Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [mmWave Beamforming]
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Re: []

Abstract: [Presentation on OFDM & SC Beamforming]

Purpose: [Presentation on OFDM & SC Beamforming]

Beamforming System Model

Beamforming System Model

- A device using the same antennas for transmission and reception, i.e. same physical antennas, is referred to as a Antenna Symmetric System (ASS), otherwise it is referred to as Antenna Asymmetric System (AAS);

- The ASS is a special case of AAS;

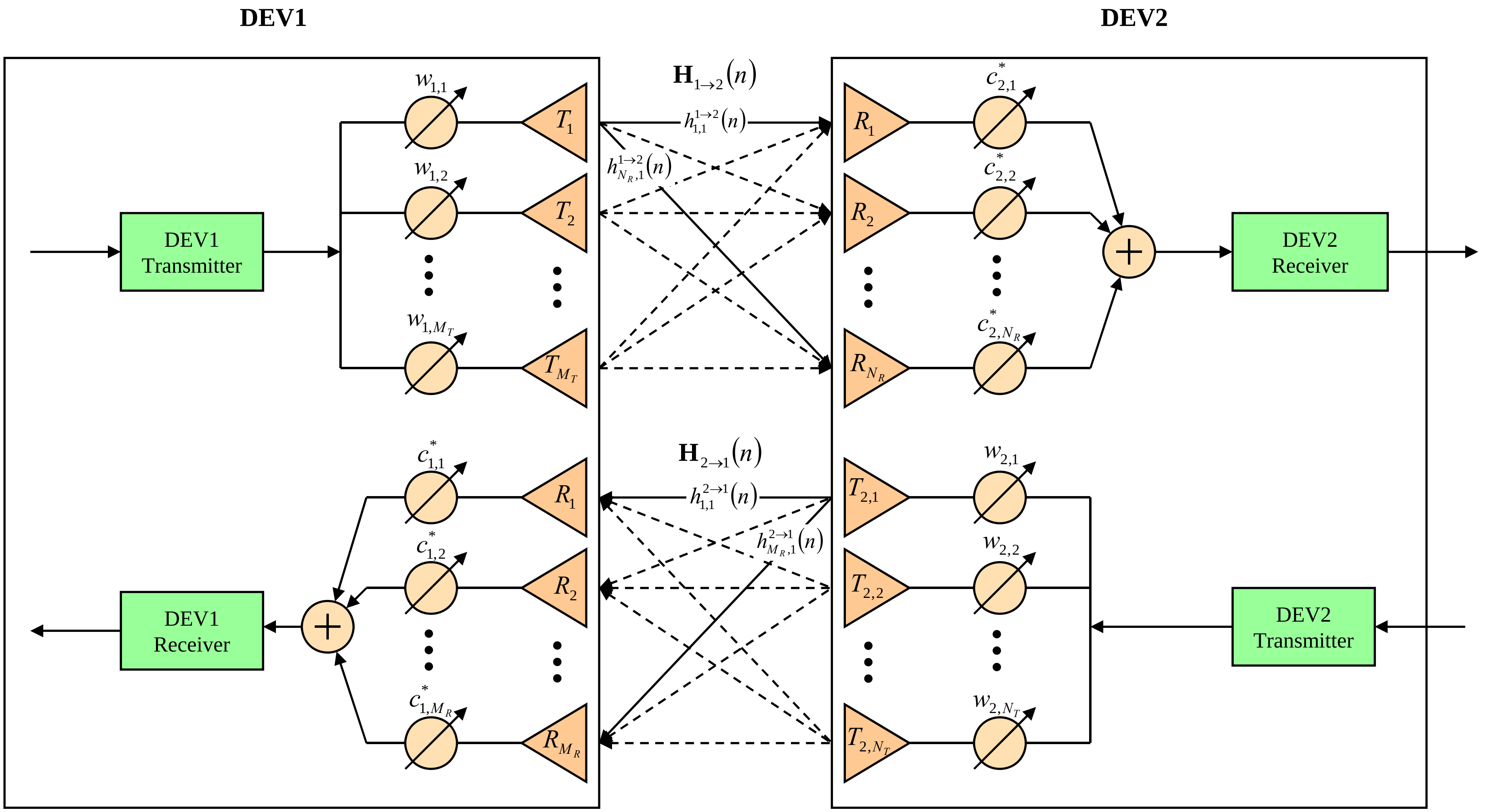
- Consider a link between two AAS devices, DEV1 and DEV2, as shown in Fig. 1:
  - DEV1 has M_{T} Transmit antennas and M_{R} Receive antennas;
  - DEV2 has N_T transmit antennas and N_R receive antennas;

- The developed model makes no assumptions regarding the antenna arrangements whether these are 1-D or 2-D antenna arrays, or any other arrangement;

- A cyclic prefixed OFDM system with an FFT length of N subcarriers and a cyclic prefixed Single Carrier (SC) system with a burst length of N have the same system model.

- We assume that the cyclic prefix is longer than any multipath delay spread between any pair of antenna elements;

Beamforming System Model



Beamforming System Model

- Consider an OFDM symbol (SC burst) transmitted from DEV1 to DEV2:

$$x(t)=\sum_{k=0}^{N-1} s_k \delta(t-kT_c)$$

where T_c is the sample (chip) duration and s_k are the complex data $s_k \in C$;

- At DEV1's transmitter, the bit stream is modulated by the ***beamformer*** *vector*:

$$\mathbf{w}_1=\begin{bmatrix} w_{1,1} & w_{1,2} & \cdots & w_{1,M_T} \end{bmatrix}^T$$

and then transmitted into a MIMO channel with a frequency domain Channel State Information (CSI) $\mathbf{H}_{1\to 2}(n)\in C^{M_T\times N_R}$ at frequency bin number n:

$$\mathbf{H}_{1\to 2}(n)=\begin{bmatrix} h_{1,1}^{1\to 2}(n) & h_{1,2}^{1\to 2}(n) & \cdots & h_{1,N_R}^{1\to 2}(n) \\ h_{2,1}^{1\to 2}(n) & h_{2,2}^{1\to 2}(n) & \cdots & h_{2,N_R}^{1\to 2}(n) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_T,1}^{1\to 2}(n) & h_{M_T,2}^{1\to 2}(n) & \cdots & h_{M_T,N_R}^{1\to 2}(n) \end{bmatrix}$$

where $h_{i,j}(n)$ denotes the cascade of the transmit/receive filtering, and the channel response between DEV1 j-th transmit antenna and DEV2 i-th receive antennas;

Beamforming System Model

- At DEV2's receiver, the received signals are processed through the ***combiner*** *vector*:

$$\mathbf{c}_2 = \begin{bmatrix} c_{2,1} & c_{2,2} & \cdots & c_{2,N_R} \end{bmatrix}^T$$

- The equivalent channel between DEV1's transmitter and DEV2's receiver is a Single Input Single Output (SISO) channel, with frequency response at frequency bins 0 to *N*-1 given by:

$$P_n = \mathbf{c}_2^H \mathbf{H}_{1\to 2}(n)\mathbf{w}_1 \quad \text{for} \quad n = 0,1,\ldots,N-1$$

- The discrete-frequency received signal model becomes:

$$Y_n = P_n S_n + B_n \quad \text{for} \quad n = 0,1,\ldots,N-1$$

where $\begin{bmatrix} S_0 & S_1 & \cdots & S_N \end{bmatrix}$ is the OFDM data symbol (FFT of the SC data burst), and $\begin{bmatrix} B_0 & B_1 & \cdots & B_N \end{bmatrix}$ is the additive white Gaussian noise vector;

- The equivalent model from DEV2's transmitter to DEV1's receiver have the same formulation but with a different SISO channel (see previous figure):

$$Q_n = \mathbf{c}_1^H \mathbf{H}_{2\to 1}(n)\mathbf{w}_2 \quad \text{for} \quad n = 0,1,\ldots,N-1$$

Beamforming Cost Function

- For both OFDM and SC, the Signal to Noise Ratio (SNR) on the *n*th subcarrier is given by:

$$SNR_n^{1\to 2} = \frac{E_s |P_n|^2}{N_0} = \frac{E_s \left|\mathbf{c}_2^H \mathbf{H}_{1\to 2}(n)\mathbf{w}_1\right|^2}{N_0}, \quad SNR_n^{2\to 1} = \frac{E_s |Q_n|^2}{N_0} = \frac{E_s \left|\mathbf{c}_1^H \mathbf{H}_{2\to 1}(n)\mathbf{w}_2\right|^2}{N_0}$$

- Define the Effective SNR (ESNR) as a mapping from the instantaneous subcarriers SNRs to an equivalent SNR that takes into account the FEC (Forward Error Correction). There are many methods that can be used to compute the ESNR:
  - Mean of SNRs over the different subcarriers
  - QSM (Quasi-Static Method: 3GPP2 1xEV-DV/DO method 1)
  - CESM (Capacity effective SINR mapping: 3GGP2 1xEV-DV/DO method 2)
  - CECM (CESM based on Convex Metric: 3GGP2 1xEV-DV/DO method 3)
  - EESM (Exponential Effective SIR Mapping: 3GGP)
  - Etc,...

- *The ultimate objective of a beamforming algorithm is to select the optimal beamformer vectors* $\mathbf{w}_1$(DEV1) and $\mathbf{w}_2$(DEV2) *and optimal combiner vectors* $\mathbf{c}_2$(DEV2) and $\mathbf{c}_1$(DEV1) *that maximize the effective SNR (or any other optimality criterion);*

Beamforming Cost Function

- Different ESNR methods can be used for SC and OFDM. A MMSE SC equalizer for example tends to have an ESNR which can be approximated by the average of the SNRs over the different subcarriers, whereas OFDM tends to have an ESNR which can be approximated by the geometric mean of the SNRs over the different subcarriers. More accurate methods that we listed before take into account the FEC, imperfections in the receiver, BER, …

- For an ASS we have the following:

$$\mathbf{c}_1 = \mathbf{w}_1 \quad \text{and} \quad \mathbf{c}_2 = \mathbf{w}_2$$

- And consequently, it is enough to consider one direction of the link, i.e. DEV1-Tx to DEV2-Rx or DEV2-Tx to DEV1-Rx but not both;

- For an AAS, both directions of the link should be considered to estimate the four vectors $\mathbf{w}_1$(DEV1), $\mathbf{w}_2$(DEV2), $\mathbf{c}_1$(DEV1), and $\mathbf{c}_2$(DEV2);

- So for the general case of AAS, the following two steps are required:
  - 1. DEV1-Tx → DEV2-Rx, in order to estimate $\mathbf{w}_1$(DEV1) and $\mathbf{c}_2$(DEV2), DEV2 has to acquire the CSI matrices $\mathbf{H}_{1\rightarrow 2}(n)$ for $n = 0,1,\ldots, N-1$;
  - 2. DEV2-Tx → DEV1-Rx, in order to estimate $\mathbf{w}_2$(DEV2) and $\mathbf{c}_1$(DEV1), DEV1 has to acquire the CSI matrices $\mathbf{H}_{2\rightarrow 1}(n)$ for $n = 0,1,\ldots, N-1$

Beamforming Procedure

- The standard should define a messaging protocol that enables the acquisition and tracking of one (ASS) or both (AAS);
- Beamforming between two devices DEV1 and DEV2 (where one device can be a PNC) can be done via the following six steps procedure:
  - 1. Acquisition: DEV2 should acquire the CSI matrices in order to estimate $\mathbf{w}_1$ and $\mathbf{c}_2$;
    - DEV1 will train DEV2 by repeated transmission of a sufficient subset of the beamformer codebook (defined later);
    - DEV2 will acquire the CSI by using a sufficient subset of its combiner codebook (defined later);
  - 2. Estimation: DEV2 will estimate the optimal beamformer vector $\mathbf{w}_1$ and optimal combiner vector $\mathbf{c}_2$ vector;
    - Left to the implementer. Different optimality criterions can be used such as EESM or mean SNR, …
  - 3. Feedback: DEV2 should feedback the optimal beamformer vector $\mathbf{w}_1$ and possibly the optimal combiner vector $\mathbf{c}_2$ to DEV1;
  - 4. For an AAS, repeat steps 1 to 3 with DEV1 replaced by DEV2 and DEV2 replaced by DEV1, i.e. from DEV2-Tx to DEV1-Rx;
  - 5. Tracking: DEV2 tracks the beamformer and combiner vectors;
    - DEV1 will transmit the sufficient subset of the beamformer codebook at a low rate (i.e. not as often as during acquisition);
  - 6. Updates feedback: DEV2 will feedback $\mathbf{w}_1$ and possibly $\mathbf{c}_2$;
    - DEV2 sends feedback at a low rate;
  - 7. For an ASS, repeat steps 5 and 6 with DEV1 tracking $\mathbf{w}_2$ and $\mathbf{c}_1$ and feeding them back to DEV2

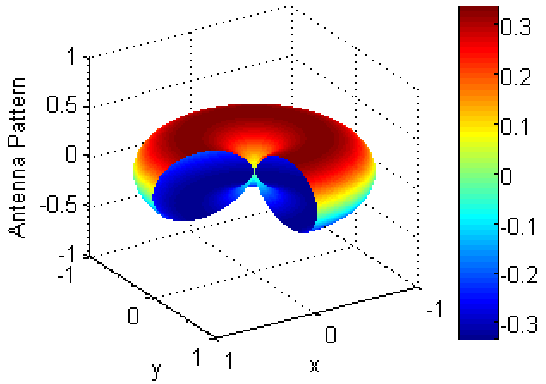
Potential Problems with LRP

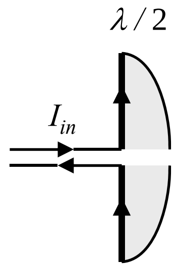
- LRP cannot provide an estimate of the SNR over the entire bandwidth, consequently it is severely suboptimal,
- Ex: delay spread of 10ns ⬄ coherence bandwidth of 100 MHz which means all subcarriers within 100 MHZ will fade in the same way,
- OFDM SNR tends to be some kind of geometric mean of SNRs over all subcarriers, LRP cannot take this into account;

Potential Antenna Elements & Arrays

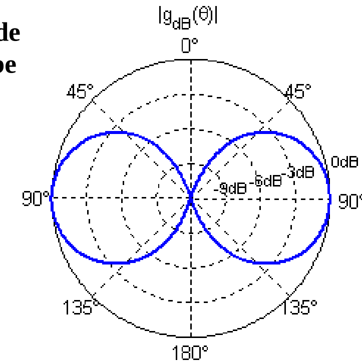
Standing-Wave Dipole Antenna

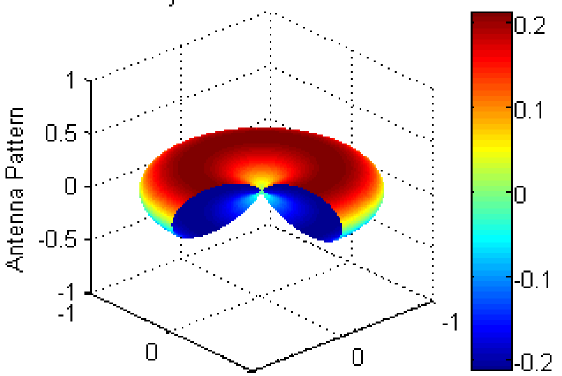
l	θ_{max}	HPBW$_\theta$	D_{max}	Z_{in} (a = 0)
λ/2	90º	78º	2.15 dB	73.1+j42.5 Ω
λ	90º	48º	3.82 dB	199.0+j? Ω
1.25 λ	90º	33º	5.16 dB	212.9-j817.6 Ω
3λ/2	42.6º,137.4º	30º,30º	3.48 dB	105.4+j45.5 Ω

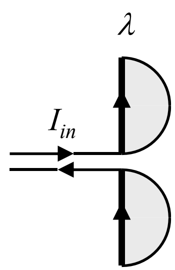




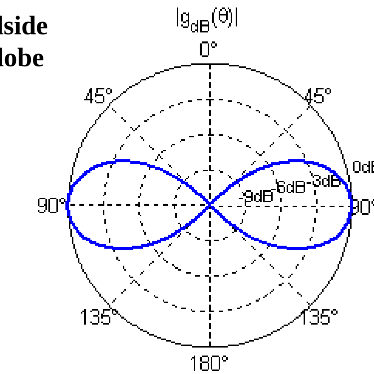
Broadside main lobe

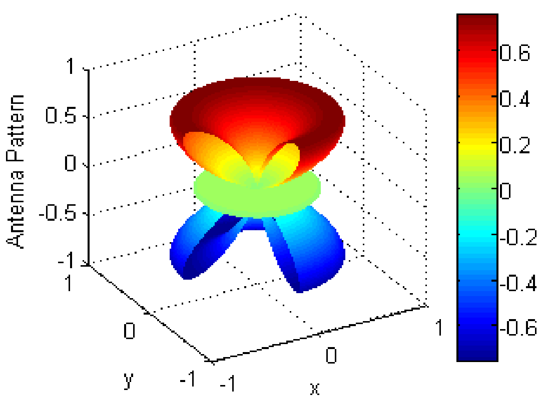


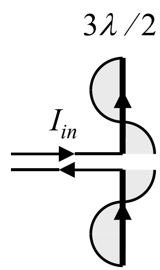




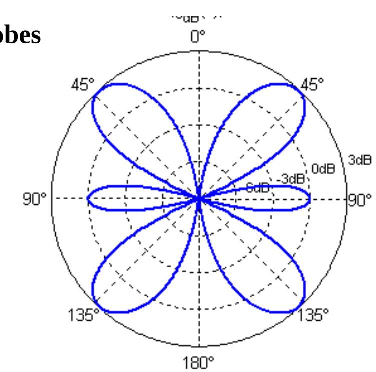
Broadside main lobe





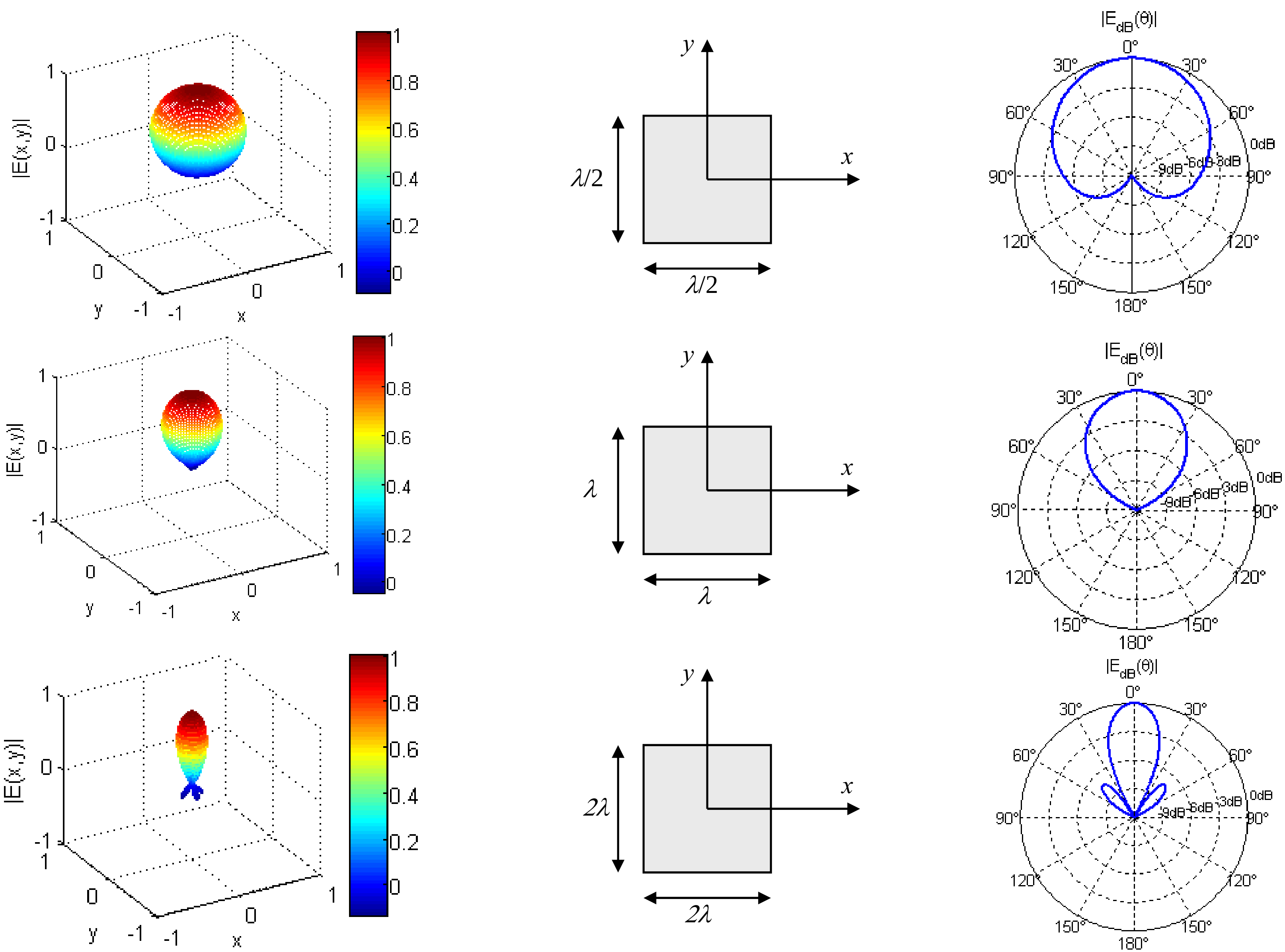


Main lobes

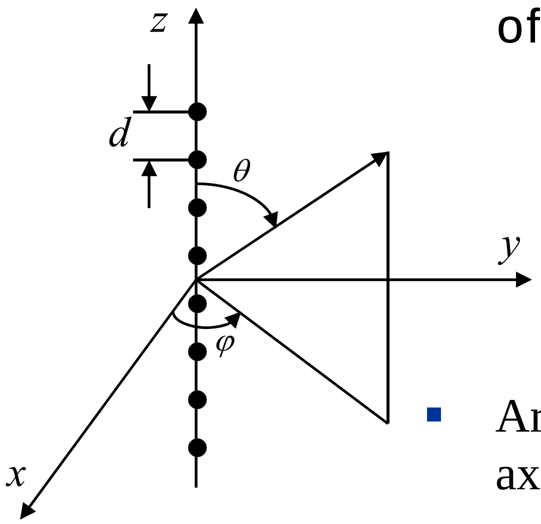


Uniform Rectangular Aperture

$D_x = D_y$	θ_{max}	$HPBW_{\theta x} = HPBW_{\theta y}$	D_{max}
$\lambda/2$	0°	101.5°	4.97 dB
λ	0°	50.8°	11.00 dB
$1.5\,\lambda$	0°	33.8°	14.51 dB
2λ	0°	25.4°	17.01 dB


|E(x,y)|
y
x
λ/2
λ/2
λ
λ
2λ
2λ
|E_dB(θ)|
0°
30°
60°
90°
120°
150°
180°
0dB
-3dB
-6dB
-9dB

1-D Antenna Array



- The power gain of an antenna array = power gain of a single antenna × abs(array factor)^2

$$g_{tot}(\theta,\varphi) = g_{SA}(\theta,\varphi)\left|A(\theta,\varphi)\right|^2$$

- Array factor of a uniformly-spaced antenna array along the z-axis:

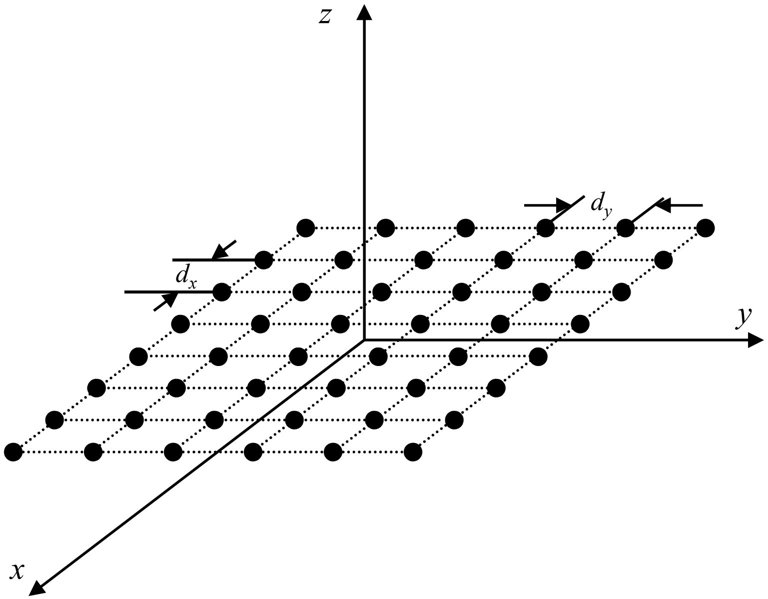
$$A(\theta) = \sum_{n=1}^{N} w_n e^{j2\pi n(d/\lambda)\cos\theta}$$

- Antenna array directivity:

$$D = \frac{\max\left|A(\theta)\right|^2}{\mathbf{w}^H \mathbf{K} \mathbf{w}} \quad \text{where} \quad K_{n,m} = \frac{\sin[2\pi(d/\lambda)(n-m)]}{2\pi(d/\lambda)(n-m)} \quad n,m = 0:N-1$$

- Maximum possible directivity: $D_{max} = N$

2-D Antenna Array



- Array factor of a 2-D antenna array :

$$A(\theta,\varphi)=\sum_{m=1}^{N_x}\sum_{n=1}^{N_y} w_{m,n} e^{j2\pi\left[m(d_x/\lambda)\sin\theta\cos\varphi+n(d_y/\lambda)\sin\theta\sin\varphi\right]}$$

- Separable 2-D antenna array with N_x elements along the x-direction and N_y elements along the y-direction:

$$w_{mn}=w_{x,m}w_{y,m} \quad \text{with} \quad m=0:N_x-1, n=0:N_y-1$$

or $\mathbf{W}_{xy}=\mathbf{w}_x\mathbf{w}_y^T$

- Array factor of a separable 2-D antenna array :

$$A(\theta,\varphi)=A_x(\theta,\varphi)A_y(\theta,\varphi)$$

$$A_x(\theta,\varphi)=\sum_{n=1}^{N_x} w_{x,n} e^{j2\pi n(d_x/\lambda)\sin\theta\cos\varphi}$$

$$A_y(\theta,\varphi)=\sum_{n=1}^{N_y} w_{y,n} e^{j2\pi n(d_y/\lambda)\sin\theta\sin\varphi}$$

Antenna Array Codebook

- In the following, we assume separable 2-D antenna arrays ⇔ to form the 2-D codebook $\mathbf{W}_{xy} \in C^{N_x \times N_y}$ we need only to specify codebooks for 1-D antenna arrays along the x-axis $\mathbf{w}_x \in C^{N_x \times 1}$ and y-axis $\mathbf{w}_y \in C^{N_y \times 1}$;

$$\mathbf{W}_{xy} = \mathbf{w}_x \mathbf{w}_y^T$$

- The simplest phased antenna array is an antenna array implementing the following phases 0^o or 180^o for each antenna element. We refer to this as scalar transmitter and the beamformer (combiner) weights are selected from {+1 , -1}

- This means each antenna element will transmit (receive) I+Q (phase 0^o), or -(I+Q) (phase 180^o). We refer to such a system as a scalar-Tx (Rx) with weights +1 or -1;

- A more flexible phased antenna array is an antenna array implementing the following phases 0^o, 90^o, 180^o or 270^o for each antenna element.

- Using a quadrature transmitter with I & Q (In-phase and Quadrature), this means each antenna element will transmit (receive) I (phase 0^o), -I (phase 180^o), Q (phase 270^o), –Q (phase 90^o). An equivalent set of signals would be: I+Q, I-Q, -I+Q, -I-Q. We refer to such a system as vector-Tx (Rx) with weights selected from {+1, -1, +j, –j};

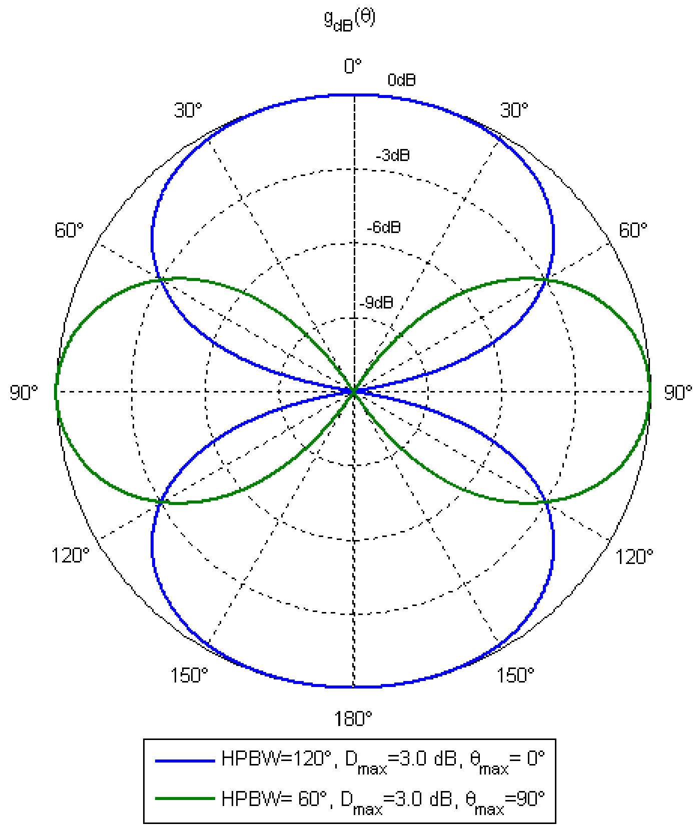
Vector Tx (Rx) Codebooks

Two-Elements 1-D Antenna Array Codebook

- Codebook ID: 0000
- Two elements separated by $\lambda/2$;
- Codebook = two orthogonal beamformer (combiner) vectors given by the columns of matrix **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 \\ -1 & +1 \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	120°	3.01 dB
1	90°	60°	3.01 dB

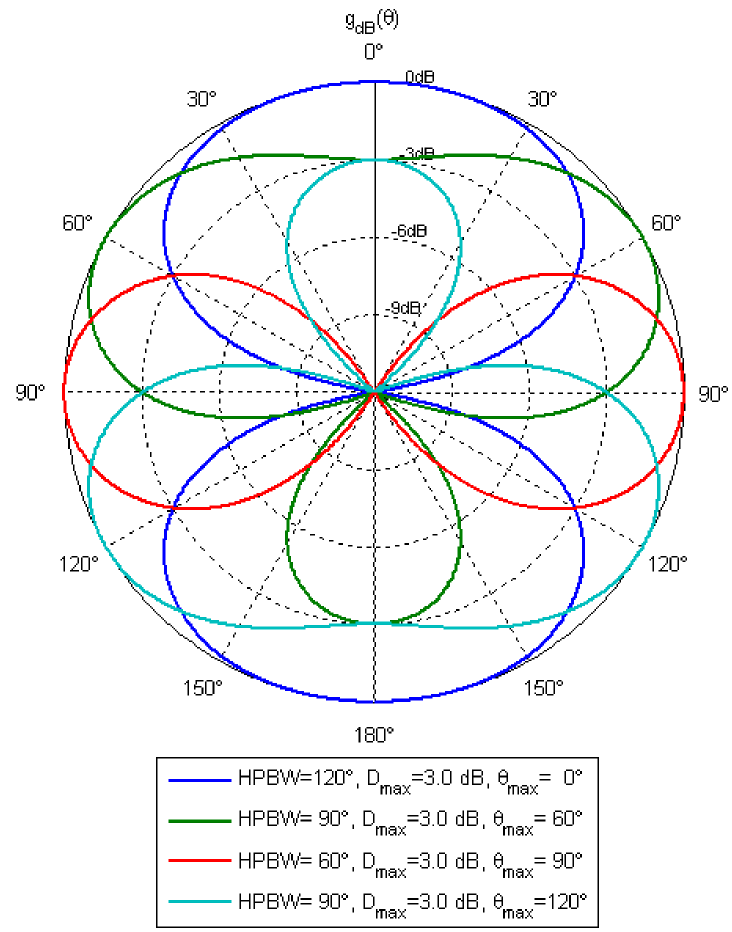


Two-Elements 1-D Antenna Array Codebook

- Codebook ID: 0001
- Two elements separated by $\lambda/2$;
- Extended codebook = four beamformer (combiner) vectors given by the columns of matrix **W**; $\mathbf{W}\mathbf{W}^H = 4\mathbf{I}$;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -j & +1 & +j \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	120º	3.01 dB
1	60º	90º	3.01 dB
2	90º	60º	3.01 dB
3	120º	90º	3.01 dB

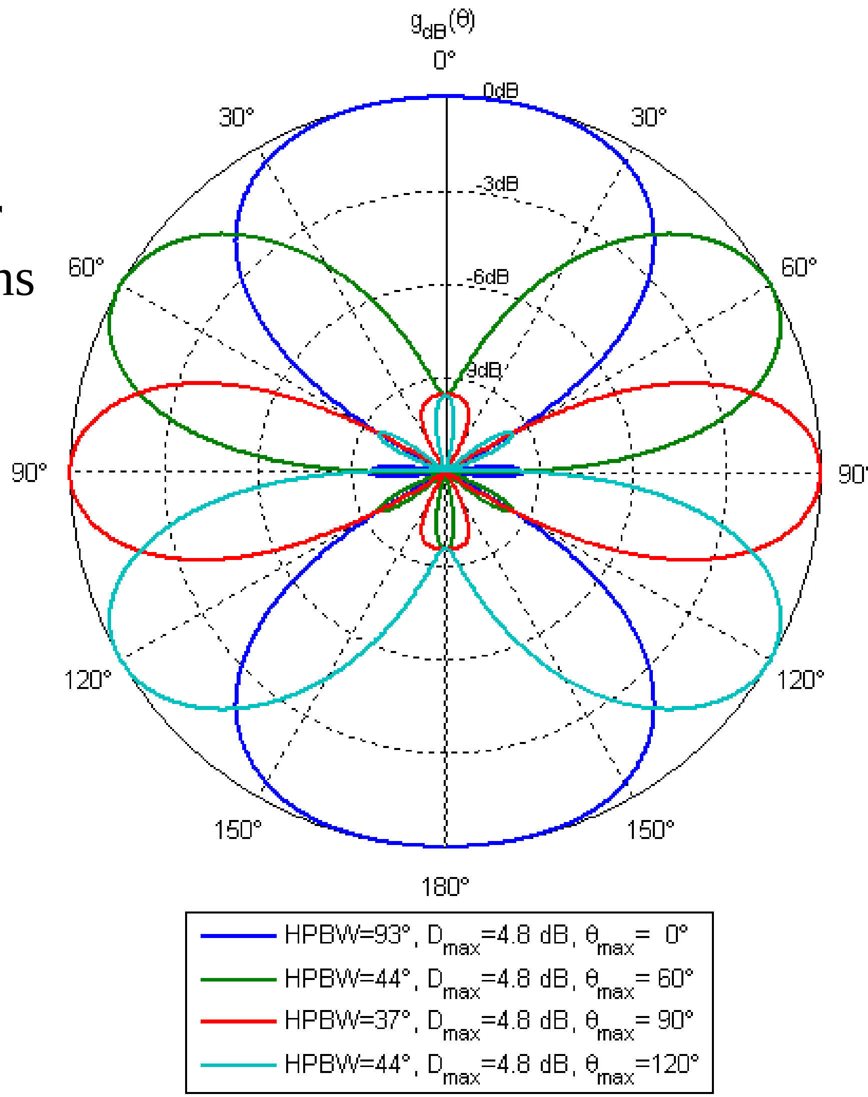


Three-Elements 1-D Antenna Array Codebook

- Codebook ID: 0010
- Three elements separated by $\lambda/2$;
- Extended codebook = four beamformer (combiner) vectors given by the columns of matrix **W**; $\mathbf{W}\mathbf{W}^H = 4\mathbf{I}$;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -j & +1 & +j \\ +1 & -1 & +1 & -1 \end{bmatrix}$$

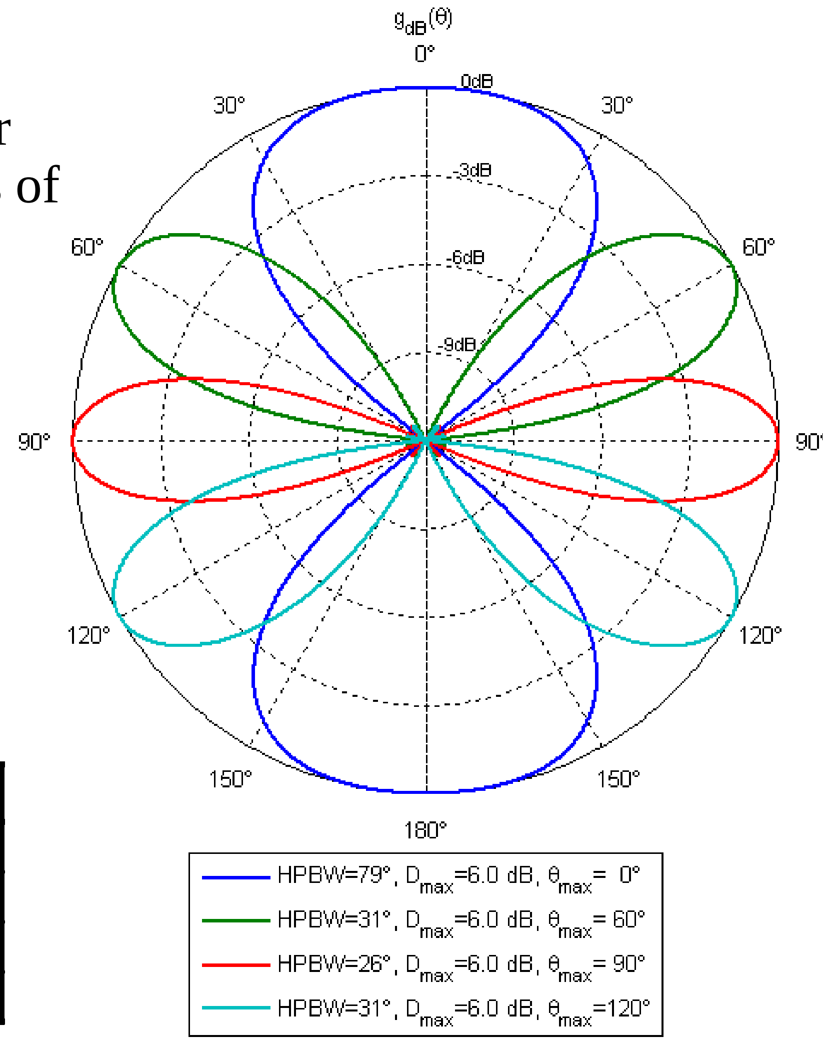
Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	93º	4.77 dB
1	60º	44º	4.77 dB
2	90º	37º	4.77 dB
3	120º	44º	4.77 dB



Four-Elements 1-D Antenna Array Codebook

- Codebook ID: 0011
- Four elements separated by $\lambda/2$;
- Codebook = four orthogonal beamformer (combiner) vectors given by the columns of matrix **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -j & +1 & +j \\ +1 & -1 & +1 & -1 \\ -1 & +j & +1 & -j \end{bmatrix}$$



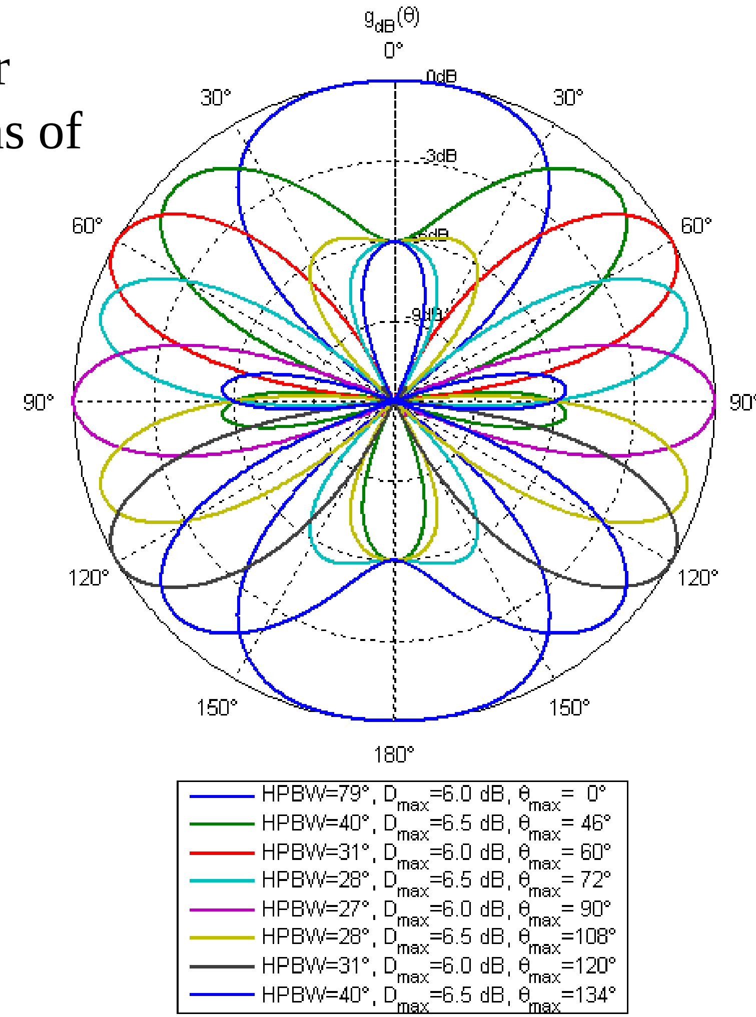
Codebook vector ID	θ_{max}	$HPBW_{\theta}$	D_{max}
0	0º	79º	6.02 dB
1	60º	31º	6.02 dB
2	90º	26º	6.02 dB
3	120º	31º	6.02 dB

Four-Elements 1-D Antenna Array Codebook

- Codebook ID: 0101
- Four elements separated by *l*/2;
- Extended codebook = eight beamformer (combiner) vectors given by the columns of matrix **W**; $\mathbf{W}\mathbf{W}^H = 8\mathbf{I}$;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & -j & +1 & +j & +j & +j \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & +1 & +j & -1 & +1 & -1 & -j & +1 \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	79°	6.02 dB
1	46°	31°	5.48 dB
2	60°	26°	6.02 dB
3	72°	26°	5.48 dB
4	90°	26°	6.02 dB
5	108°	26°	5.48 dB
6	120°	26°	6.02 dB
7	134°	31°	5.48 dB

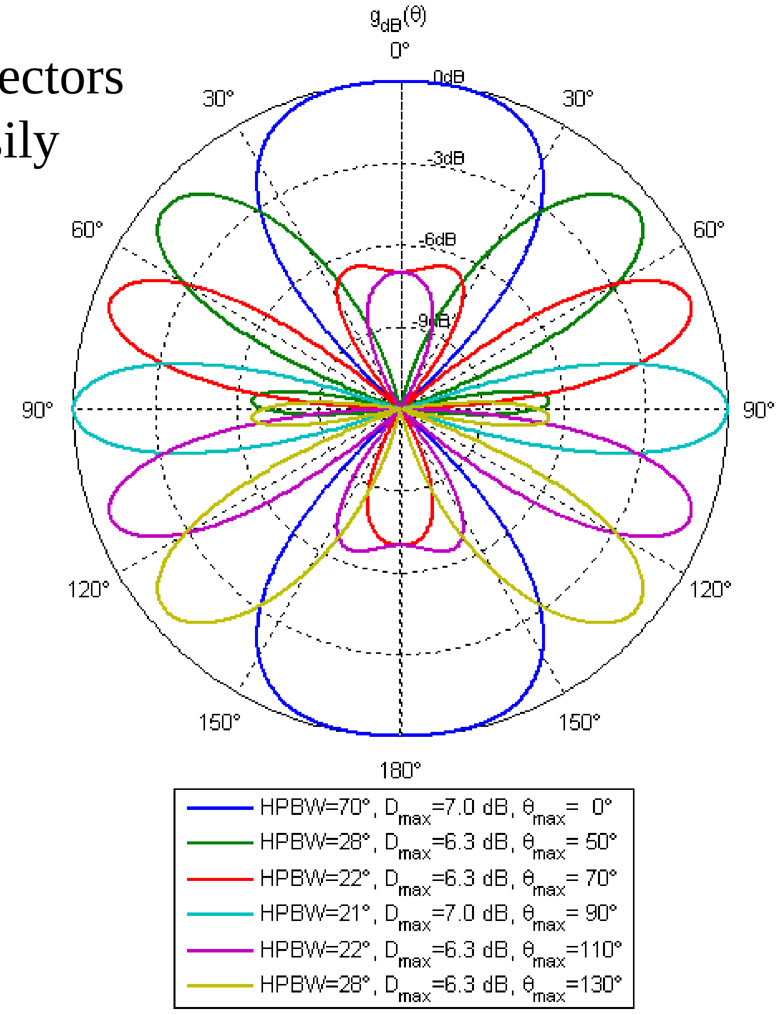


Five-Element 1-D Antenna Array Codebook

- Codebook ID: 0110
- Five elements separated by $\lambda/2$;
- Codebook = 6 beamformer (combiner) vectors given by the columns of **W**; $\mathbf{W}\mathbf{W}^H$ is easily invertible;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & +1 & +j & +j \\ +1 & +j & -j & +1 & -1 & -1 \\ -1 & +1 & -1 & +1 & -1 & +1 \\ +1 & -j & +j & +1 & -j & +j \end{bmatrix}$$

Beamformer vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	70°	7.0 dB
1	50°	28°	6.3 dB
2	70°	22°	6.3 dB
3	90°	21°	7.0 dB
4	110°	22°	6.3 dB
5	130°	28°	6.3 dB

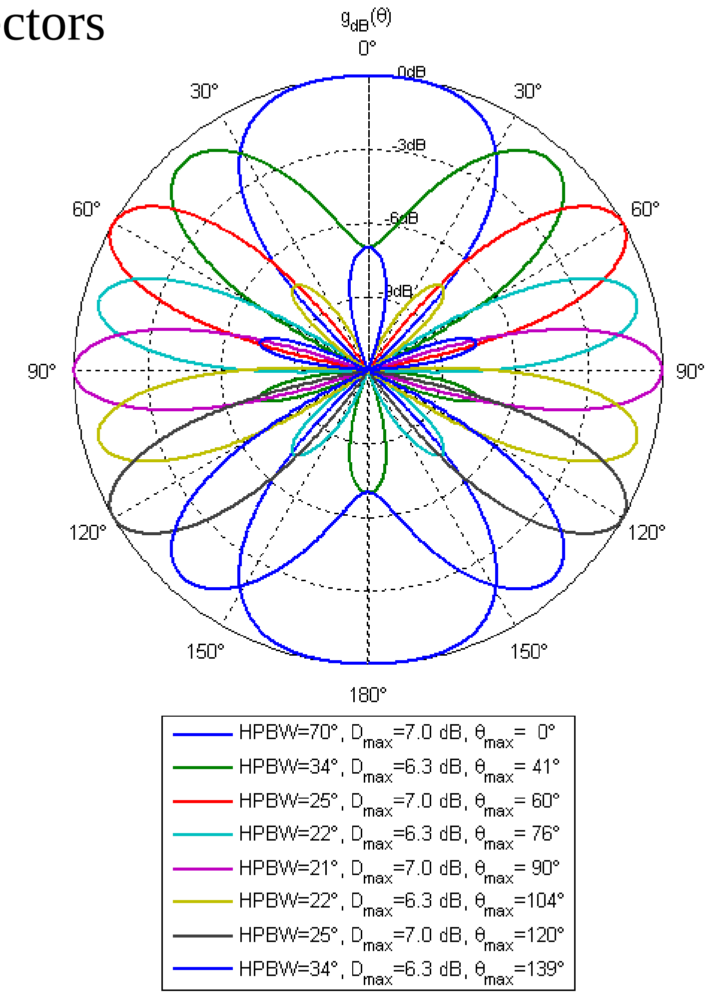


Five-Element 1-D Antenna Array Codebook

- Codebook ID: 0111
- Five elements separated by $\lambda/2$;
- Codebook = 8 beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & -j & +1 & +j & +j & +j \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & +1 & +j & -1 & +1 & -1 & -j & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	70°	7.0 dB
1	41°	34°	6.3 dB
2	60°	25°	7.0 dB
3	76°	22°	6.3 dB
4	90°	21°	7.0 dB
5	104°	22°	6.3 dB
6	120°	25°	7.0 dB
7	139°	34°	6.3 dB

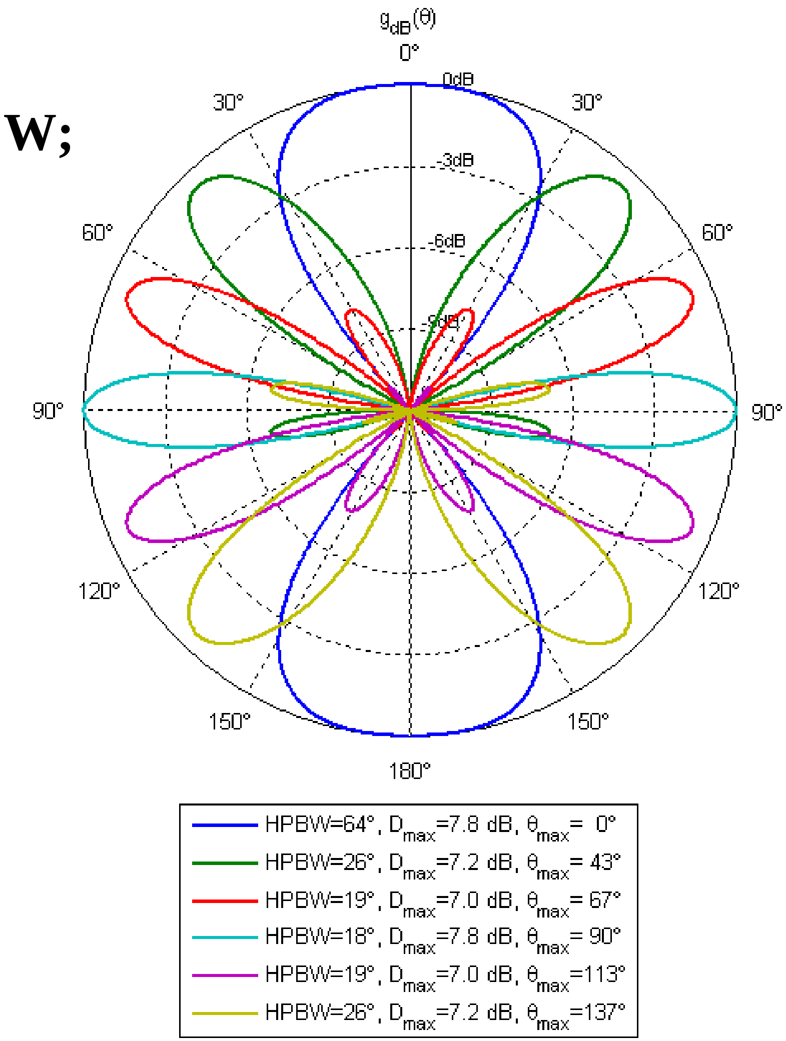


Six-Element 1-D Antenna Array Codebook

- Codebook ID: 1000
- Eight elements separated by $\lambda/2$;
- Codebook = 6 non-orthogonal beamformer (combiner) vectors given by the columns of **W;** $\mathbf{W}\mathbf{W}^H$ is easily invertible;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & +1 & +j & +j \\ +1 & +j & -j & +1 & +j & -j \\ -1 & +1 & -1 & +1 & -1 & +1 \\ +1 & -1 & +j & +1 & -j & -1 \\ -1 & +j & +1 & +1 & +1 & -j \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	64º	7.8 dB
1	43.3º	26º	7.2 dB
2	67.0º	19º	7.0 dB
3	90.0º	18º	7.8 dB
4	113.0º	19º	7.0 dB
5	137º	26º	7.2 dB

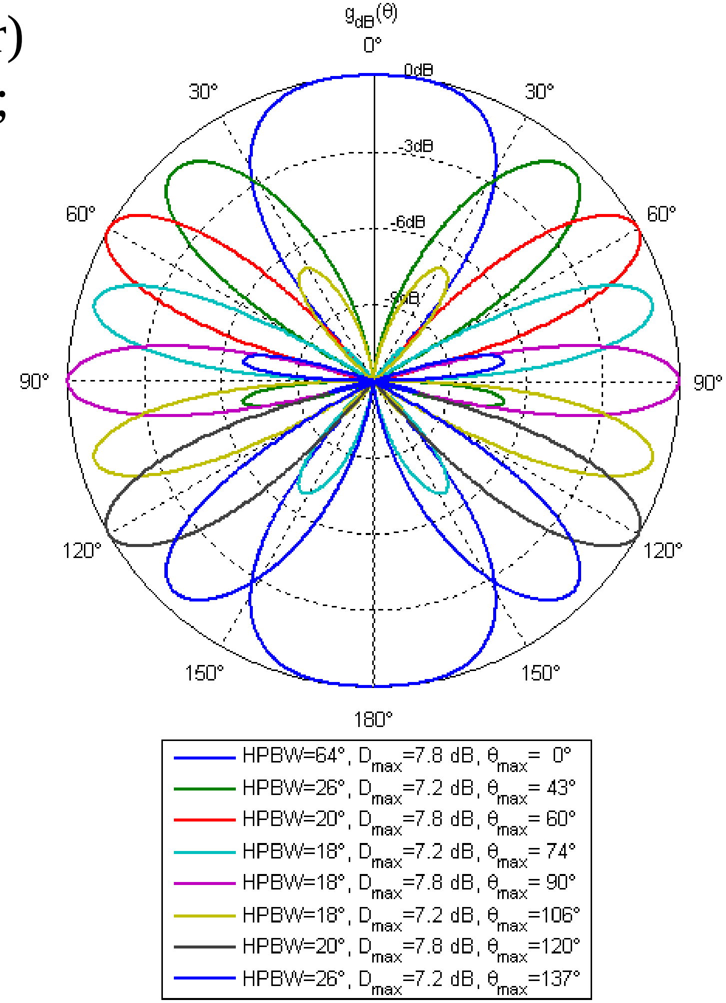


Six-Element 1-D Antenna Array Codebook

- Codebook ID: 1001
- Eight elements separated by $\lambda/2$;
- Extended codebook = 8 beamformer (combiner) vectors given by the columns of $\mathbf{W}$; $\mathbf{W}\mathbf{W}^H = 8\mathbf{I}$;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & -j & +1 & +j & +j & +j \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & +1 & +j & -1 & +1 & -1 & -j & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ -1 & +j & -j & +j & +1 & -j & +j & -j \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	63.9°	7.78 dB
1	43.3°	26.1°	7.16 dB
2	60.0°	20.4°	7.78 dB
3	74.2°	18.0°	7.16 dB
4	90.0°	17.6°	7.78 dB
5	105.8°	18.0°	7.16 dB
6	120.0°	20.4°	7.78 dB
7	136.7°	26.1°	7.16 dB

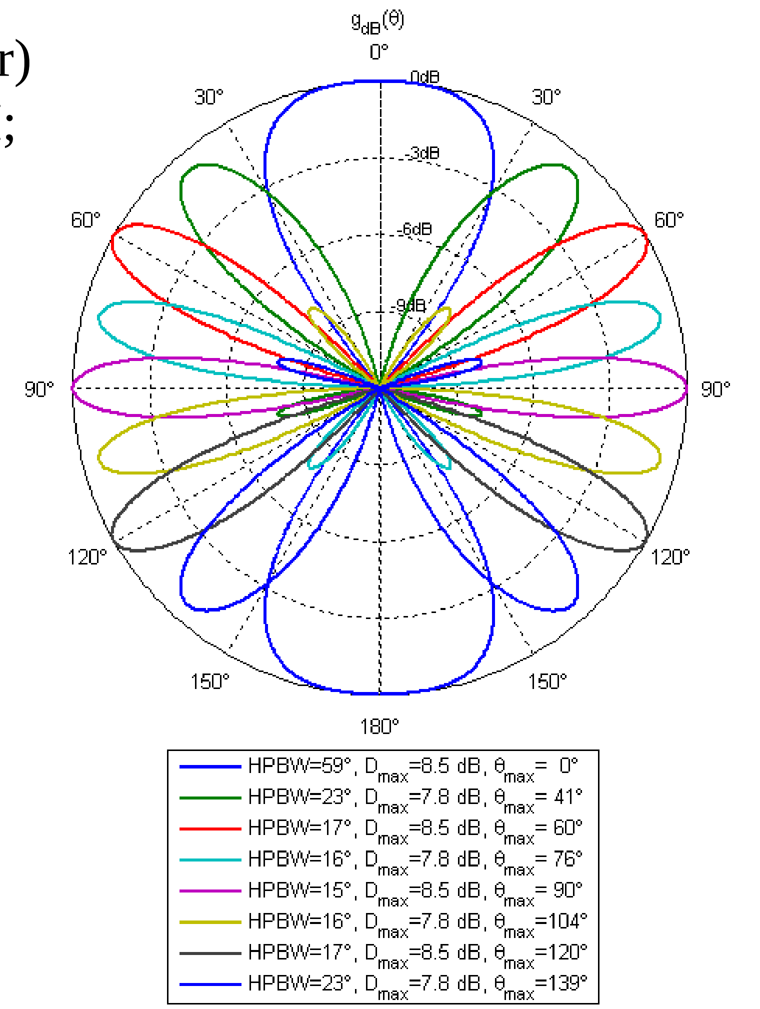


Seven-Element 1-D Antenna Array Codebook

- Codebook ID: 1010
- Seven elements separated by $l/2$;
- Extended codebook = 8 beamformer (combiner) vectors given by the columns of **W**; $\mathbf{W}\mathbf{W}^H = 8\mathbf{I}$;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & -j & +1 & +j & +j & +j \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & +1 & +j & -1 & +1 & -1 & -j & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ -1 & +j & -j & +j & +1 & -1 & +j & -j \\ +1 & -j & -1 & +j & +1 & -j & -1 & +j \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	59º	8.5 dB
1	41º	23º	7.8 dB
2	60º	17º	8.5 dB
3	76º	16º	7.8 dB
4	90º	15º	8.5 dB
5	104º	16º	7.8 dB
6	120º	17º	8.5 dB
7	137º	23º	7.8 dB

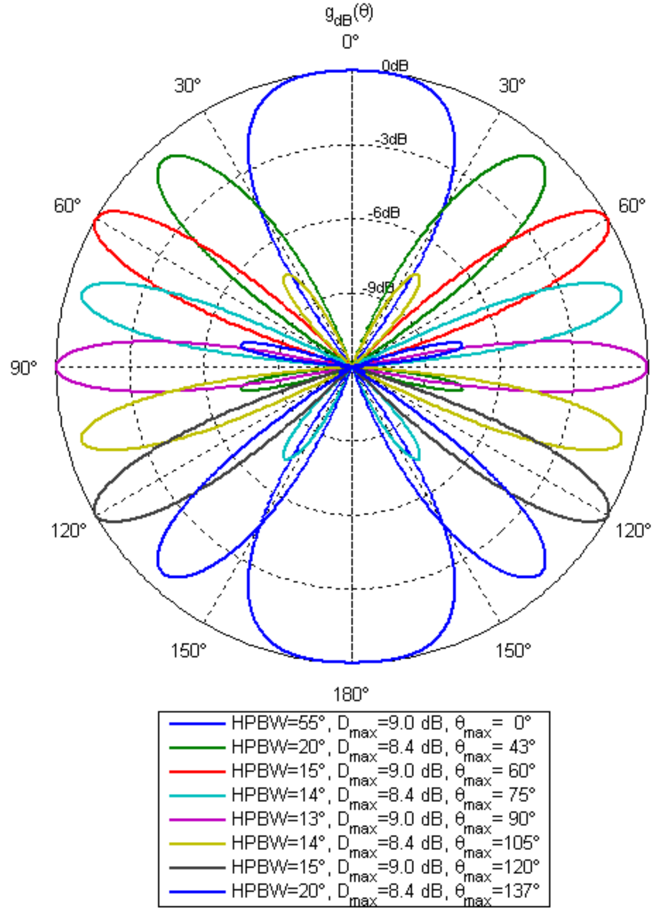


Eight-Element 1-D Antenna Array Codebook

- Codebook ID: 1011
- Eight elements separated by $\lambda/2$;
- Codebook = 8 orthogonal beamformer (combiner) vectors given by the columns of **W**

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -j & -j & -j & +1 & +j & +j & +j \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & +1 & +j & -1 & +1 & -1 & -j & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ -1 & +j & -j & +j & +1 & -j & +j & -j \\ +1 & -j & -1 & +j & +1 & -j & -1 & +j \\ -1 & -1 & +j & +1 & +1 & +1 & -j & -1 \end{bmatrix}$$

Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	55.2°	9.03 dB
1	42.5°	19.6°	8.38 dB
2	60.0°	15.1°	9.03 dB
3	74.8°	13.5°	8.38 dB
4	90.0°	13.1°	9.03 dB
5	105.2°	13.5°	8.38 dB
6	120.0°	15.1°	9.03 dB
7	137.5°	19.6°	8.38 dB

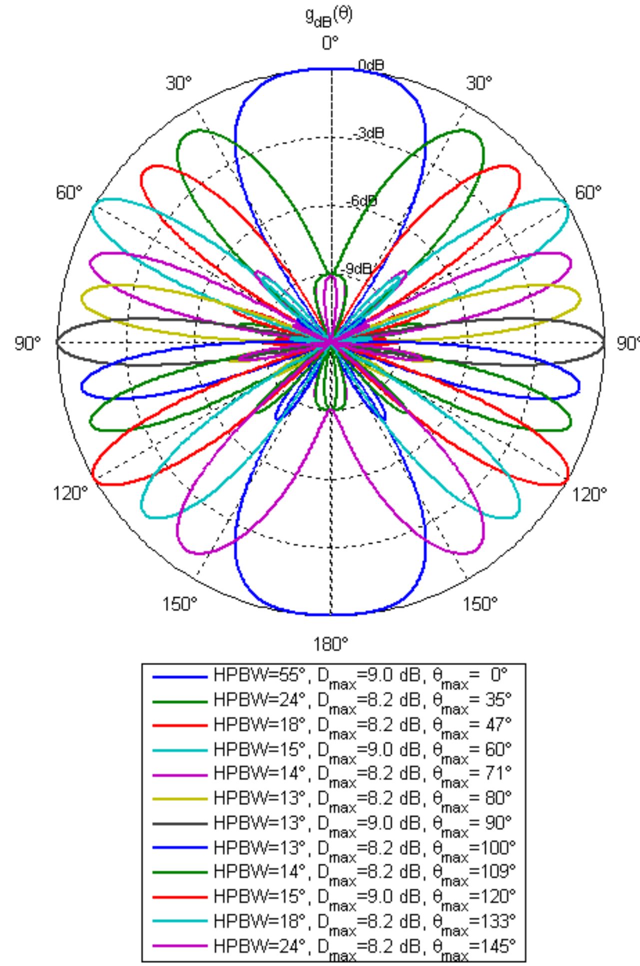


Eight-Element 1-D Antenna Array Codebook

- Codebook ID: 1100
- Eight elements separated by *l*/2;
- Extended codebook = 12 beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W}=\begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -1 & -j & -j & +1 & -j & +1 & +j & +1 & +j & +j & -1 \\ +1 & +1 & -1 & -1 & -j & -j & +1 & +j & +j & -1 & -1 & +1 \\ -1 & -j & +1 & +j & -1 & -j & +1 & +j & -1 & -j & +1 & +j \\ +1 & +j & -j & +1 & -1 & -1 & +1 & -1 & -1 & +1 & +j & -j \\ -1 & +1 & +j & -j & +j & -1 & +1 & -1 & -j & +j & -j & +1 \\ +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 & +1 & -1 \\ -1 & +1 & -j & +j & +1 & +j & +1 & -j & +1 & -j & +j & +1 \end{bmatrix}$$

Beamformer vector ID	θ_{max}	HPBW$_\theta$	D_{max}
0	0º	55º	9.0 dB
1	35º	24º	8.2 dB
2	47º	18º	8.2 dB
3	60º	15º	9.0 dB
4	71º	14º	8.2 dB
5	80º	13º	8.2 dB
6	90º	13º	9.0 dB
7	100º	13º	8.2 dB
8	119º	14º	8.2 dB
9	120º	15º	9.0 dB
10	133º	18º	8.2 dB
11	145º	24º	8.2 dB

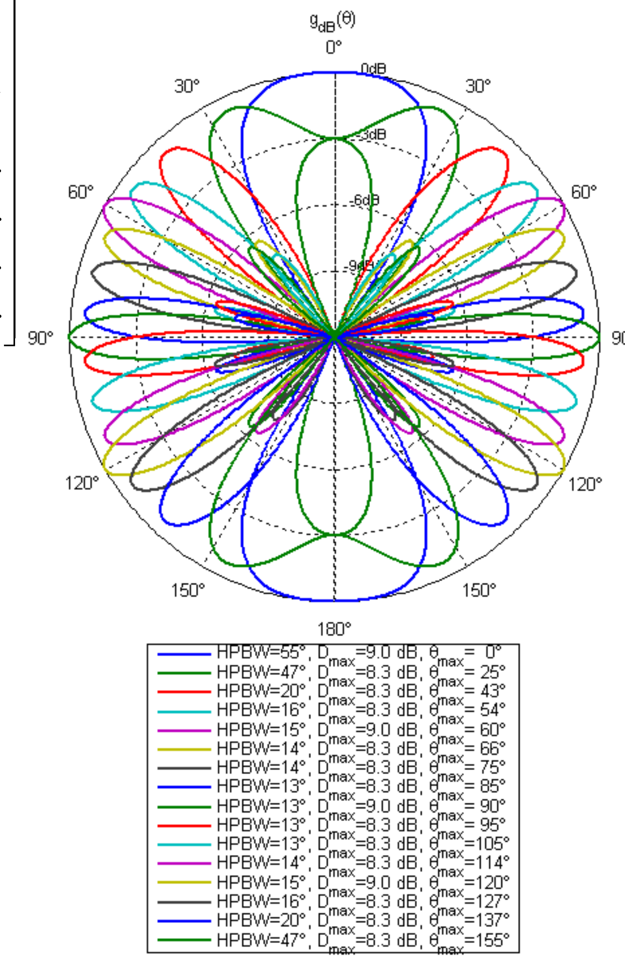


Eight-Element 1-D Antenna Array Codebook

- Codebook ID: 1101
- Eight elements separated by $\lambda/2$;
- Codebook = 16 beamformer (combiner) vectors given by the columns of **W**; $\mathbf{W}\mathbf{W}^H = 16\mathbf{I}$

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 & +1 \\ -1 & -1 & -j & -j & -j & -j & -j & +1 & +1 & +1 & +j & +j & +j & +j & +j & -1 \\ +1 & +1 & +j & -1 & -1 & -1 & -j & +1 & +1 & +1 & +j & -1 & -1 & -1 & -j & +1 \\ -1 & -1 & +1 & +j & +j & +j & -1 & +1 & +1 & +1 & +j & -j & -j & -j & +1 & -1 \\ +1 & +j & -1 & -j & +1 & +j & -1 & -j & +1 & +j & -1 & -j & +1 & +j & -1 & -j \\ -1 & -j & +j & -1 & -j & +1 & +j & -j & +1 & +j & -1 & +1 & +j & -1 & -j & +j \\ +1 & +j & -j & +j & -1 & -j & +j & -j & +1 & +j & -j & +j & -1 & -j & +j & -j \\ -1 & -j & -1 & +1 & +j & -1 & +1 & -j & +1 & +j & +1 & -1 & -j & +1 & -1 & +j \end{bmatrix}$$

Beamformer vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	55º	9.03 dB
1	25º	47º	8.38 dB
2	43º	20º	9.03 dB
3	54º	16º	8.38 dB
4	60º	15º	9.03 dB
5	66º	14º	8.38 dB
6	75º	14º	9.03 dB
7	85º	13º	9.03 dB
8	90º	13º	9.03 dB
9	95º	13º	9.03 dB
10	105º	13º	9.03 dB
11	114º	14º	9.03 dB
12	120º	15º	9.03 dB
13	127º	16º	9.03 dB
14	137º	20º	9.03 dB
15	155º	47º	9.03 dB



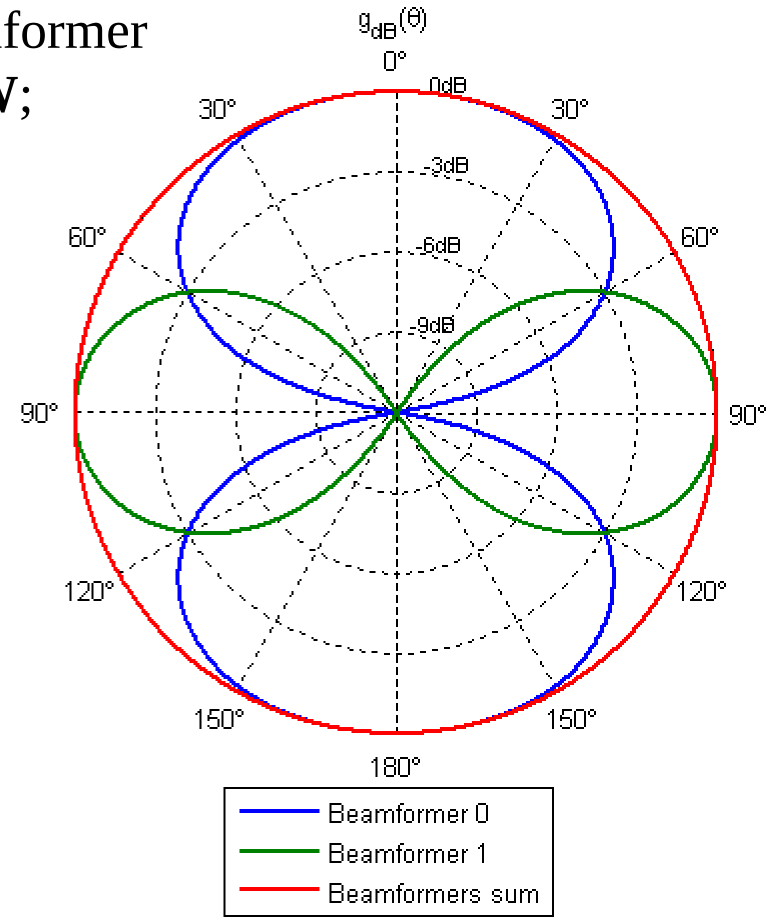
VECTOR-Tx (Rx) QUASI-OMNI & COMPLEMENTARY PATTERNS

Two-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0000
- Two complementary Golay patterns: $g_1(\theta,\varphi)+g_2(\theta,\varphi)=2$
- Quasi-omni codebook = two orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W}=\begin{bmatrix}+1 & +1\\ -1 & +1\end{bmatrix}$$

Codebook vector ID	θ_{max}	HPBW$_\theta$	D_{max}
0	0º	120.5º	3.0 dB
1	90º	60.4º	3.0 dB

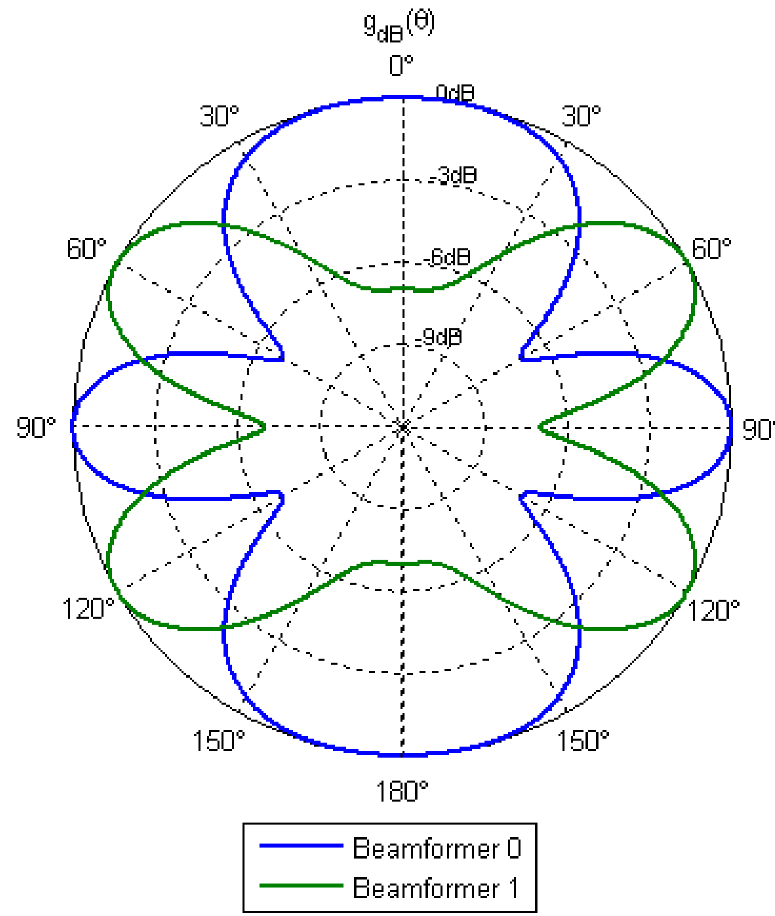


Three-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0001
- Quasi-omni codebook = two quasi-orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 \\ +j & +1 \\ +1 & -1 \end{bmatrix}$$

Codebook vector ID	$HPBW_\theta$	D_{max}
0	123.6º	2.22 dB
1	80.0º	2.22 dB

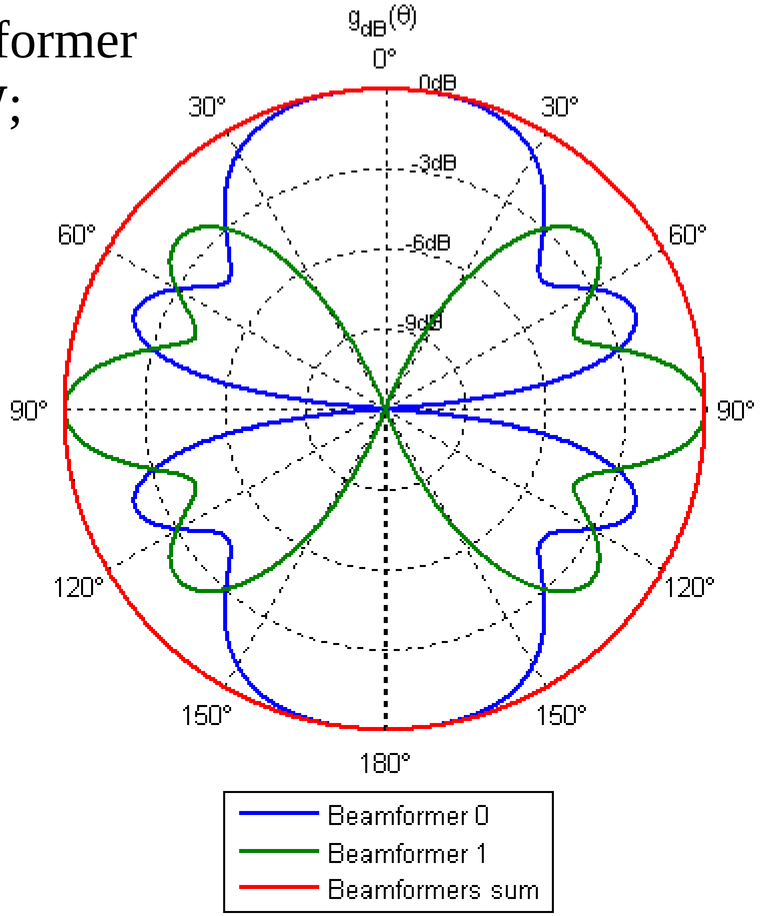


Four-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0010
- Two Golay complementary patterns: $g_1(\theta,\varphi)+g_2(\theta,\varphi)=2$
- Quasi-omni codebook = two orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W}=\begin{bmatrix}+1 & +1\\ -j & +j\\ +j & +j\\ -1 & +1\end{bmatrix}$$

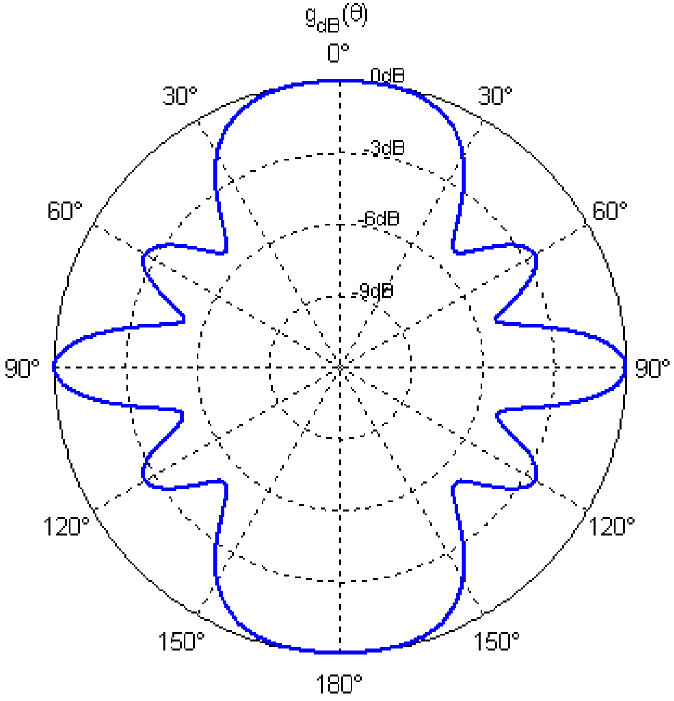
Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0º	83.4º	3.01 dB
1	90º	29.4º	3.01 dB



Five-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0011
- Quasi-omni codebook = one beamformer (combiner) vectors given by the column of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 \\ -1 \\ +1 \\ +1 \\ +1 \end{bmatrix} \qquad D_{\max} = 2.55 \text{ dB}$$

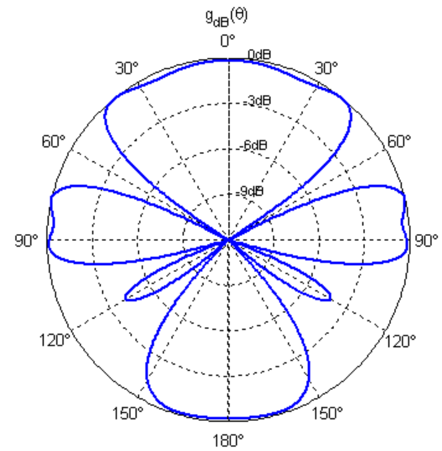


Six-Elements Antenna Array: Complementary Patterns

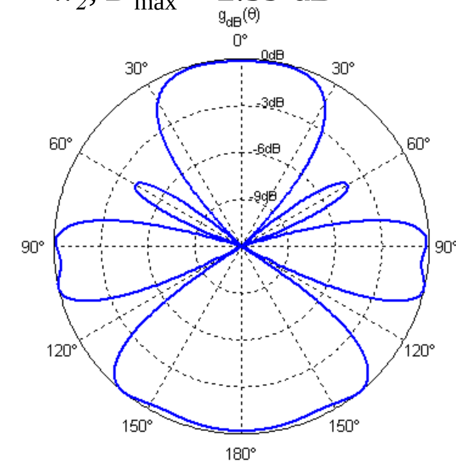
- Codebook ID: 0101
- Quasi-omni codebook = four beamformer (combiner) vectors given by the column of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -1 & +1 & +1 \\ +j & -j & -j & +j \\ -1 & -1 & -1 & -1 \\ +j & -j & +1 & +1 \\ +j & -j & -1 & -1 \end{bmatrix}$$

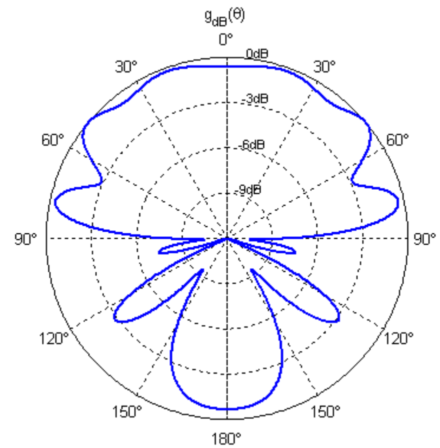
$\mathbf{w}_1$, D_{max} = 2.39 dB



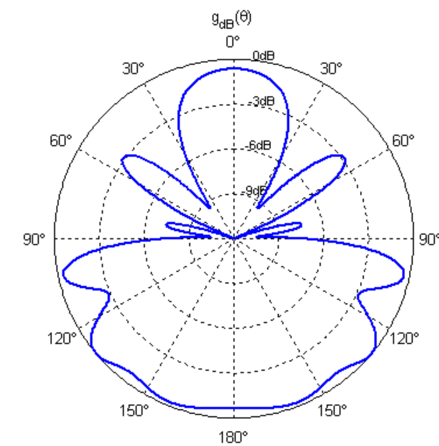
$\mathbf{w}_2$, D_{max} = 2.39 dB



$\mathbf{w}_3$, D_{max} = 2.86 dB



$\mathbf{w}_4$, D_{max} = 2.86 dB

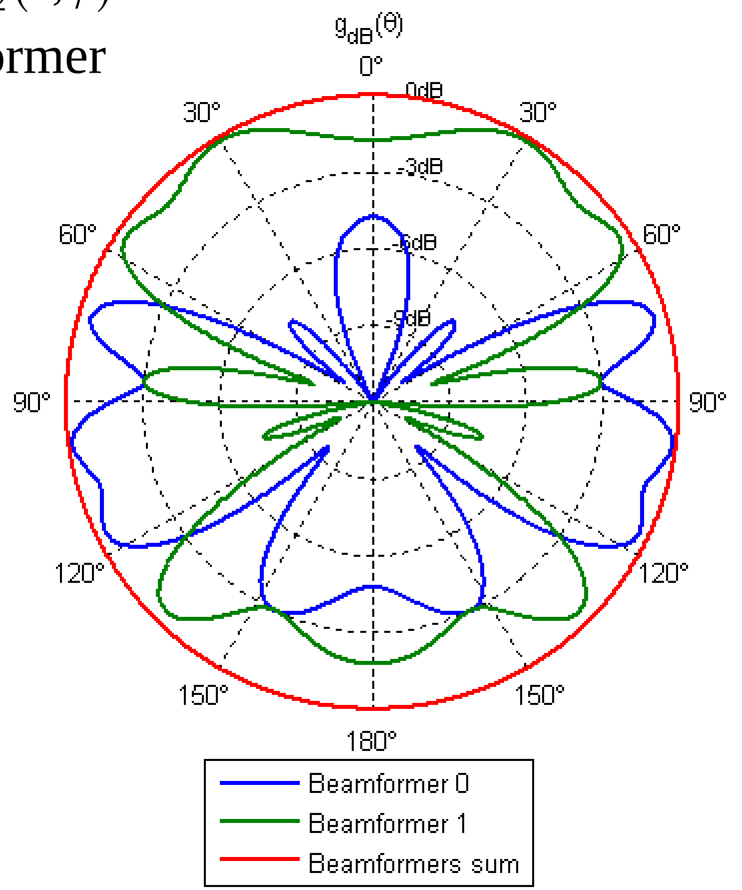


Six-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0110
- Two Golay complementary patterns: $g_1(\theta,\varphi)+g_2(\theta,\varphi)=1.93$
- Quasi-omni codebook = two orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W}=\begin{bmatrix}+1 & +1\\ -j & +j\\ -j & -j\\ -j & +j\\ +1 & +1\\ +j & -j\end{bmatrix}$$

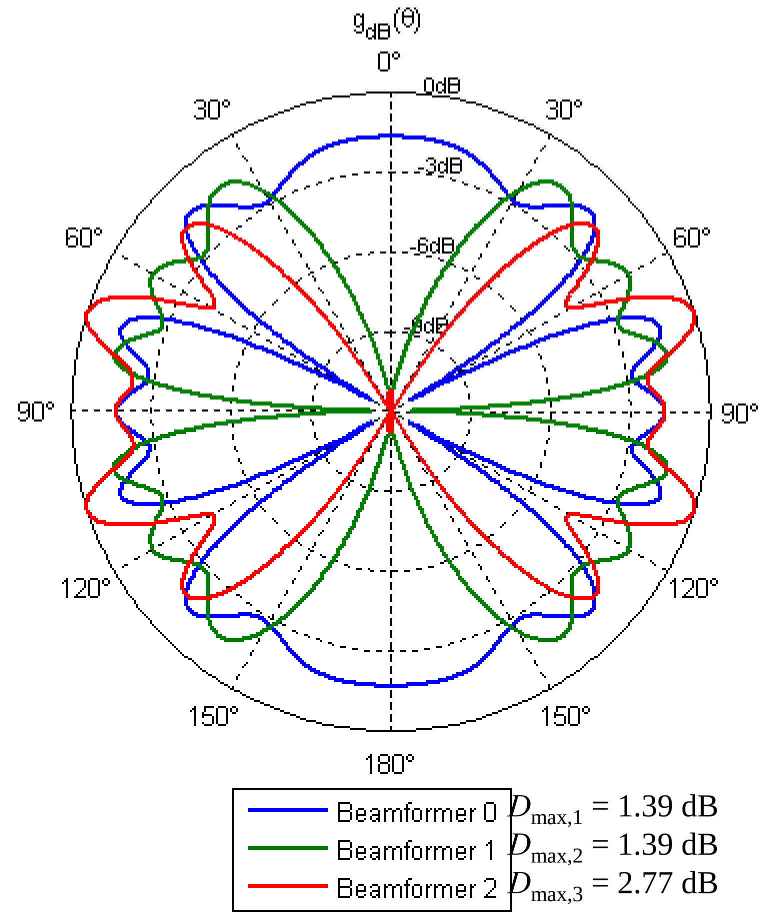
Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	31°, 149°	120.7°	2.86 dB
1	82°, 98°	61.2°	2.86 dB



Seven-Elements Antenna Array: Complementary Patterns

- Codebook ID: 0111
- Quasi-omni codebook = three beamformer (combiner) vectors given by the column of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 & +1 \\ +j & +1 & -1 \\ -1 & +1 & -1 \\ +j & -1 & +1 \\ -1 & -1 & +1 \\ +j & +1 & +1 \\ +1 & -1 & +1 \end{bmatrix}$$

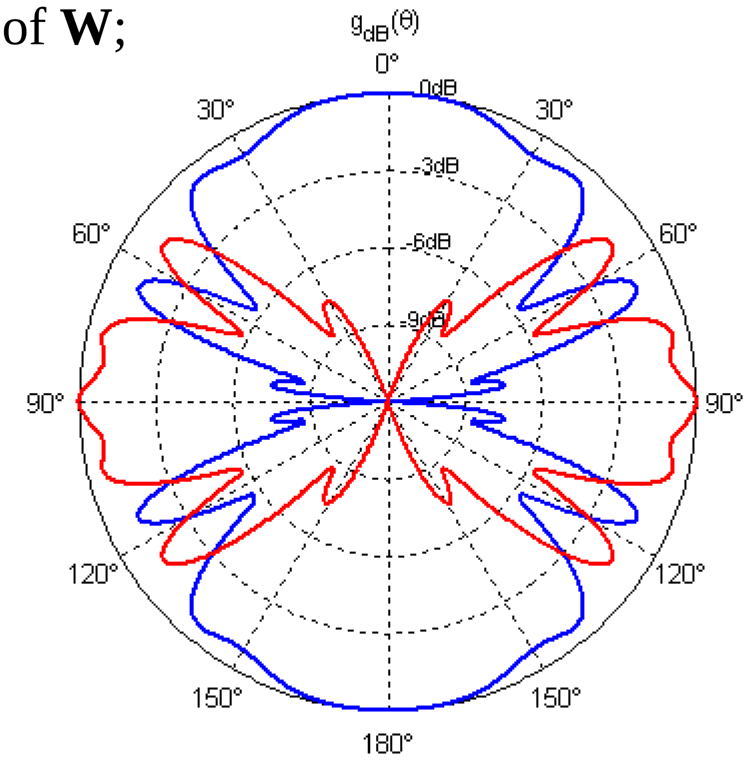


$D_{\max,1}$ = 1.39 dB
$D_{\max,2}$ = 1.39 dB
$D_{\max,3}$ = 2.77 dB

Eight-Elements Antenna Array: Complementary Patterns

- Codebook ID: 1010
- Two complementary patterns: $g_1(\theta,\varphi)+g_2(\theta,\varphi)=2$
- Quasi-omni codebook = two orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W}=\begin{bmatrix}+1 & +1\\ +1 & -1\\ -1 & -1\\ -1 & +1\\ +1 & +1\\ -1 & +1\\ +1 & +1\\ -1 & +1\end{bmatrix}$$

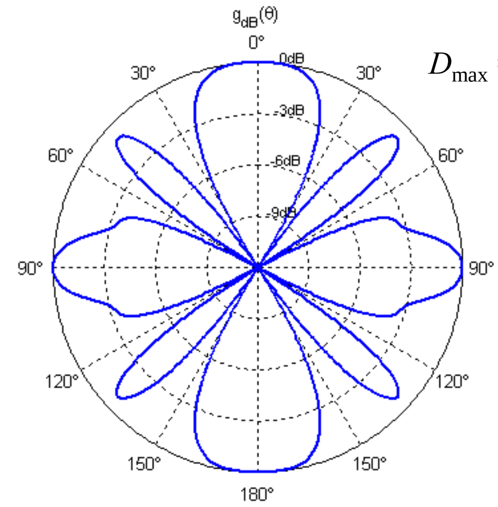


Codebook vector ID	θ_{max}	$HPBW_\theta$	D_{max}
0	0°	98.7°	3.0 dB
1	90°	40.9°	3.0 dB

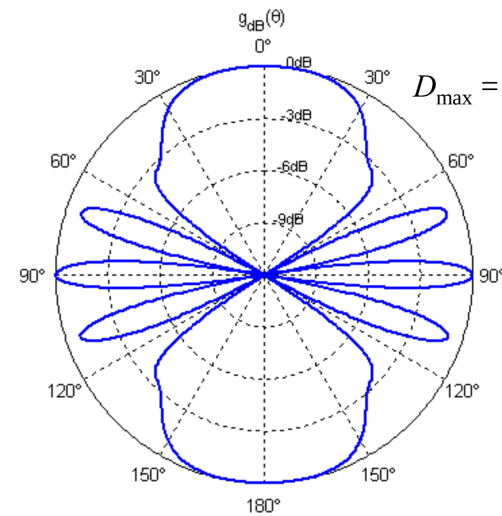
Eight-Elements Antenna Array: Complementary Patterns

- Codebook ID: 1001
- Quasi-omni codebook = two orthogonal beamformer (combiner) vectors given by the columns of **W**;

$$\mathbf{W} = \begin{bmatrix} +1 & +1 \\ +1 & -1 \\ -1 & +1 \\ +1 & +1 \\ -1 & +1 \\ +1 & +1 \\ +1 & +1 \\ +1 & -1 \end{bmatrix}$$



D_{max} = 3.01 dB



D_{max} = 3.01 dB

Single Antenna,
Sectored & Switched Antennas

Sectored & Switched Antennas

- The codebook of an Single Antenna (SA) is 1:

$$\mathbf{W} = [1]$$

- The codebook of a sectored antenna array (SEAA) or switched antenna array (SWAA) with *N* elements is the identity matrix:

$$\mathbf{W} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix}$$

- Each beamformer vector has only one entry that is ones since only one element is active at a time.

- When no distinction is needed between SEAA and SWAA, we shall refer to them as SAA;

Beamforming Protocol

Messaging Protocol

- A unified messaging protocol that supports :
  - 1. Different antenna configurations on either side (Tx or Rx):
    - Omni, quasi-omni, or directional Single Antenna (SA)
    - Sectored or Switched Antenna Arrays (SAA)
    - Beamforming Antenna Arrays (BAA) such as Phased Antenna Arrays (PAA)
    - Etc,…
  - 2. ASS and AAS
  - 2. Both pro-active and on-demand beamforming
  - 3. Different usage models
    - Per packet beamforming from PNC to multiple DEVs and DEVs to PNC
    - PNC to one DEV
    - DEV-DEV
    - Others,…

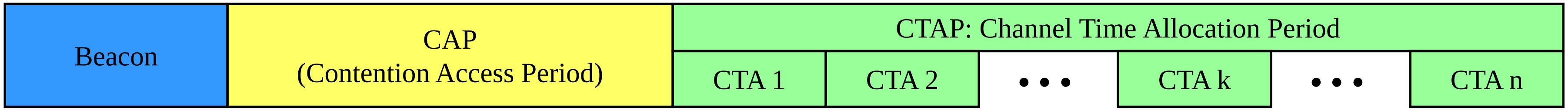
- The unified messaging protocol should be independent of the specifics of the beamforming estimation algorithm and antenna configuration implementation. Therefore, the actual beamforming algorithm (estimation of **w** and **c**) will be left to the implementer.

- However, the tools enabling the beamforming should be defined. These tools should support all scenarios while enabling:
  - 1. Reduced latency
  - 2. Reduced overhead
  - 3. Fast beamforming

Beamforming Protocol

- Two different protocols are needed:
  - 1. Pro-active beamforming protocol;
  - 2. On-demand beamforming protocol;
- Pro-active beamforming can be used when the PNC is the source of data to one or multiple DEVs. It takes place in the beacon part of the superframe;
  - Usage model example: Kiosk, STB, Laptop:
    - The PNC is the source of data to multiple DEVs;
    - The PNC can send each packet in a different direction, optimized to the destined device.
- On-demand beamforming can be used between two devices or between PNC and one DEV. It takes place in the CTA (Channel Time Allocation) part of the superframe allocated to the 2 DEVs (PNC and one DEV);
- Both protocol rely on the same principles:
  - 1. Quasi-omni transmission (s) that carriers the information regarding the structure of the directional training sections;
  - 2. The directional training sections for CSI acquisition and tracking.

Superframe Structure



Pro-Active Beamforming

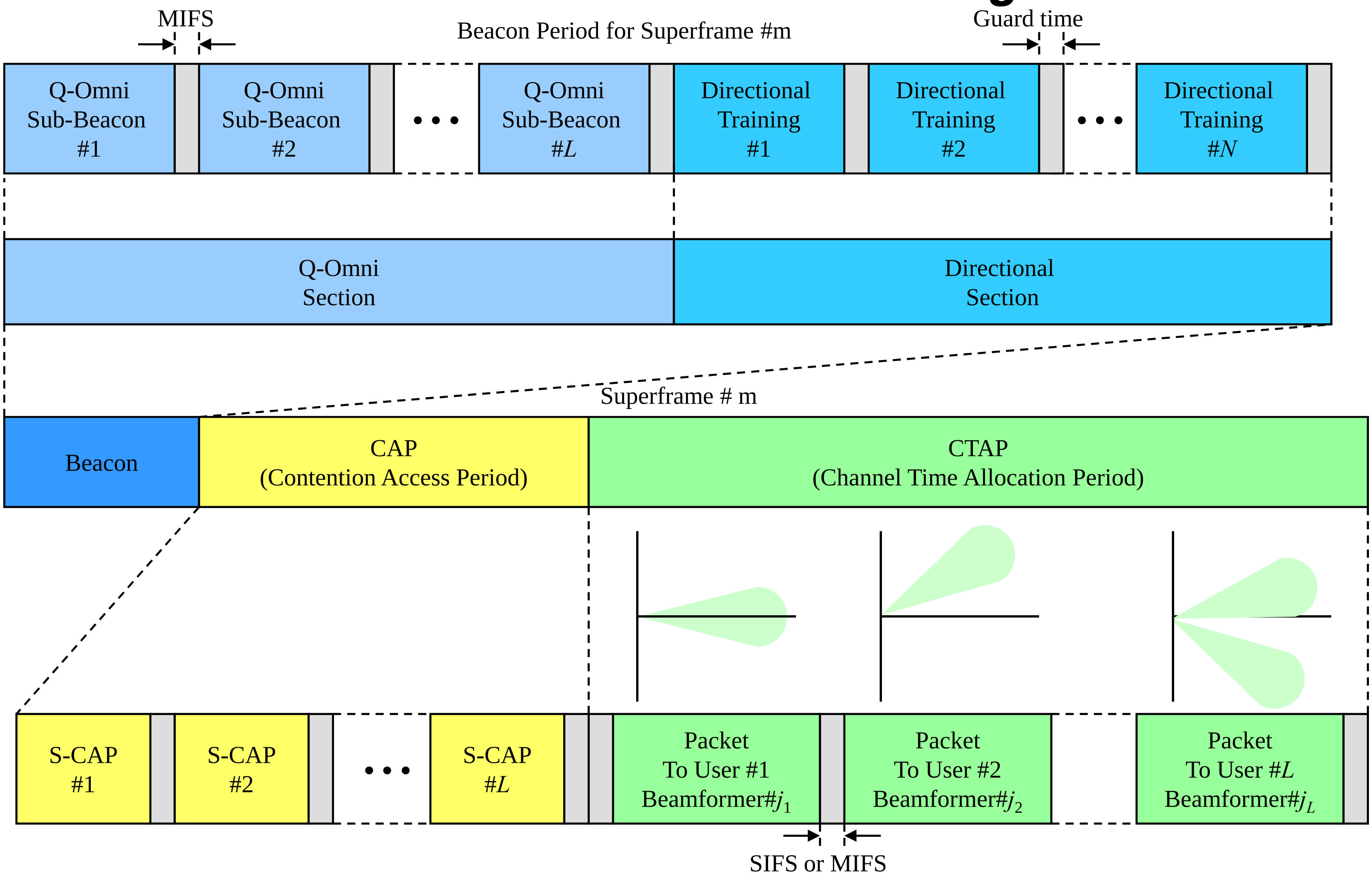
- The PNC beacon is constituted of two sections:
  - Quasi-omni (Q-omni) section;
  - Directional section;

- The Q-omni section consists of *L* **identical** Q-omni sub-beacons (S-beacons) that cover different (possibly overlapping) areas around the PNC and together cover the target space around the PNC. Each Q-omni sub-beacon is transmitted using a different Q-omni beamformer (for its antenna array) chosen from the appropriate Q-omni codebook provided before;

- The directional section consists of *N* **repetitions** of a training sequence where each repetition is transmitted with the PNC using a different orthogonal or quasi-orthogonal beamformer vector from the appropriate orthogonal (or quasi-orthogonal) codebook provided before;

- The CAP is divided into *L* identical periods referred to as Sub-CAPs (S-CAPs). These L S-CAPs correspond to the *L* Q-omni beacons. During the l^{th} S-CAP, the PNC is listening using the same Q-omni beamformer vector it used for transmission during the l^{th} S-Omni beacon.

Pro-Active Beamforming



Pro-Active Beamforming: Q-Omni Section

- The Q-omni section consists of L **identical** Q-omni S-beacons. The packet structure of an S-beacon is shown in the next slide for OFDM and single Carrier (SC). Depending on the antenna gain of the Q-omni beacon, the PNC might select to change the length of the SYNC, the data rate in the header and the PSDU fields;

- The number L should be minimized in order to reduce the overhead;

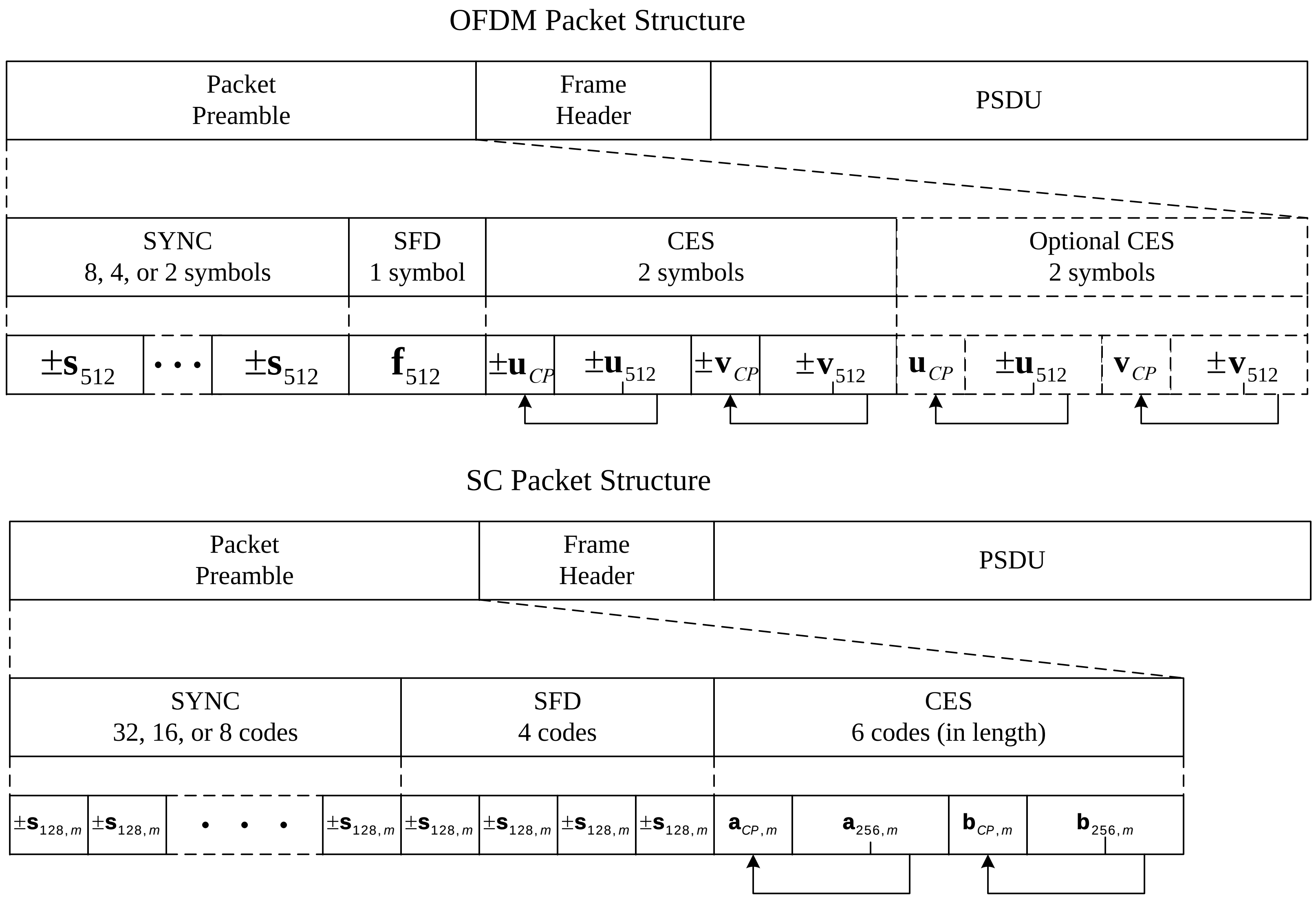
- For a SA, $L = 1$ & for a SAA, L is the number of sector (switched) antennas;

- For a BAA or PAA, L is preferably 1 or 2 but can be more. In this case during transmission, the PNC shall use L Quasi-omni beamformer vectors from the quasi-omni codebook (as specified before for different lengths), one Q-omni beamformer per Q-omni sub-beacon transmission:

  – Example 1: A 1-D vector-Tx PAA with 6 elements can use $L = 1$, and transmit the Q-omni sub-beacon using the Q-omni beamformer: $\mathbf{w} = [+1\ -1\ +j\ -1\ +j\ +j\ ]^T$;

  – Example 2: A 2-D vector-Tx PAA with $Nx = 4$ and $Ny = 3$ can use $L = 2$, and transmit the 1st Q-omni sub-beacon using the beamformer where $\mathbf{w}_{x,1} = [+1\ –j\ +j\ -1]^T$ and $\mathbf{w}_{y,1} = [+1\ +1\ -1]^T$, and transmit the 2nd Q-omni sub-beacon using the beamformer where $\mathbf{w}_{x,2} = [+1\ +j\ +j\ +1]^T$ and $\mathbf{w}_{y,1} = [+1\ +1\ -1]^T$;

Pro-Active Beamforming: Q-Omni Section



Pro-Active Beamforming: Directional Section

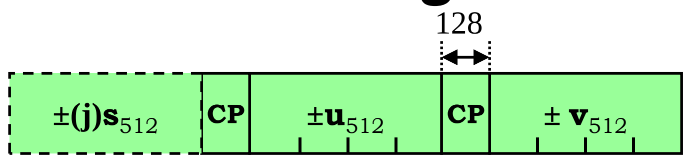
- The directional section consists of *N* **repetitions** of a training sequence;
- The OFDM and SC training sequences are shown in next slide;

- The training sequence consists of *Ns* repetitions (*Ns* can be zero) of the sync sequence **s** followed by *Nc* (one or two) repetitions of the CES field;

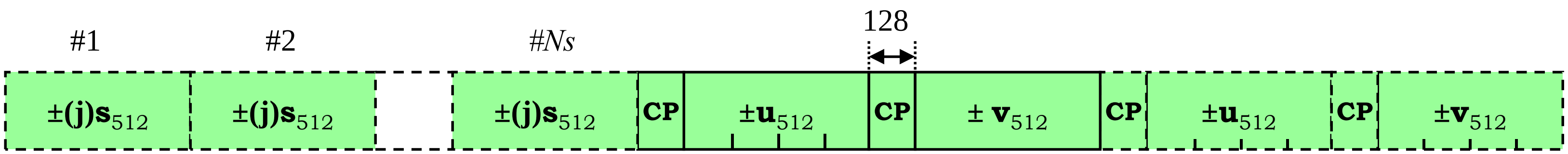
- A typical setting for OFDM and SC are shown and labeled as short training sequences. In this case,
  - 1. The two sync sequence can be used to adjust the AGC,
  - 2. The CES field is used to acquire the information related to the CSI. It is worth noting that by using a Golay matched filter, adding the outputs (after aligning them in time) corresponding to the correlation with **u** and **v** would provide a perfect channel estimate whereas the difference would provide a perfect noise estimate;

- Each training sequence is transmitted with the PNC being steered to a different orthogonal (or quasi-orthogonal) beamformer chosen from the orthogonal (quasi-orthogonal) codebook provided before;

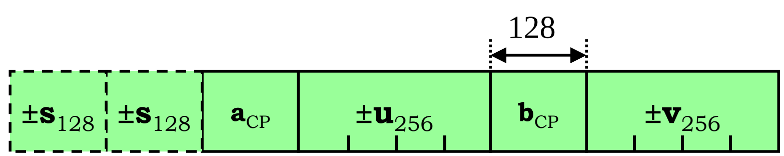
Pro-Active Beamforming: Directional Section



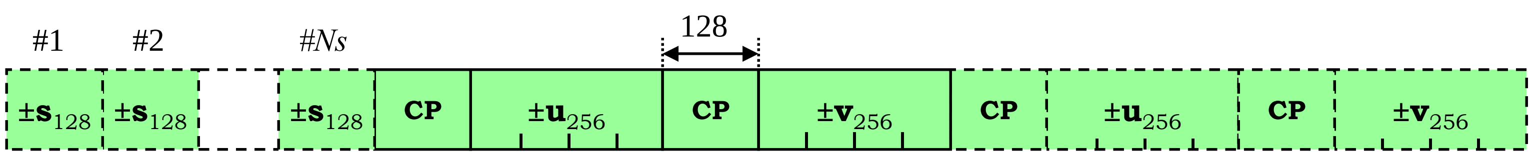
Short OFDM training sequence



OFDM training sequence



Short SC training sequence



SC training sequence

Pro-Active Beamforming: Directional Section

- Consider for example a vector-Tx BAA with Nx = 4 and Ny = 2. The x-axis codebook can be of length 4, 6, or 8 as shown before. Assume here that the x-axis orthogonal codebook of length 4 is used:

$$\mathbf{W}_x = \begin{bmatrix} \mathbf{w}_{x,1} & \mathbf{w}_{x,2} & \mathbf{w}_{x,3} & \mathbf{w}_{x,4} \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & -j & +1 & +j \\ +1 & -1 & +1 & -1 \\ -1 & +j & +1 & -j \end{bmatrix}$$

The y-axis codebook can be of length 2 or 4. Using the length 2 codebook:

$$\mathbf{W}_y = \begin{bmatrix} \mathbf{w}_{y,1} & \mathbf{w}_{y,2} \end{bmatrix} = \begin{bmatrix} +1 & +1 \\ -1 & +1 \end{bmatrix}$$

the total number of orthogonal beamformer matrices is J = 8 , i.e. where m = 1,2,3,4 and n = 1,2:

$$\mathbf{W}_{xy,11} = \begin{bmatrix} +1 & -1 \\ -1 & +1 \\ +1 & -1 \\ -1 & +1 \end{bmatrix} \quad \mathbf{W}_{xy,12} = \begin{bmatrix} +1 & +1 \\ -1 & -1 \\ +1 & +1 \\ -1 & -1 \end{bmatrix} \quad \cdots \quad \mathbf{W}_{xy,41} = \begin{bmatrix} +1 & -1 \\ +j & -j \\ -1 & +1 \\ -j & +j \end{bmatrix} \quad \mathbf{W}_{xy,42} = \begin{bmatrix} +1 & +1 \\ +j & +j \\ -1 & -1 \\ -j & -j \end{bmatrix}$$

Pro-Active Beamforming: Directional Section

- In the above example, the PNC completes a cycle of training by transmitting *J* = 8 training sequences, each one being sent in a different direction as specified by the beamformer matrices $\mathbf{W}_{xy,11}$, $\mathbf{W}_{xy,12}$, ..., $\mathbf{W}_{xy4,2}$. More specifically, the first training sequence is sent in the direction specified by the beamformer matrix $\mathbf{W}_{xy,11}$, the second training sequence is sent in the direction specified by the beamformer matrix $\mathbf{W}_{xy,12}$, and so on.

- It should be noted that the PNC might decide to transmit only a subset of the available beamformer matrices. For example the PNC does not need to transmit in a direction that is not part of the antenna element pattern, or the PNC might decide to cover only 180º rather than the entire 360º. The indices of the codebook vectors that the PNC decides to use along the x-axis and y-axis should be carried by the *L* identical Q-omni S-beacons.

- The number of cycles per superframe, or the number of superframes per cycle is a parameter that should be carried by the *L* identical Q-omni S-beacons.

- Let *J* be the PNC directional codebook size. This is the subset of beamformer matrices that the PNC will use to train the DEVs. A transmission of *J* training sequences in these *J* directions is referred to as a cycle.

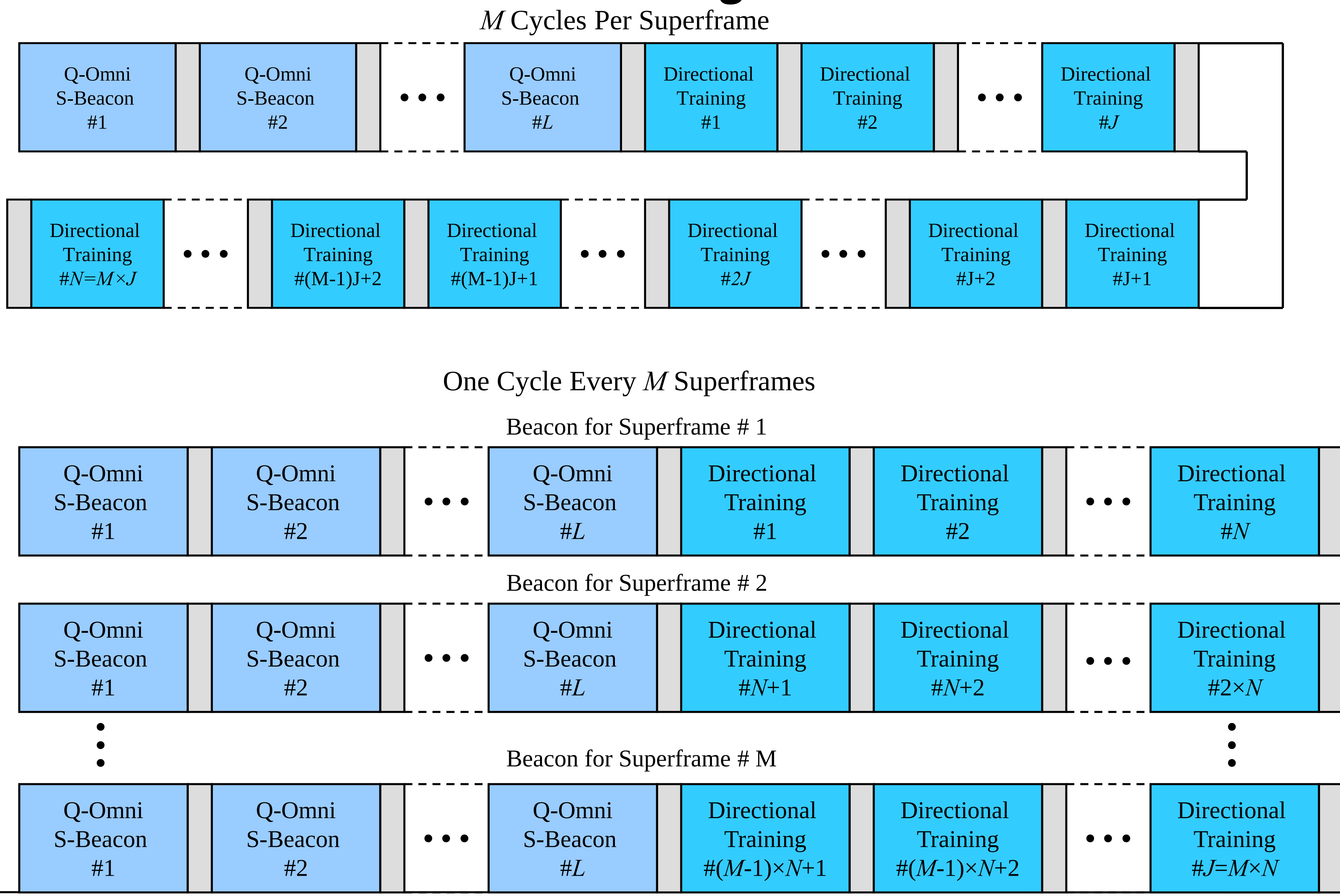
Pro-Active Beamforming: Directional Section

- The PNC might transmit multiple cycles per superframe (i.e. N is an integer multiple of J; $N = M \times J$) as shown in next slide. M can be 1 which means one cycle per superframe;

- The PNC might transmit one cycle every M superframes (i.e. J is an integer multiple of N; $J = N \times N$) as shown in the next slides. This means it takes R superframes to complete a cycle;

- A DEV would listen first to the Q-omni transmissions. Upon detection of any of them, DEV would decode the content of the Q-omni S-beacon and understand the entire structure of the directional section;
- DEV steers its antenna to one direction by using the appropriate codebook vector, than it listens to a cycle. DEV steers to another direction using another vector from the codebook and listens to a cycle, and so on;
- DEV might choose to listen to Q cycles corresponding to the useful subset of its codebook, than from the acquired CSI matrix H, it would estimate the beamformer that the PNC should use, and the combiner vector that it should use;
- Alternatively, for a ASS, DEV might choose to listen enough until it detects a good combination of directions PNC-DEV that is adequate for its application. Than it would inform PNC of this combination and continue further data communication using this combination.

Pro-Active Beamforming: Directional Section



Pro-Active Beamforming: Directional Section

- In addition to the required content from 802.15.3c, the identical Q-omni S-beacons should carry the information regarding the exact structure of the directional section. This is the list of the overall dependent information:
  - 1. The type of PNC antenna (SA, SEAA, SWAA, BAA, PAA, ...)
  - 2. Scalar or vector Tx, and scalar or vector Rx;
  - 3. ASS or AAS;
  - 4. The number Nx of antennas along the x-axis (when applicable);
  - 5. The number Ny of antennas along the x-axis (when applicable);
  - 6. The ID of the codebook used along the x-axis (when applicable);
  - 7. The ID of the codebook used along the y-axis (when applicable);
  - 8. The size *Jx* and ID of the subset of the beamformer vectors to be used along the x-axis (when applicable);
  - 9. The size *Jy* and ID of the subset of the beamformer vectors to be used along the y-axis (when applicable);
  - 10. The number of training sequences per superframe, *N*;
  - 11. The number of SYNC repetitions, *Ns*;
  - 12. The number of CES repetitions, *Nc*;
  - 13. The guard interval duration in units of $32 \times Tc$ (where *Tc* is the chip or sampling duration);

- It is worth noting that the codebook size $J = Jx \times Jy$;
- The number of cycles per superframe = *N/J*
- The number of superframes per cycle = *J/N*
- In steps 4 and 5, we can add the exact content of the codebook;

Pro-Active Beamforming IE

Beamforming IE (Information element)

0 or 2	0 or 6	1	1		1	1
TRAINING SEQUENCE INFO	Tx & RX ANTENNA ARRAY INFO	ANTENNA TYPE	CURRENT Q-OMIN S-BEACON IDENTIFER (4bits)	NUMBER OF Q-OMNI S-BEACONS (4bits)	Length (=3 or 7)	Element ID

"Antenna Type" carries the following information:

1. BAA or PAA or SA or SEAA or SWAA, …
2. ASA or AAA,
3. Vector or scalar Tx, vector or scalar Rx, …

Tx (Rx) Antenna Array Information

4b	4b	4b	4b	4b	4b
LAST Y-VECTOR ID	FIRST Y-VECTOR ID	LAST X-VECTOR ID	FIRST X-VECTOR ID	Y-CODEBOOK ID	X-CODEBOOK ID

Training Sequence Information

7b	1b	4b	4b
GUARD TIME DURATION	CES MODE	NUMBER OF SYNCs PER TRAINING SEQUENCE	NUMBER OF TRAINING SEQUENCES PER SUPERFRAME

For SA and SAA, there is no directional section and the "Antenna Array Info" and "Training Sequence Info" fields are not applicable and will not be present;

Pro-Active Beamforming Procedure

- In summary, pro-active beamforming works as follows:
  - 1. PNC Transmits L Q-omni S-beacons and N directional training sequences per superframe;
  - 2. DEV listens and should be able to decode one of the Q-omni S-beacons (number l for example) and reads from it all the required information related to the directional section;
  - 3. DEV selects the appropriate subset of an orthogonal (quasi-orthogonal) codebook (as specified before) of size J_{DEV} and starts its scanning procedure.

    Iteration: DEV steers to a direction using a vector from the codebook and listens to a PNC cycle and might chose to store a Link quality Factor (LQF) or the CSI related to matrices
    ;

    DEV repeats iteration until it has found an appropriate LQF or until it has finished listening with all J_{DEV} codebook vectors (one PNC cycle per vector) and *it has acquired the CSI matrix*
    .
  - 4. DEV will estimate the optimal PNC beamformer vector $\mathbf{w}_1$ and its (DEV) optimal combiner vector $\mathbf{c}_2$ vector;
  - 5. DEV will feedback the optimal beamformer vector $\mathbf{w}_1$ and possibly optimal combiner vector $\mathbf{c}_2$ to DEV1 by associating to the PNC during the lth S-C
  - 6. For an ASS, DEV and PNC can now exchange data packets during a CTAP;
  - 7. For an ASS, DEV tracks the beamformer and combiner vectors by periodically scanning the beacon;
  - 8. For an ASS, DEV feedback periodically any updates on $\mathbf{w}$ and $\mathbf{c}$;

On-Demand Beamforming

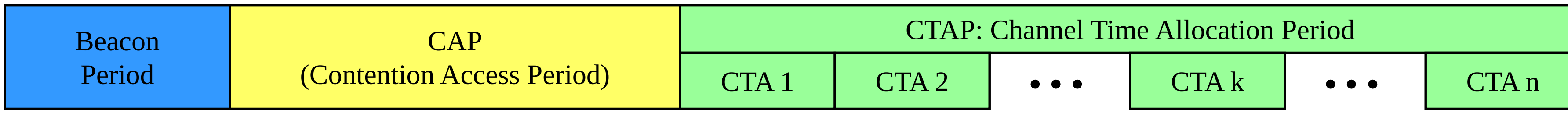
- On-demand beamforming is used between two DEVs or between PNC and one DEV. It takes place in the CTA (Channel Time Allocation) part of the superframe allocated to the 2 DEVs;

- On-demand beamforming is based on two steps:
  - 1. Antenna information exchange during association
  - 2. Quasi-omni Acquisition phase
  - 3. Directional Acquisition phase
  - 4. Tracking phase

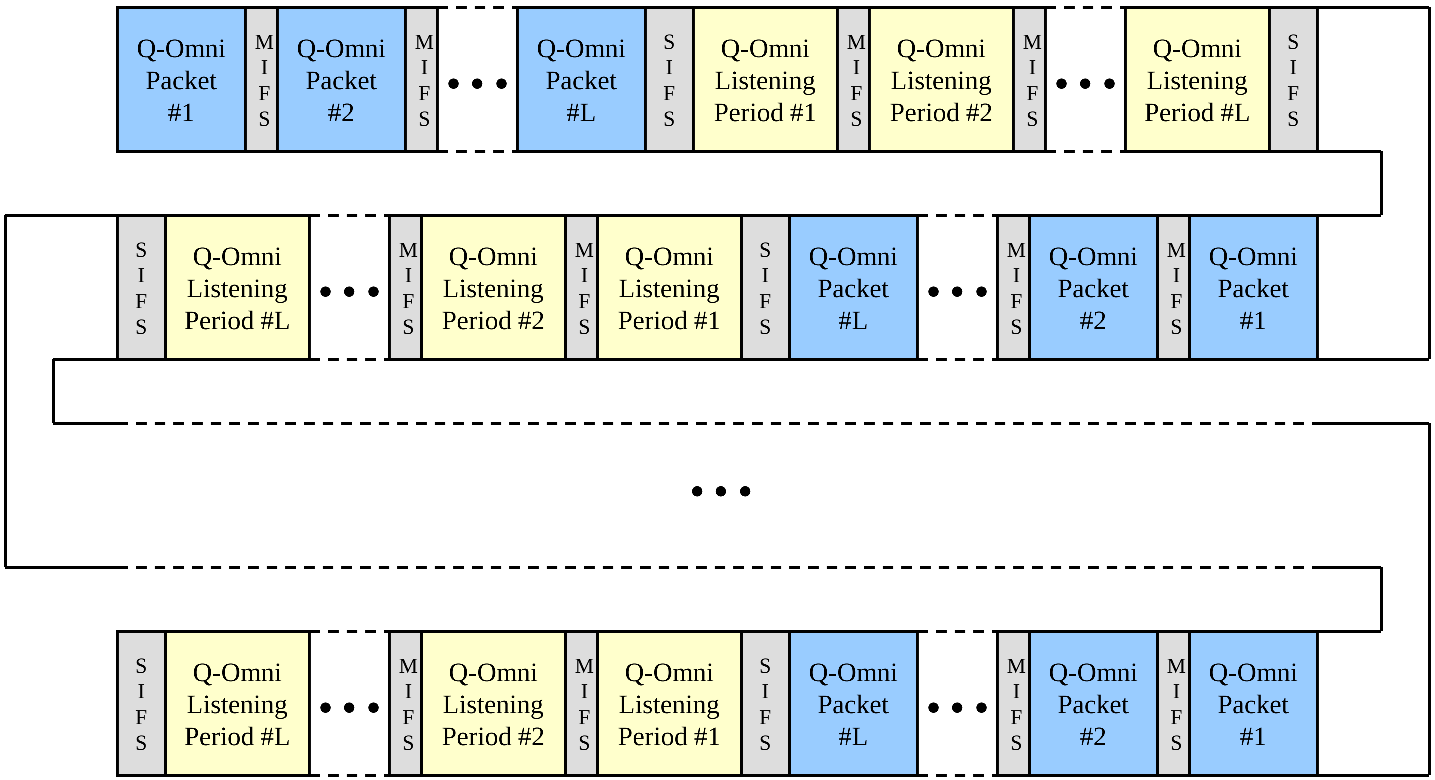
- Quasi-omni acquisition is shown on next slide:
  - DEV1 transmits *L* quasi-omni packets that carry the “Beamforming IE” defined earlier. Each *L* transmissions is followed by *L* listening periods (ACKs).
  - DEV1 keep repeating this structure until it receives an ACK in one of the *L* listening periods, say number l.
  - From this point on, DEV1 needs only one Q-omni using lth Q-omni direction from the Q-omni codebook and DEV2 already know its best Q-omni direction and will use that for any future Q-omni transmission/reception;

On-Demand Beamforming

Superframe Structure



Q-omni training section



On-Demand Beamforming

- The directional phase (shown on the next slide) has a periodic structure.
- A "directional acquisition period" is constituted of:
  - 1. An optional Q-omni packet followed by a listening period;
  - 2. One cycle of directional training sequences corresponding to all J orthogonal (quasi-orthogonal) beamformer vectors from the selected codebook;
  - 3. the cycle is followed by a listening period (ACK) to listen to any feedback from DEV2.
- DEV1 keeps repeating this period until DEV2 have acquired the CSI (or found an adequate LQI);
- DEV2 will estimate and feedback the optimal beamformer vector **w** and optimal combiner vector **c** to DEV1 during the listening period;
- The same procedure can be repeated from DEV2 to DEV1 if needed where DEV2 is training DEV1;
- DEV1 and DEV2 will start data communications by using this optimal combination of beamformer vector **w** and optimal combiner vector **c**;
- DEV1 continues to transmit a "directional acquisition period" but not so often (once every x microseconds) to allow DEV2 to track and update **w** and **c**. In the same way, DEV2 can transmit a "directional acquisition period" every while to allow DEV1 to track and update **w** and **c**. The number x should be known t both parties

On-Demand Beamforming