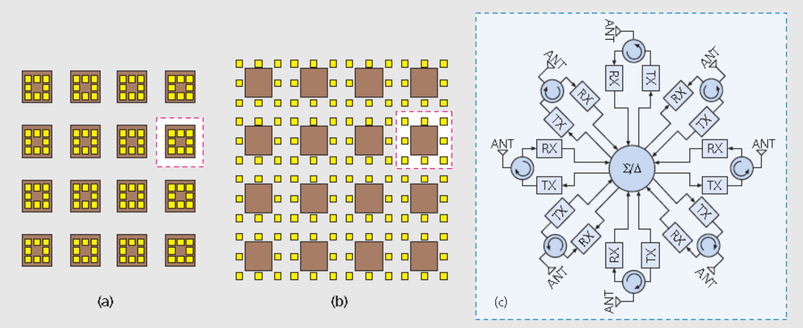




mmWave Antenna Array Chipsets

Example (60GHz Antenna Array Chipset (Qualcomm))

Example (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

mmWave MIMO: Main Advantages and Challenges

Advantages

- Achieves 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 Tx 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.

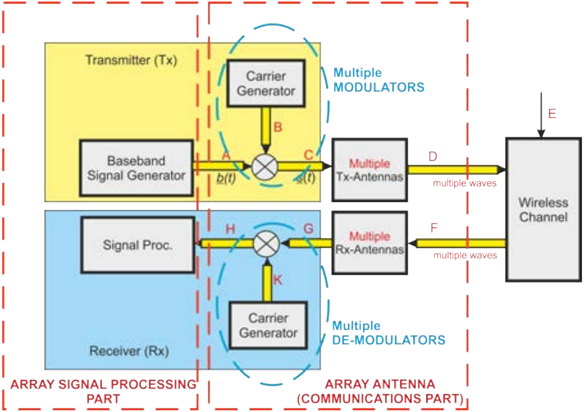
mmWave Beamformers

Digital Beamformers

- 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.

Software Defined Radio Implementation

- Radio HW impementation (e.g mixers, filters, amplifiers, modulators, demodulators, detectors, etc), nowdays are implemented in software
- Basic MIMO System Architecture and SDR



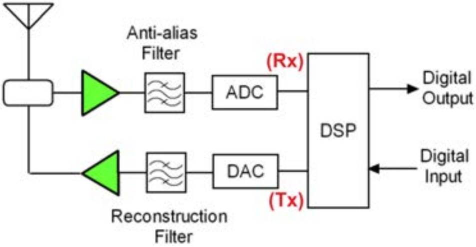
$\uparrow$ DSP (e.g. RuspberryPie,PC) $\uparrow$ SDR (e.g. FunCube Dongle, LimeDSR-mini)

Abbreviations

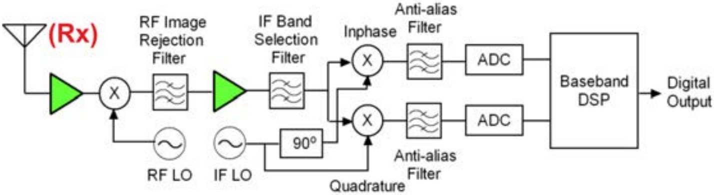
LO	Local Oscillator	DDC	Digital Down Converter
CLK	Clock	DUC	Digital Up Converter
IF	Intermediate Frequency	ADC	Analogue to Digital Converter
LPF	Low Pass Filter	DAC	Digital to Analogue Converter
BPF	Band Pass Filter	DDS	Direct Digital Synthesiser
PA	Power Amplifier	LNA	Low Noise Amplifier

SDR - Single Antenna

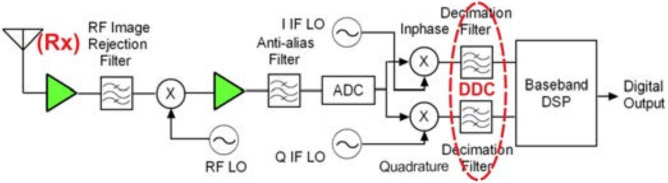
- The best SDR would have a high speed (and expensive) ADC for Rx and a high speed DAC for Tx at RF frequency.



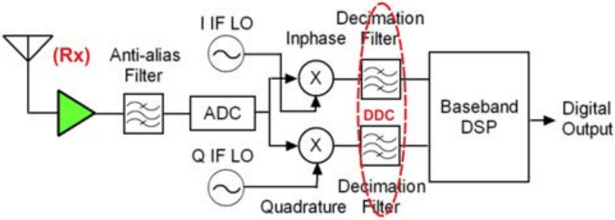
- 1st Generation SDR Rx:



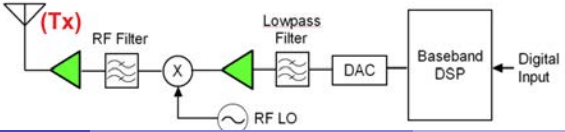
- 2nd Generation SDR Rx:



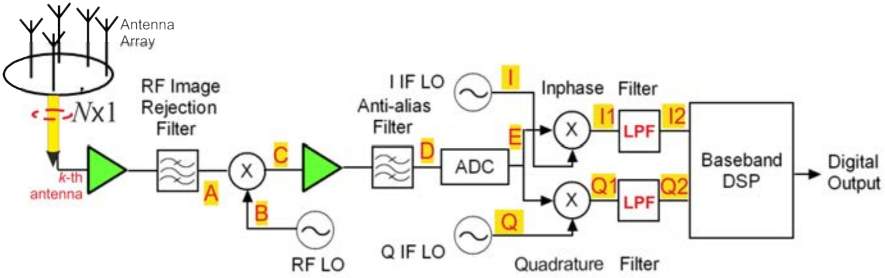
- 3rd Generation SDR Rx:



- SDR Tx:



Modelling a Single Branch of a Digital Beamformer

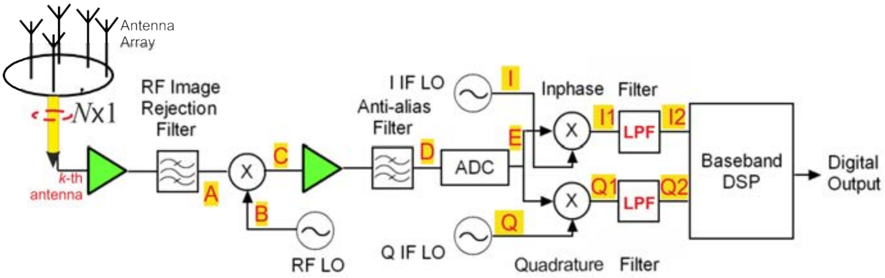


$$\boxed{A} = k\text{-th antenna} = m(t)\cos\left(2\pi F_{RF}\left(t - \frac{\underline{r}_k^T \underline{k}_i}{c}\right)\right)$$

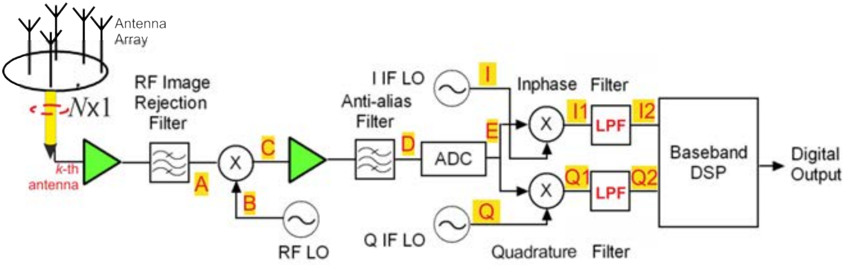
$$= m(t)\cos\left(2\pi F_{RF} t - \psi_k\right)$$

where $\psi_k \triangleq 2\pi F_{RF}\frac{\underline{r}_k^T \underline{k}_i}{c}$; $F_{RF} = F_c =$ carrier frequ.

$$\boxed{B} = 2\cos(2\pi F_{LO} t) \quad \text{where } F_{LO} = F_{RF} - F_{IF}$$



$$
\begin{aligned}
\boxed{C} &= \boxed{A} \times \boxed{B} \\
&= 2m(t)\cos\left(2\pi F_{RF} t - \psi_k\right)\cos(2\pi F_{LO} t) \\
&= m(t)\cos\left(2\pi\left(F_{RF} + F_{LO}\right)t - \psi_k\right) \\
&\quad + m(t)\cos\left(2\pi\underbrace{(F_{RF} - F_{LO})}_{\triangleq F_{IF}}t - \psi_k\right) \\
\boxed{D} &= m(t)\cos\left(2\pi F_{IF} t - \psi_k\right) \\
\boxed{E} &= m(t_\ell)\cos\left(2\pi F_{IF} t_\ell - \psi_k\right)
\end{aligned}
$$

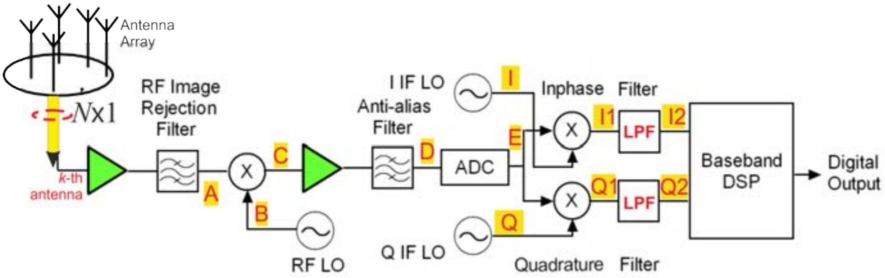


- Inphase:

$$\begin{aligned}
\mathbf{I} &= 2\cos\left(2\pi F_{DLO} t_\ell\right) \\
\mathbf{I1} &= m\left(t_\ell\right)\cos\left(2\pi(F_{IF}+F_{DLO})t_\ell-\psi_k\right)+m\left(t_\ell\right)\cos\psi_k \\
\mathbf{I2} &= m\left(t_\ell\right)\cos\left(\psi_k\right)
\end{aligned}$$

- Quadrature:

$$\begin{aligned}
\mathbf{Q} &= 2\sin\left(2\pi F_{DLO} t_\ell\right) \\
\mathbf{Q1} &= m\left(t_\ell\right)\sin\left(2\pi(F_{IF}+F_{DLO})t_\ell-\psi_k\right)+m\left(t_\ell\right)\sin\psi_k \\
\mathbf{Q2} &= m\left(t_\ell\right)\sin\psi_k
\end{aligned}$$



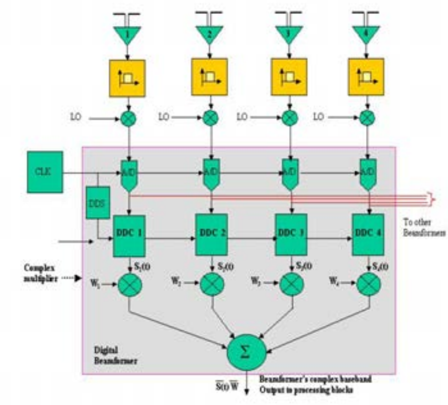
- Baseband input signal (k-th antenna):

$$\begin{aligned} x_k(t_\ell) &= \boxed{\mathbf{I2}} + j\,\boxed{\mathbf{Q2}} \\ &= m(t_\ell)\cos\psi_k + jm(t_\ell)\sin\psi_k = m(t_\ell)\underbrace{\exp\left(j\frac{2\pi F_{RF}}{c}\underline{r}_k^T\underline{k}_i\right)}_{\substack{k^{\text{th}}\text{ element of.} \\ \text{manifold vector}}} \end{aligned}$$

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

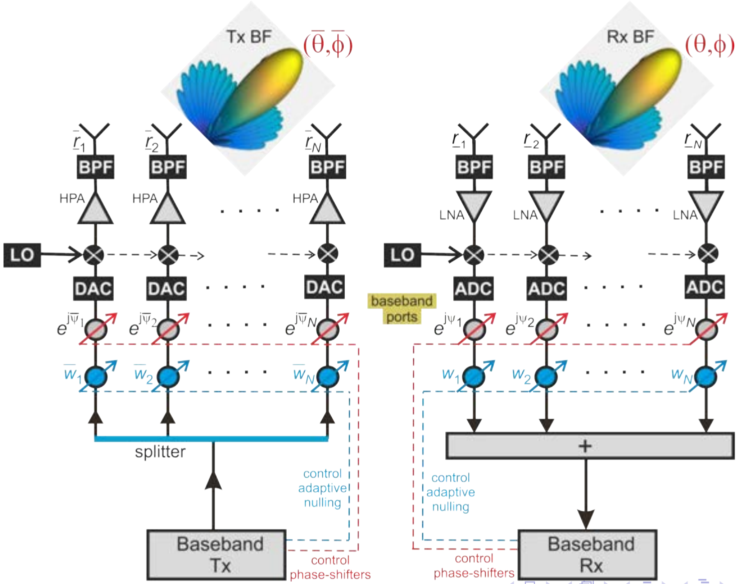
Digital mmWave Beamformer Implementation

Digital Beamformer

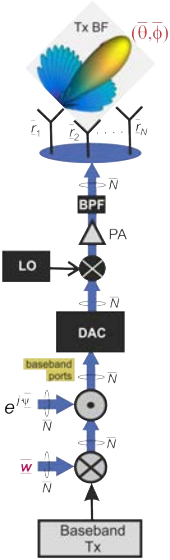


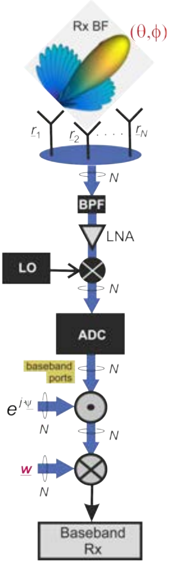
LO	Local Oscillator	DDC	Digital Down Coverter
CLK	Clock	DDS	Direct Digital Synthesiser
A/D	Analogue to Digital Converter		

Digital Tx and Rx Beamforming



Digital Tx and Rx Beamforming



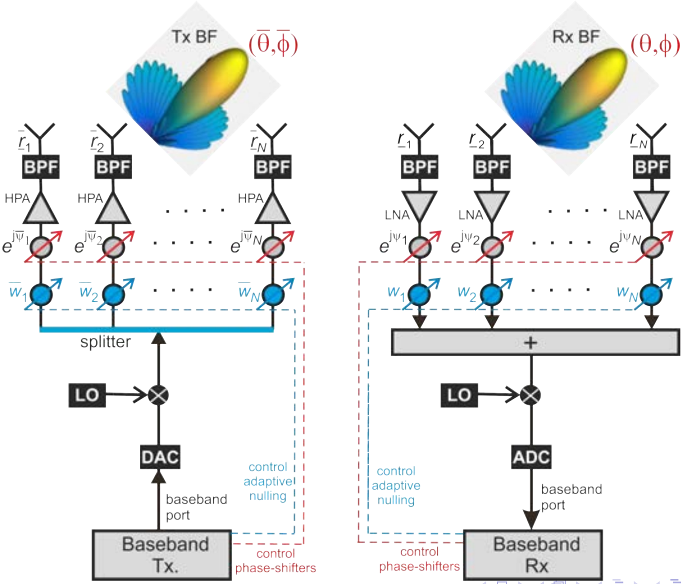


Analogue mmWave Beamformers

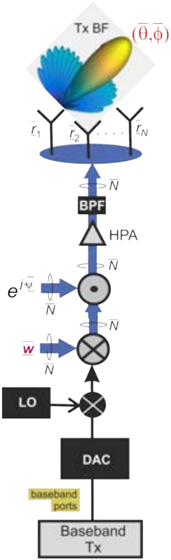
- In analogue beamforming, **one baseband port** feeds an analogue beamforming network where the beamforming weights are applied either directly on the analog baseband components, at some intermediate frequency, or at RF. For example, an RF beamforming network may consist of several phase shifters, one per antenna element, and optionally also variable gain amplifiers.

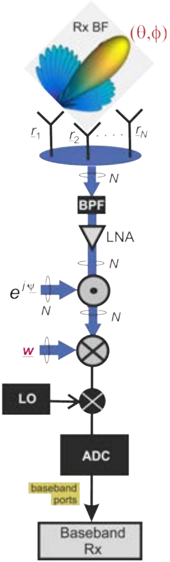
- In any case, an analogue beamforming network typically generates physical beams but cannot generate a complex beam pattern. Especially in a multi-user environment this can lead to interference, if pure beam separation is not sufficient.

Analogue Tx and Rx Beamforming



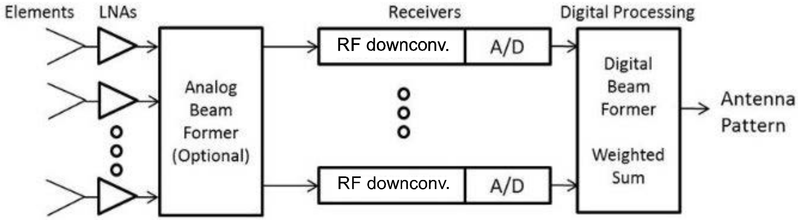
Analogue Tx and Rx Beamforming



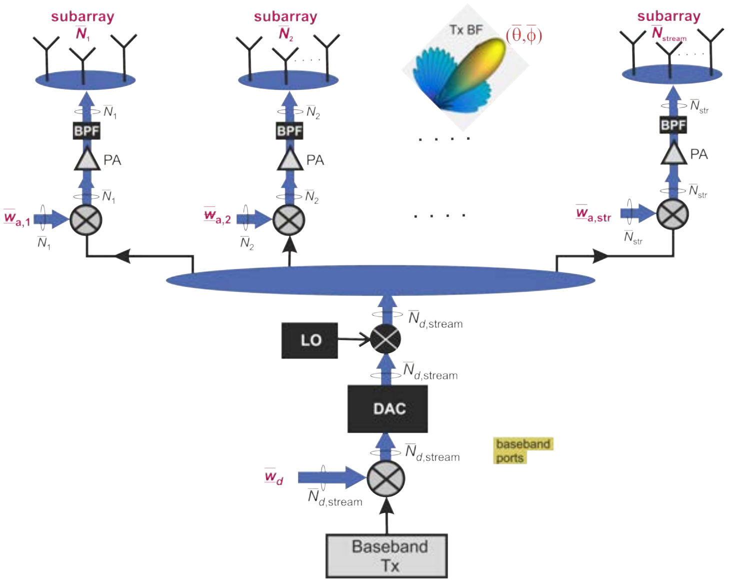


- **Hybrid beamforming,** is a compromise between Digital and Analogue Beamformers where a digital beamformer operating on a few baseband ports is followed by an analog beamforming network.

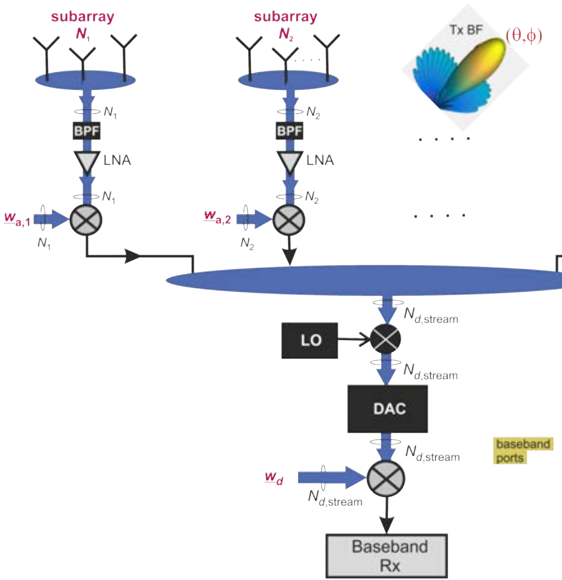
- This architecture enables a compromise with respect to both complexity and flexibility between analogue and full digital beamformer



Hybrid Tx-Beamforming (vector representation)



Hybrid Rx-Beamforming (vector representation)

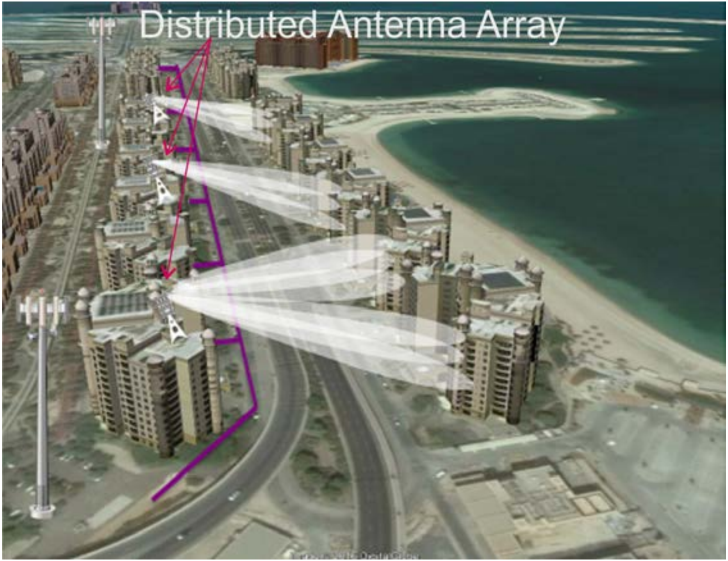


Comments

- 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.

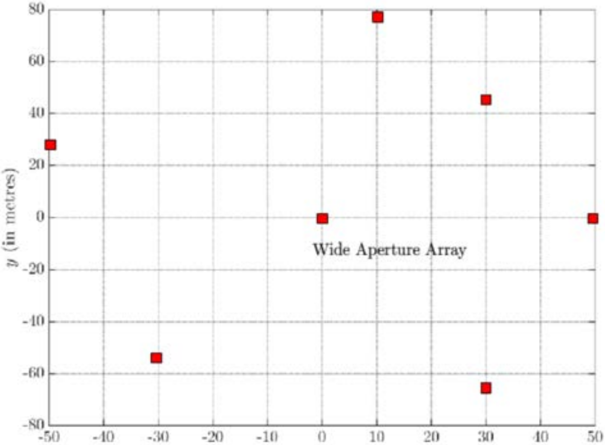
Digital BF	Hybrid BF	Analogue BF
TX/RX weights at baseband (i.e. digital)	TX/Rx weights at both RF (analogue) and baseband (digital)	Tx/Rx weights at RF to form beams
Each antenna element (or antenna port) has a transceiver chain i.e. $\overline{N}_{stream}=\overline{N}$, $N_{stream}=N$ (i.e. overall, high number of transceiver units)	Each RF-beam has a transceiver unit (i.e. moderate number of transceivers): $\overline{N}_{stream}<\overline{N}$; $N_{stream}<N$	One transceiver unit and one RF-beam: $\overline{N}_{straem}=1<\overline{N}$; $N_{stream}=1<N$.
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

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)



Wideband Assumption (WB-assumption)

Definition (Narrowband Assumption)

If the transmitted baseband wavefront does not change while travelling across the sensors of an array then different sensors **see the same part** of the transmitted signal and this is defined as the "narowband-assumption" (NB-assumption)

Definition (Wideband Assumption)

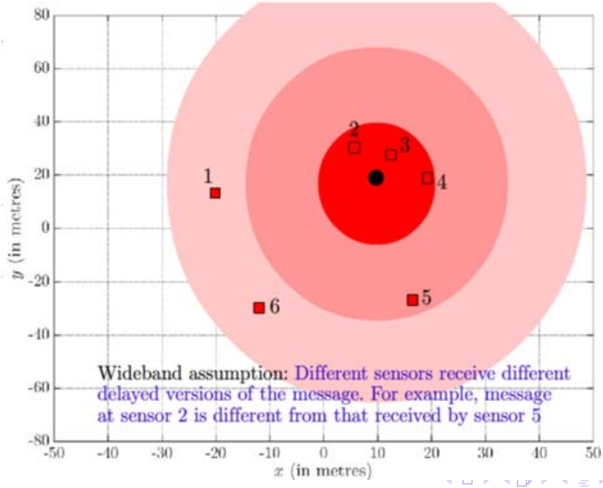
If the transmitted baseband wavefront changes while travelling across the sensors of an array then different sensors **see different parts** of the transmitted signal and this is defined as the "wideband-assumption" (WB-assumption)

- N.B.: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:

$$\text{NB-assumption:} \qquad \underline{x}(t) = \sum_{i=1}^{M} \underline{S}_i m_i(t) + \underline{n}(t) \tag{36}$$

$$\text{WB-assumption:} \qquad \underline{x}(t) = \sum_{i=1}^{M} \underline{S}_i \odot \underline{\mathbf{m}}_i(t) + \underline{n}(t), \tag{37}$$

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:

$$\mathbb{R}_{xx} = \sum_{i=1}^{M} P_i \underline{S}_i \underline{S}_i^H + \mathbb{R}_{nn} \tag{38}$$

  - WB-assumption:

$$\mathbb{R}_{xx} = \sum_{i=1}^{M} \underline{S}_i \underline{S}_i^H \odot \mathbb{R}_{\underline{\mathbf{m}}_i \underline{\mathbf{m}}_i} + \mathbb{R}_{nn} \tag{39}$$

where

$$\mathbb{R}_{\underline{\mathbf{m}}_i \underline{\mathbf{m}}_i} = \mathcal{E}\left\{ \underline{\mathbf{m}}_i(t) \, \underline{\mathbf{m}}_i(t)^H \right\} \tag{40}$$

Example (Multi-source Trajectory Tracking)

- In the reference below[a], both the Wide-Band and Narrow-Band assumptions are used for an array of sensors - where the sensors are distributed in space,
- the targets/sources parameters (kinematics of the targets) included in the modelling are:
  - ranges,
  - directions,
  - velocities and associated Doppler effects.

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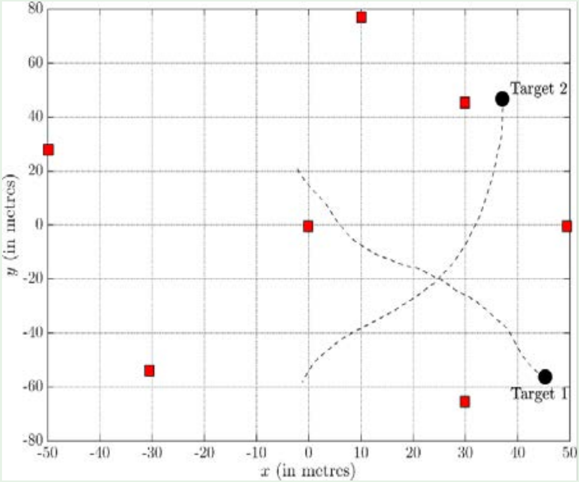
[a]

"Multi-source Spatiotemporal Tracking using Sparse Large Aperture Arrays",IEEE Trans on Aerospace and Electronic Systems, pp.837-853, 2017

Example (cont.)




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

Introduction

Definition

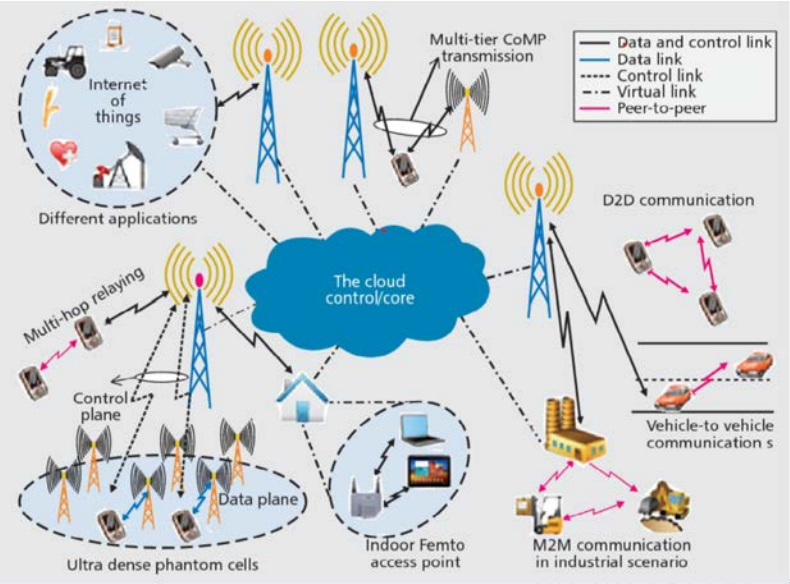
5G is the 5th generation of mobile networks.

- This is a significant evolution of todays 4G LTE networks. There are also those who believe that this not simply an "evolution" but a "revolution" (4th industrial revolution, 5G ecosystem).

- 5G has been designed to meet the very large growth in data and connectivity of today's modern society, the internet of things with billions of connected devices, and tomorrow's innovations.

- 5G will initially operate in conjunction with existing 4G networks before evolving to fully standalone networks in subsequent releases and coverage expansions.

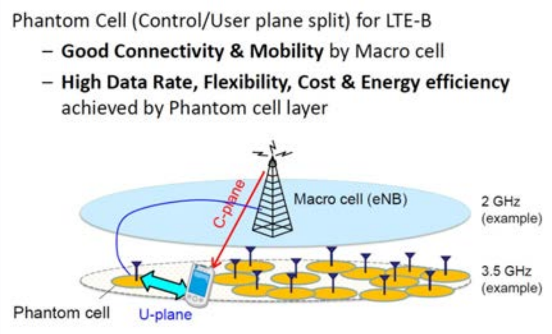
5G Ecosystem



Definitions

1. **Femtocell:** A femtocell is a small, low-power cellular base station, typically designed for use in a home or small business. A broader term which is more widespread in the industry is small cell, with femtocell as a subset. It is also called femto AccessPoint (AP).

2. **Fantom Cell:** (new concept in LTE-B)



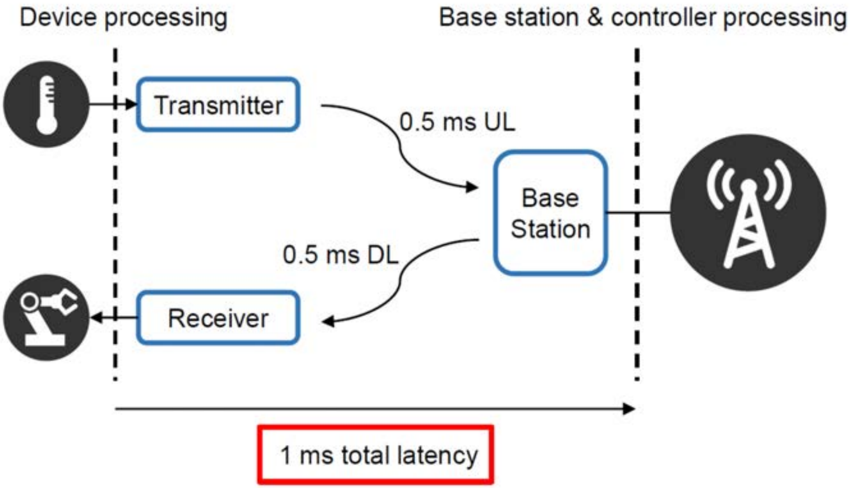
Revolutionary Changes: Latency

- In addition to delivering faster connections and greater capacity, a very important advantage of 5G is the fast response time referred to as latency.
- Latency is the time taken for devices to respond to each other over the wireless network.

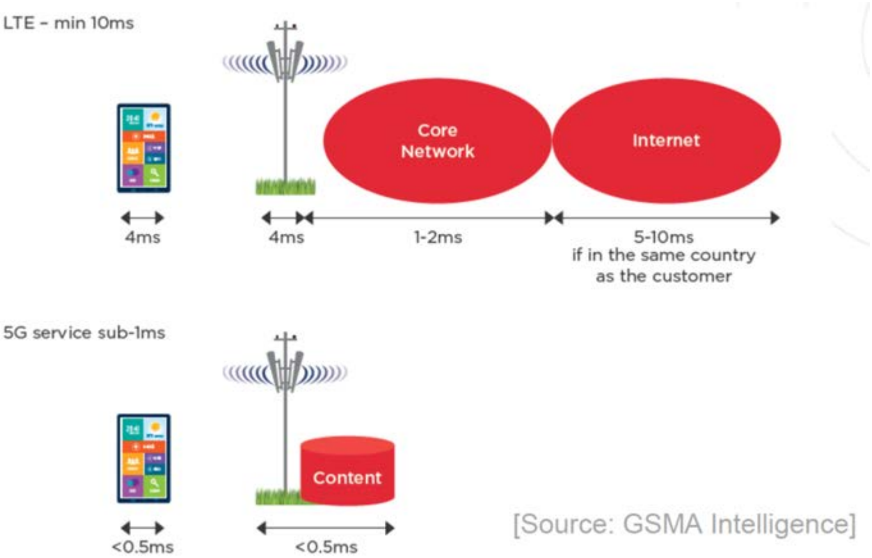
Examples (Latency)

- 3G networks had a typical response time of 100 milliseconds,
- 4G is around 30 milliseconds and
- 5G will be as low as 1 millisecond
  (this is virtually instantaneous - opening up a new world of connected applications)

- 5G Latency

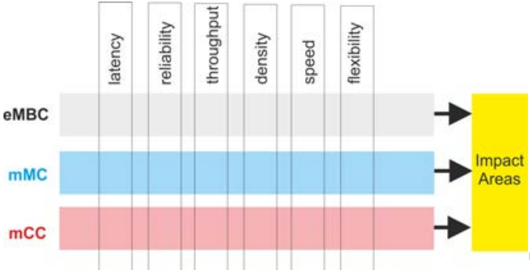

Device processing
Base station & controller processing
Transmitter
0.5 ms UL
Base Station
0.5 ms DL
Receiver
1 ms total latency

- LTE vs 5G Latency

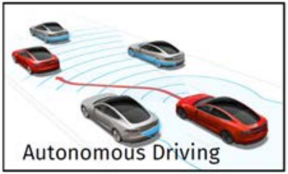


Revolutionary Changes: New Comm. Families

- **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 comm. 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)

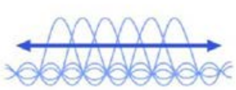


5G Use Examples (Impact Areas)



Other Revolutionary Changes

Scalable OFDM-based air interface



Scalable OFDM numerology

Address diverse services, spectrum, deployments

Flexible slot-based framework

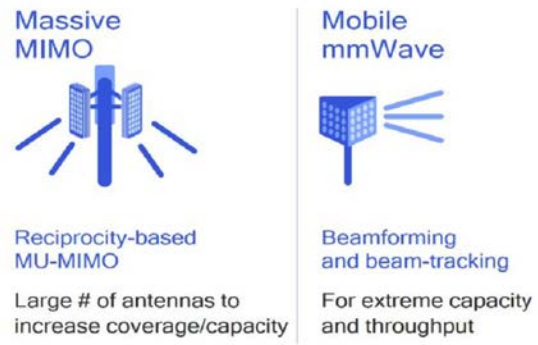
Self-contained slot structure

Low latency, URLLC, forward compatibility

Advanced channel coding

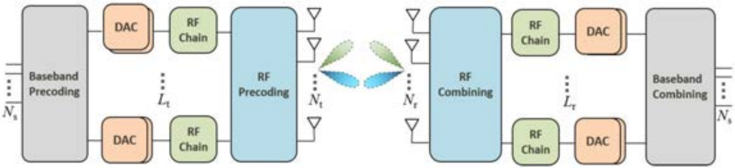
Multi-Edge LDPC and CRC-Aided Polar

Support large data blocks, reliable control channel

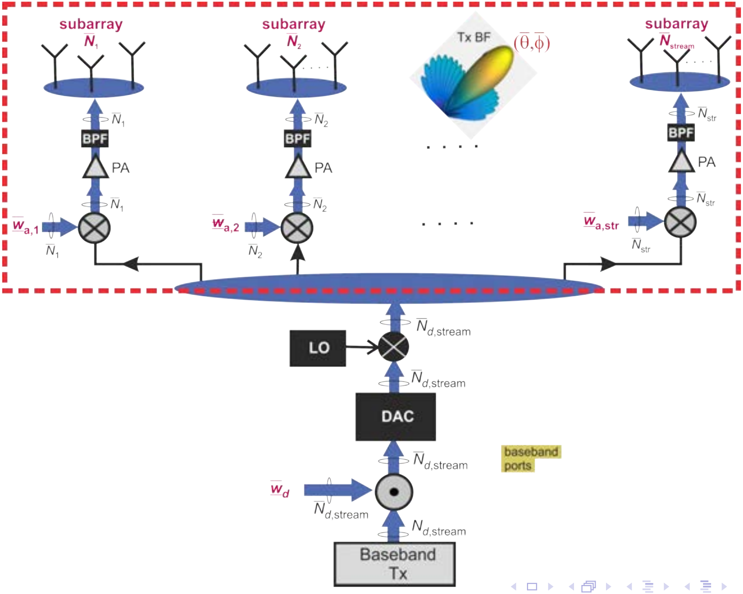

Massive
MIMO
Reciprocity-based
MU-MIMO
Large # of antennas to
increase coverage/capacity
Mobile
mmWave
Beamforming
and beam-tracking
For extreme capacity
and throughput

- 5G Operates
  - on higher frequency bands, which offers significantly more available bandwidth,
  - on smaller cells, running at lower power and allowing network densification.

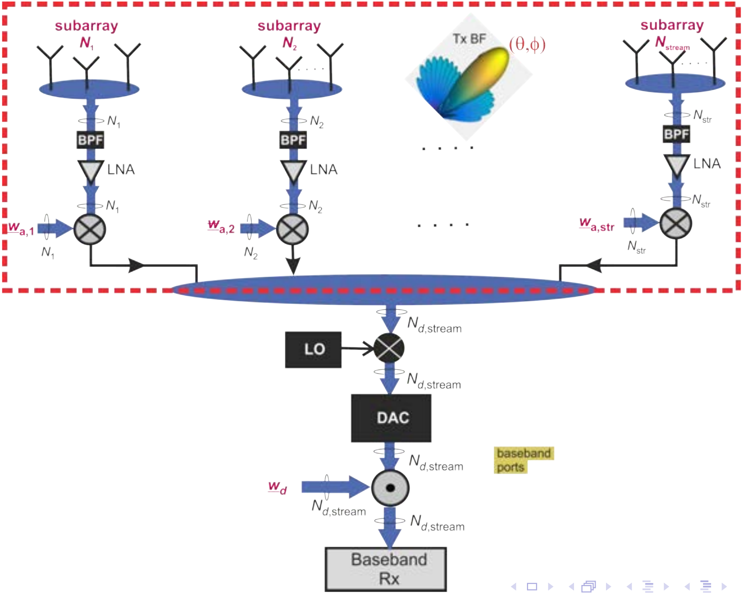
- 5G uses MIMO antenna schemes (maximizing the reuse of scarce bandwidth).
  - With massive MIMO beamforming, it becomes possible to move the network forward from the traditional point-to-multipoint paradigm to a real-time adaptive point-to-point link, with the base station tracking the user and steering its signal to them.



MIMO Tx Implementation



MIMO Rx Implementation

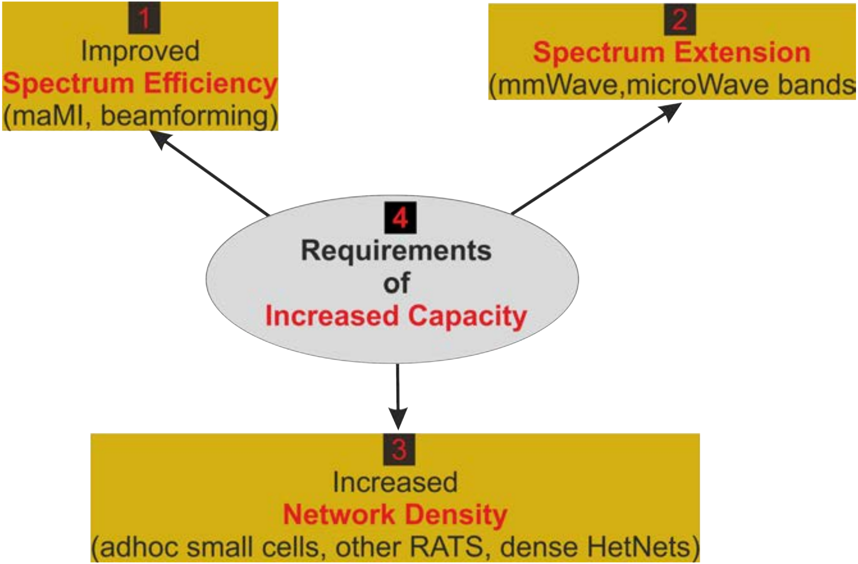


- 5G: Typical massive MIMO designs will range from tens to hundreds of antennas, beamforming in azimuth and elevation.
- Improved antenna gain overcomes path loss, enabling higher data rates per Hz compared with an isotropic signal at the same power.
- mmWave in 5G:
  1. (+) directional communications $\Rightarrow\Downarrow\Downarrow$
     - ★ (-) risk of deadness
     - ★ (-) Need of beam alighment/tracking to maintain connectivity (beamwidth vs tracking overheads trade-off)
  2. (+) Massive MIMO $\Rightarrow$ $(-)$Power consumption and device complexity

Summary of 5G New Characteristics

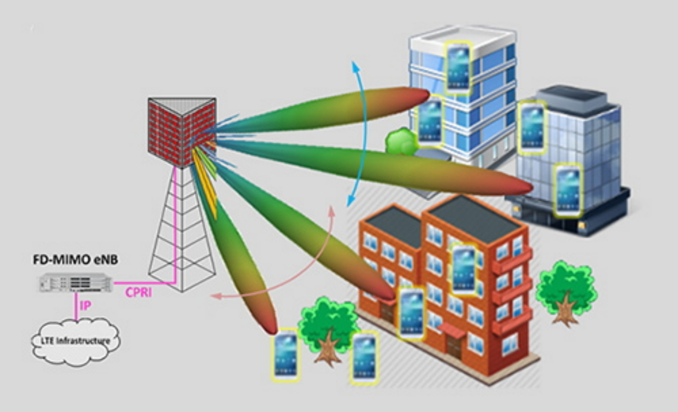
1. **Flexibility** for expanding connectivity needs
2. **multi-connectivity** across spectrum bands and technologies⇒improves coverage and mobility
3. **Diverse spectrum types and bands** (narrowband, wideband, UWB, TDD, FDD, exclusive use, shared use, or shared exclusive use)
4. A **new unified air-interface** provides the foundation (see NR)

High Capacity Requirements

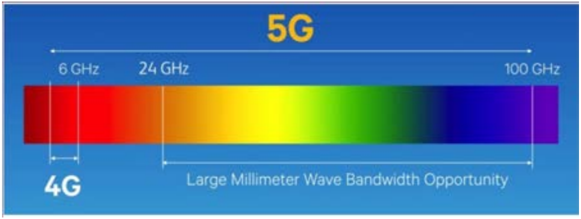


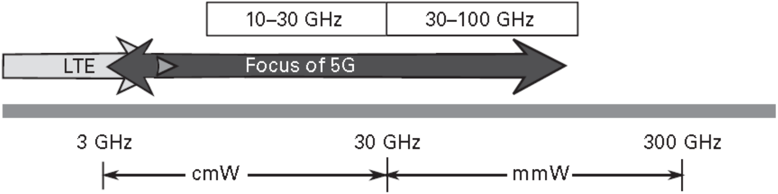
1. Improve Spectrum Efficiency:

- 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



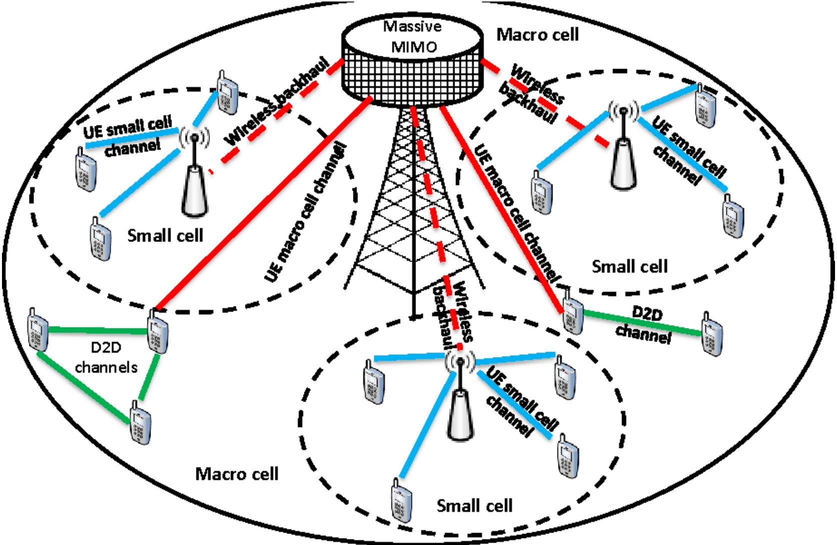
2. Spectrum Extension (up to 100GHz)



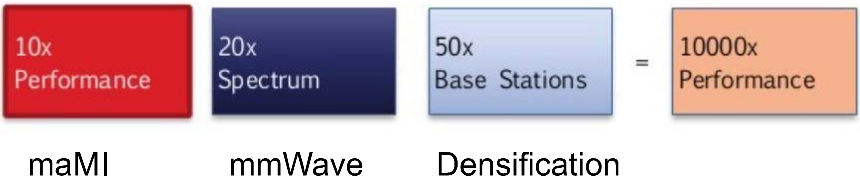


3. Increase Network Density

- Many BSs and many cells of different size



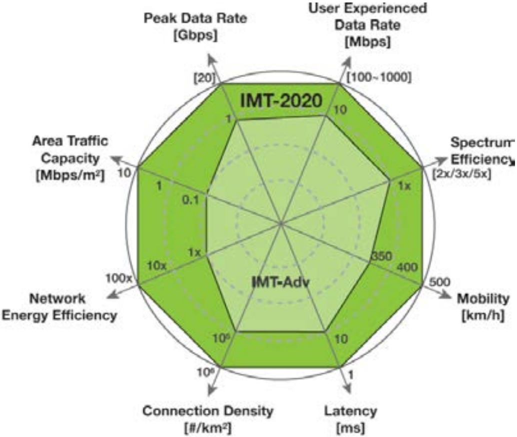
4. Overall Performance (Capacity)



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

$$\text{Overall} \;>> 10000 \times \mathit{Performance}$$

ITU Recommendations (IMT2020 Spinder Diagram)

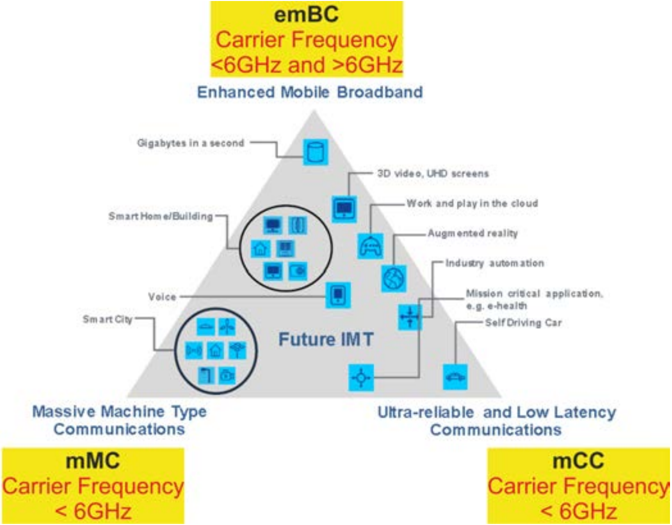


Key Capabilities

Peak data rate	20	Gbps
User data rate	100	Mbps
Spectrum Efficiency	3 ×	
Mobility	500	km/h
Latency	1	ms
Connection density	10^6	$\frac{\text{devices}}{\text{km}^2}$
Energy efficiency	100 ×	
Area traffic capacity	10	$\frac{\frac{\text{Mbits}}{\text{s}}}{\text{m}^2}$

Recommendation ITU R M. 2083 0, "IMT Vision Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015.

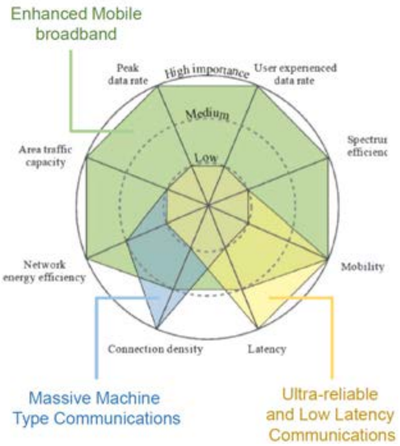
ITU Recommendations (Triangle Diagram)



Importance of Key Capabilities

The importance of key capabilities in different usage scenarios

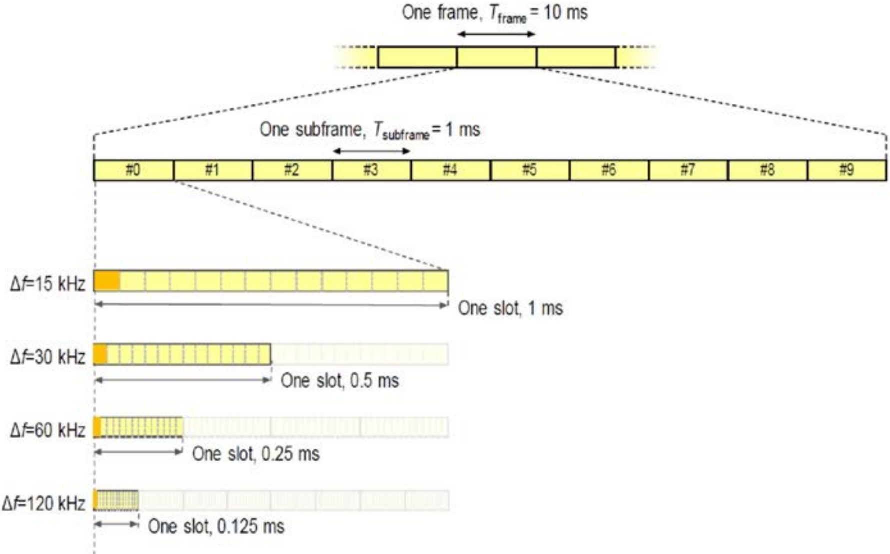
	eMBB	mMTC	URLLC
Peak data rate	★★★	★	★
User experienced data rate	★★★	★	★
Spectrum efficiency	★★★	★	★
Mobility	★★★	★	★★★
Latency	★★	★	★★★
Connection density	★★	★★★	★
Energy efficiency	★★★	★★	★
Area traffic capacity	★★★	★	★



"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 **emBC, mMC, mCC**
  - NR supports **spectrum** below and above 6GHz (this could be licensed or unlicenced)

5G Frame Structure



Note-1: Some Current Matlab Useful Toolboxes

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

Note-2: Typical Array Design Elements

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

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. This is a 1995 vision of the future.