Beamforming

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Outline

- Antenna Classification
- Adaptive Arrays
- Beamforming
- Types of Beamforming
- Beamforming in MIMO
- 5G Use Cases
- Beamforming in 5G NR
- Conclusion

Antenna Classification

Individual Elements

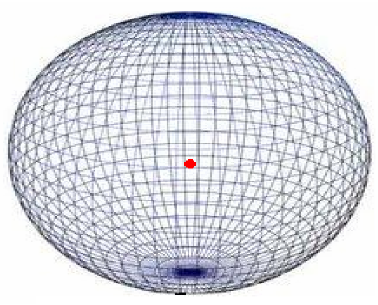
- Isotrophic
- Omnidirectional
- Directional

Antenna Arrays (>1 Antenna)

- Phased Arrays
- Adaptive Arrays

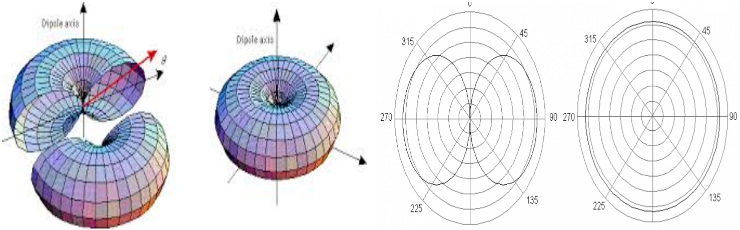
Isotrophic Antenna

- Radiates its energy equally in all directions.
- Such elements are not physically realizable.
- Often used as references to compare to them the radiation characteristics of actual antennas.



Omnidirectional Antenna

- An isotropic pattern in a given plane and directional in an orthogonal plane.



- Disadvantage : Only a small amount of radiated signal energy is received at the desired user.

Motivation for directional Antenna

- This unfocused approach scatters signals, reaching desired users with only a small percentage of the overall energy sent out into the environment.
- Majority of transmitted signal power radiates in directions other than the desired user
- Single-element approach cannot selectively reject signals interfering with those of served users.

Directional Antennas

- Concentrates power primarily in certain directions or angular regions.

Challenges of directional antennas

Mechanical Steering

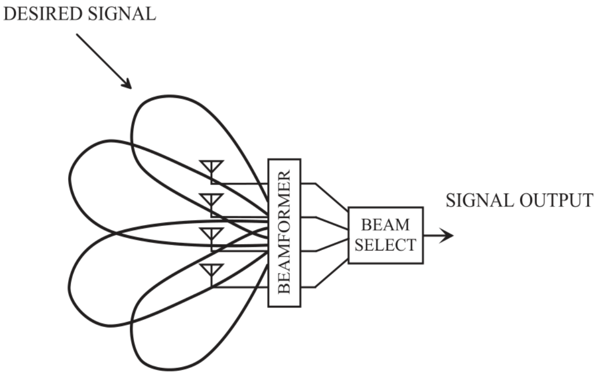
- This involves manually tuning the antenna to face the direction of interest.
- Mechanical steering becomes undesirable and difficult when we consider factors such as antenna size, weight, and weather conditions. This is often performed by means of **electric motors**.
- Its use is limited to static or very slow changing environments due to the limitation in steering speed. Also, rotating mechanisms are prone to **mechanical failure** due to fatigue and wearing of moving parts.

Solution ?

- The solutions for these problem led to **electronic ways** of steering beams.

Electronic Steering - Phased Arrays

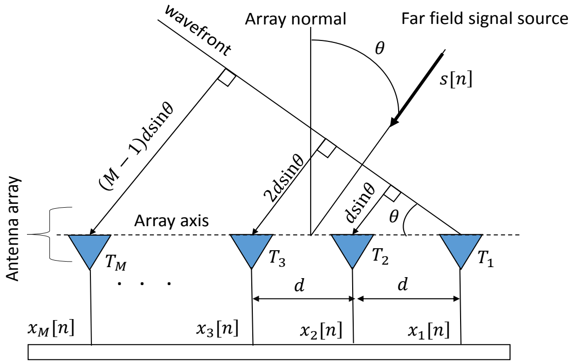
- A phased array antenna uses an array of single elements and combines the signal induced on each element to form the array output.
- The direction where the maximum gain occurs is usually controlled by adjusting properly the **amplitude and phase** between the different elements.



Adaptive Arrays

- Radiation characteristics of these arrays are adaptively changing according to changes and requirements of the radiation environment.
- They have well-known advantages for providing flexible, rapidly configurable, beamforming and null-steering patterns.
- Continuously adjusts its own pattern by means of **feedback control**.
- The pattern of the array can be steered toward a desired direction space by applying phase weighting across the array and can be shaped by amplitude and phase weighting the outputs of the array elements.
- Adaptive antenna arrays are commonly equipped with signal processors which can automatically adjust by a simple adaptive technique the variable antenna weights of a signal processor so as to maximize the signal-to-noise ratio.

Uniform Linear Array



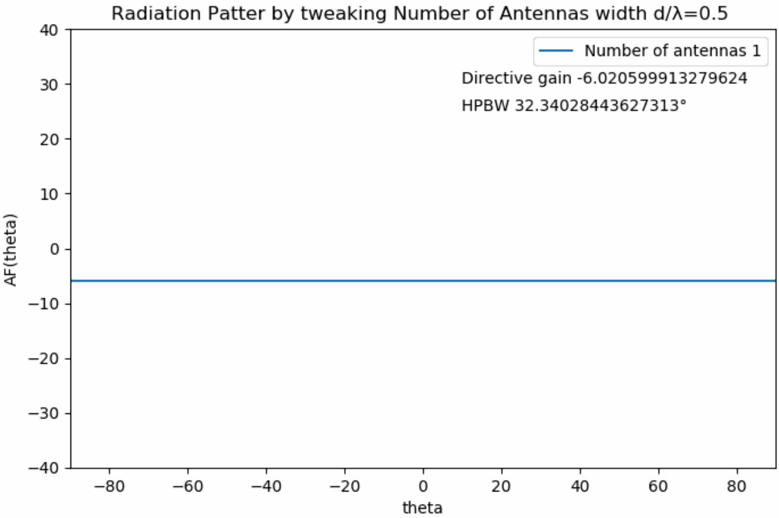
Uniform Linear Array

- For antenna array there are several parameters to control.
  1. Spacing between Antennas.
  2. Number of Antennas.

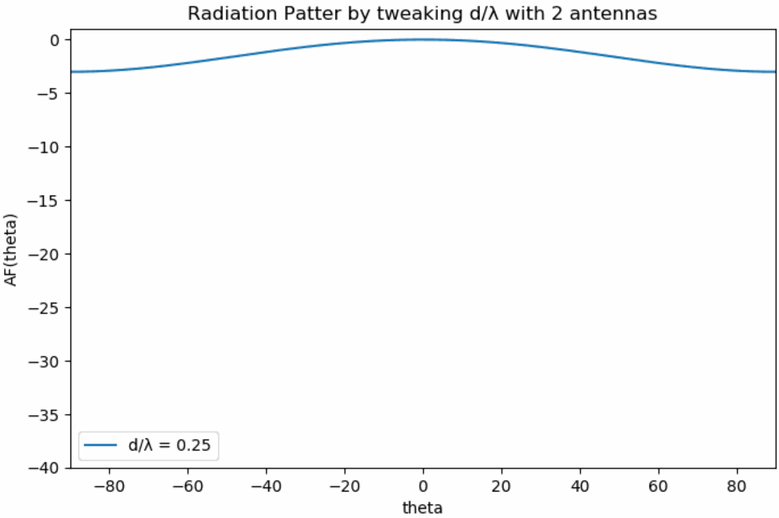
Questions to answer..

- What is the ideal spacing between antennas and what happens if we change it?
- What is the gain if we increase number of antennas?

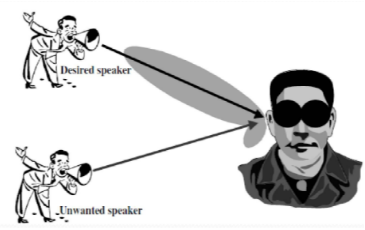
Tweaking Number of Antennas ULA

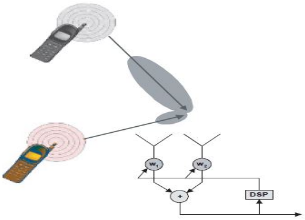


Tweaking distance between Antennas ULA



Beamforming





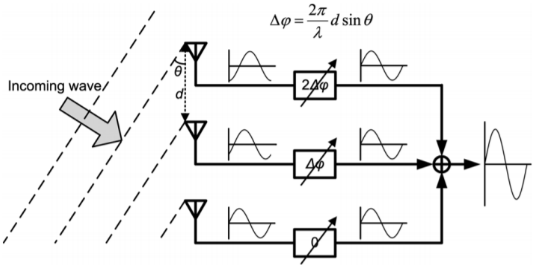
Origin of the word "Beamforming" or "Forming Beams"

Early spatial filters were designed to form pencil beams in order to receive signal from a specific location and attenuate signals from other directions.

Definition

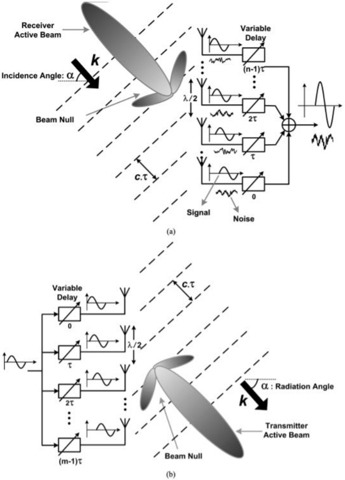
Beamforming or spatial filtering is a signal processing technique used in sensor arrays for directional signal transmission or reception

Consider an AWGN (Additive white gaussian channel) channel between the transmitter and receiver.



[0] S. Jeon et al., "A Scalable 6-to-18 GHz Concurrent Dual-Band Quad-Beam Phased-Array Receiver in CMOS," in IEEE Journal of Solid-State Circuits, vol. 43, no. 12, pp. 2660-2673, Dec. 2008

Understanding beamforming

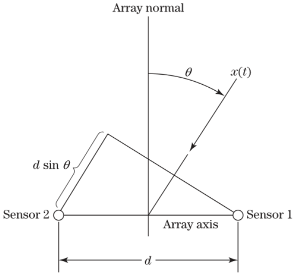


[0] A. Hajimiri, H. Hashemi, A. Natarajan, Xiang Guan and A. Komijani, "Integrated Phased Array Systems in Silicon," in Proceedings of the IEEE, vol. 93, no. 9, pp. 1637-1655, Sept. 2005

AWGN Channel

Received signal

Consider the pair (N = 2) of identical isotropic point sources spaced apart by a distance d. An isotropic point source radiates equally in all directions. Let a signal x(t) impinge on the two sensor elements in a plane containing the two elements and the signal source from a direction θ with respect to the array normal. Figure shows that element 2 receives the signal τ after element 1.



$$\tau = \frac{dsin(\theta)}{c} \quad (1)$$

- Let the array output signal y(t) be given by the sum of the two sensor element signals so that

$$y(t) = x(t) + x(t - \tau) \quad (2)$$

- If x(t) is a narrowband signal having center frequency f, then the time delay τ corresponds to a phase shift of $2\pi(d/\lambda)\ sin(\theta)$ radians, where λ is the wavelength corresponding to the center frequency, $\lambda = c/f$.

- We know that x(t) is some modulated signal. So

$$
\begin{aligned}
x(t) &= k(t)e^{j2\pi ft} \\
x(t-\tau) &= k(t-\tau)e^{j2\pi f(t-\tau)}
\end{aligned} \tag{3}
$$

- As we consider k(t) as narrowband signal (where $\tau << T$)

$$
\begin{aligned}
k(t-\tau) &\approx \text{k(t)} \\
x(t-\tau) &= k(t)e^{j2\pi f(t-\tau)} \\
x(t-\tau) &= x(t)e^{-j2\pi f\tau}
\end{aligned} \tag{4}
$$

- The overall array response is the sum of the signal contributions from the two array elements. That is,

$$
\begin{aligned}
y(t) &= \sum_{i=1}^{i=2} x(t)e^{-j(i-1)\psi} \\
\psi &= 2\pi(d/\lambda)sin(\theta)
\end{aligned} \tag{5}
$$

- Let's consider **M** antennas at receiver,array response vector is defined as

$$\mathbf{a}(\theta) = \left[1 \ e^{-j\frac{2\pi d}{\lambda}sin(\theta)} \dots e^{-j(M-1)\frac{2\pi d}{\lambda}sin(\theta)}\right]^T = \left[1 \ e^{-j\pi sin(\theta)} \dots e^{-j(M-1)\pi sin(\theta)}\right]^T. \tag{6}$$

$$\mathbf{y(t)} = \mathbf{a}(\theta)x(t) + \mathbf{w(t)} \tag{7}$$

- where the vectors $\mathbf{y}(t)$ and $\mathbf{w}(t)$ are defined as

$$\mathbf{y(t)} = [y_1(t) \ y_2(t) \ \dots \ y_M(t)]^T$$
$$\mathbf{w(t)} = [w_1(t) \ w_2(t) \ \dots \ w_M(t)]^T.$$

- Beamforming weight is set to be equal to the array response vector of the desired signal.
- For any particular direction θ_0, the antenna pattern formed using the weight vector $w_b = a(\theta_0)$ has the maximum gain in this direction compared to any other possible weight vector of the same magnitude.
- w_b adjusts the phases of the incoming signals arriving at each antenna element from a given direction θ_0 so that they add in-phase (or constructively).

Projection on the steering vector

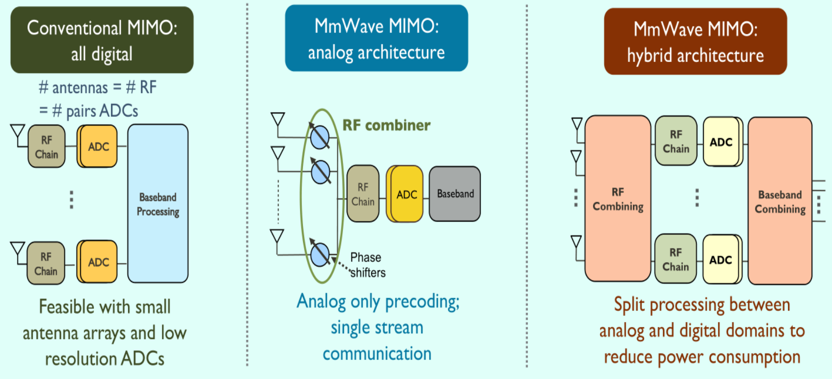
$$z(t) = \mathbf{a}^H(\theta_0)\mathbf{y}(t). \tag{8}$$

Other Beamforming techniques

STATISTICAL ALGORITHMS	ADAPTIVE ALGORITHMS
Maximum SNR Beamformer	Least Mean-Square(LMS)
Multiple Sidelobe Canceller	Recursive Least-Squares (RLS)
Maximum SINR Beamformer	Constant-Modulus (CM)
Minimum Mean Square Error (MMSE)	Affine-Projection (AP)
Direct Matrix Inversion (DMI)	Quasi-Newton (QN)
Linearly Constrained Minimum Variance	

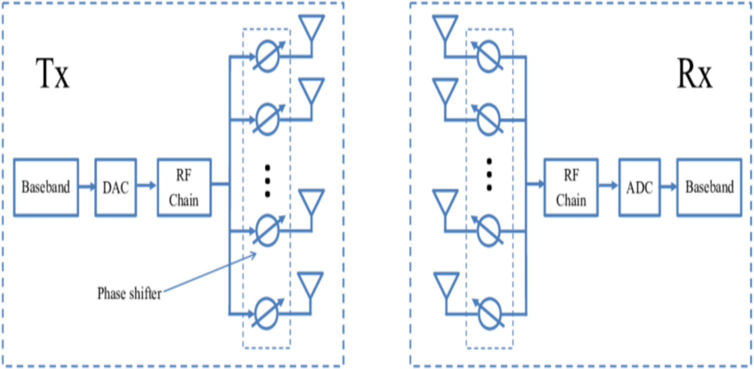
Types of Beamforming

- Beamforming can be divided into three categories :-
  1. Analog Beamforming
  2. Digital Beamforming
  3. Hybrid Beamforming



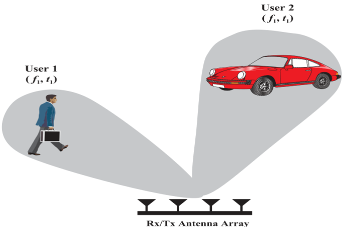
Analog Beamforming

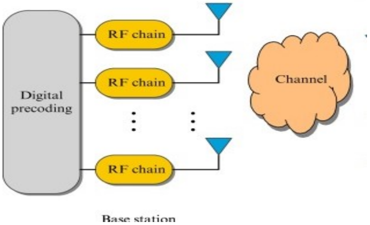
- Same signal is fed to each antenna and then analog phase-shifters are used to steer the signal emitted by the array. This is what a phased array would do.



Digital Beamforming

- A large number of independently steered high-gain beams can be found without any resulting degradation in SNR.
- Beams can be assigned to individual users, there by assuring that all links operate with maximum gain. All users can be accommodated at the same time and same frequency but different spatial directions which we term as **spatial division multiple access(SDMA)**.





Analog BF Vs Digital BF

Table: Differences between Analog and Digital Beamforming(BF)

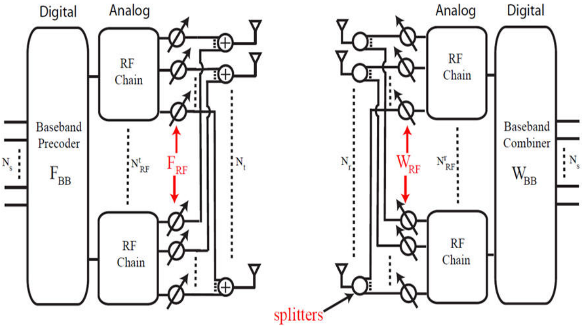
Parameter	**Analog BF**	**Digital BF**
No. of users supported	1	$\min(N_t, N_r)$
No. of RF chains	1	Min req. No. of users
Hardware complexity	Less	More
Cost and Power	Less	More

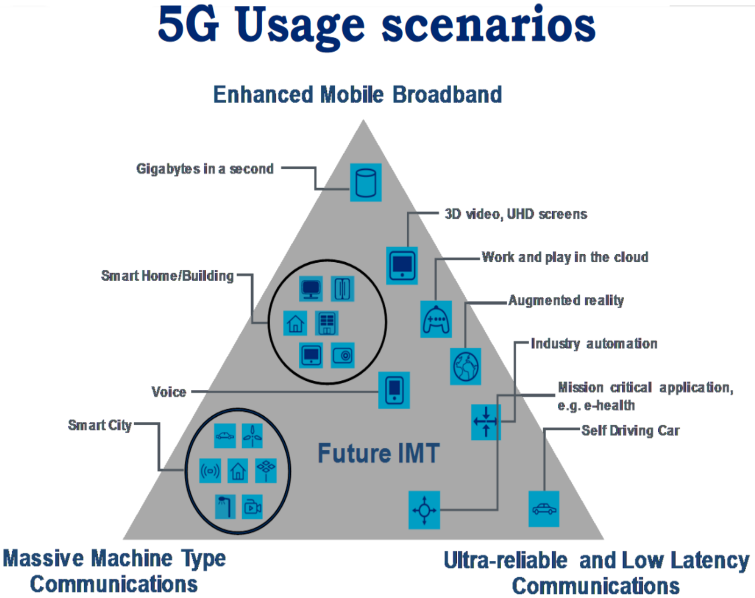
Motivation for Hybrid Beamforming

- For mmWave communication above 6GHz, signal suffers from significant path loss and penetration loss.
- One solution to solve this problem is to deploy large-scale antenna array to achieve high beamforming gain to compensate the loss. It is a practical solution in high frequency system due to smaller wavelength of high-frequency signal.
  f $\alpha \frac{1}{\lambda} => f\uparrow \lambda\downarrow =>$ Spacing between antennas decreases
- When antenna scale is so large, fully exploiting multiple-input multiple-output (MIMO) gain by pure digital beamforming in base-band is not realistic due to the problems on *hardware cost*, *power consumption* and standardization complexity since it requires *dedicated RF chain* for each baseband antenna port.
- The problem to the solution lies in the **hybrid analog-digital beamforming** (>6 GHz)

Hybrid Beamforming Contd...

- A combination of analog beamformers in the RF domain, together with digital beamforming in the baseband, connected to the RF with a smaller number of up/downconversion chains.
- Number of up-downconversion chains is only lower-limited by the number of data streams that are to be transmitted.
- Beamforming gain and diversity order is given by the number of antenna elements if suitable RF beamforming is done.



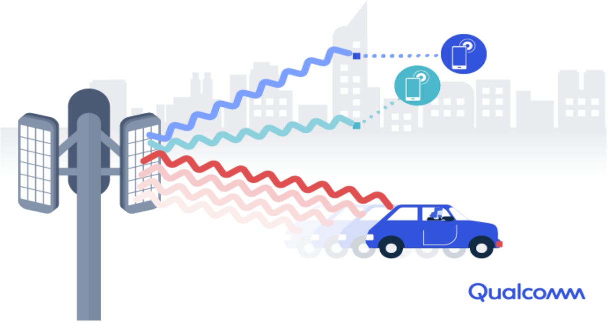


5G Usage scenarios
Enhanced Mobile Broadband
Gigabytes in a second
3D video, UHD screens
Work and play in the cloud
Smart Home/Building
Augmented reality
Industry automation
Voice
Mission critical application, e.g. e-health
Smart City
Self Driving Car
Future IMT
Massive Machine Type Communications
Ultra-reliable and Low Latency Communications

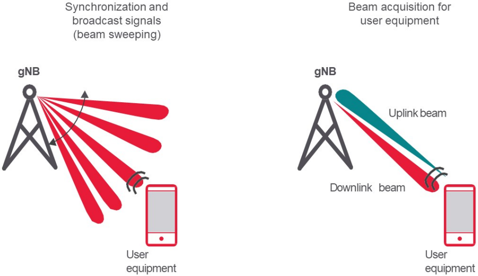
Beamforming used in 5G NR

Beamforming has a key role to play in meeting the above requirements.

- 3D Beamforming : It creates horizontal and vertical beams toward users, increasing data rates (and capacity) for all users—even those located in the top floors of high-rise buildings.



- Initial access : 5G NR specifies new initial access procedures to ensure alignment of the directional transmissions used in beam steering. New initial access techniques use beam sweeping to have the base station transmit multiple beams and then identify the strongest beam and establish a communication link.



Conclusion and Future scope

- As we are scaling up in frequencies from 4G to 6G, propagating loss and channel sparsity increases. This mandates us to use beamforming to increase the coverage and SINR.
- Deep learning can be used for channel estimation and beam-selection in massive MIMO systems.
- The lack of freely available data sets impairs the data-driven lines of investigation. It is challenging to implement learning algorithms for massive beamforming with limited computation capacity of radio hardware in real time.
- ML inference with hard realtime constraints at the micro-to-nanosecond time scales is required.
  References: - [**Link to references**]

Thank you