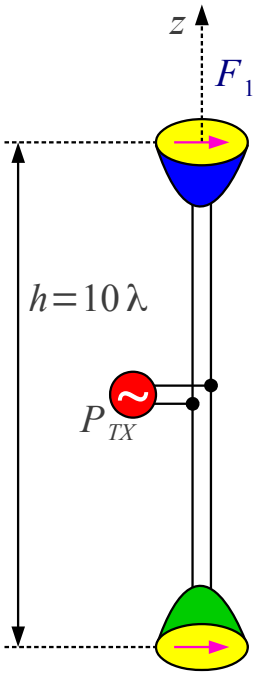
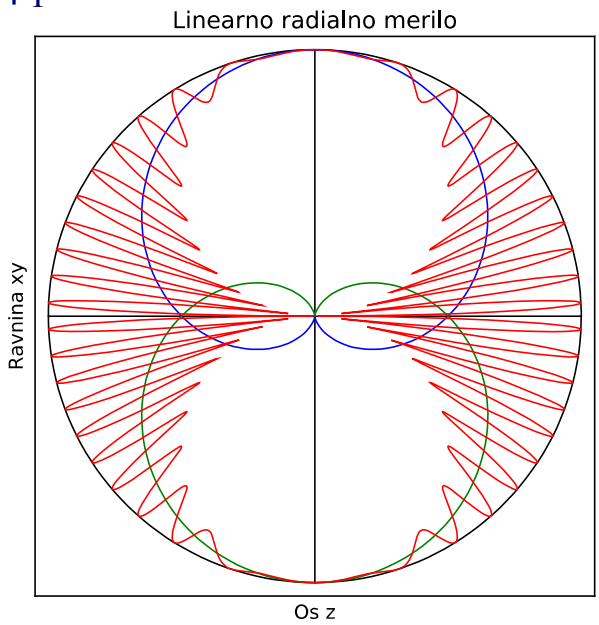
11. Skupine anten

Višja smernost oziroma dobitek je mogoče najpogostejši, ampak nikakor ni edini namen sestavljanja skupine anten (angleško: antenna array). Skupina anten omogoča tudi doseganje drugačne polarizacije, pokrivanje širšega frekvenčnega pasu ali več ločenih frekvenčnih pasov, smerne diagrame, ki jih z eno samo anteno ne moremo narediti, električno odklanjanje smeri sevanja brez mehanskega premikanja antene in podobno.

Pri sestavljanju skupine moramo biti previdni. Doseganje ene lastnosti lahko poruši druge lastnosti skupine anten. Preprost zgled je antena na letalu ali umetnem satelitu, ki mora oddajati in sprejemati iz poljubne smeri. Ko je plovilo dosti večje $d \gg \lambda$ od valovne dolžine, se je senci plovila zelo težko izogniti ne glede na to, kam namestimo eno samo anteno na površino plovila. Radijsko zvezo v poljubno smer omogočata dve ločeni anteni, nameščeni na nasprotni strani plovila, da vsaka antena vidi neovirano poloblo:



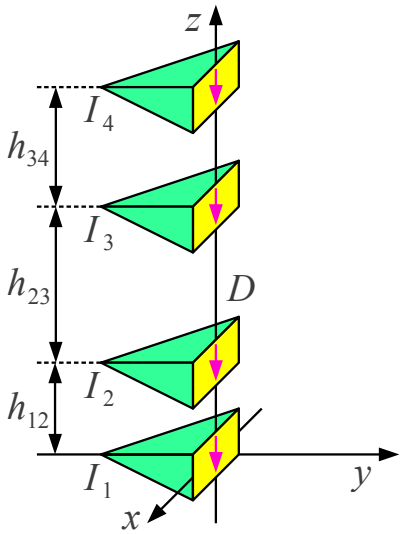


$$F(\Theta,\Phi)=F_1(\Theta,\Phi)e^{j\frac{kh}{2}\cos\Theta}-F_2(\Theta,\Phi)e^{-j\frac{kh}{2}\cos\Theta}$$

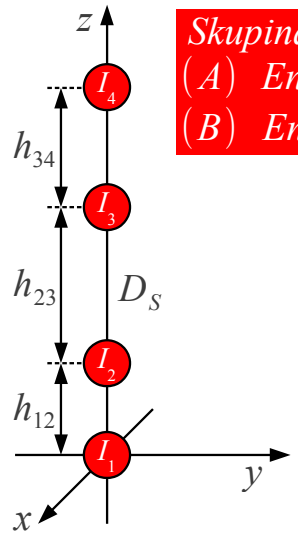
Nesmiselna skupina dveh anten

Poloblo odlično pokriva Huygensov izvor. Dva Huygensova izvora na gornji in spodnji strani plovila naj bi omogočala radijsko zvezo v poljubno

smer. Žal se delovanje opisane naprave poruši, ko obe anteni na nasprotnih straneh plovila povežemo vzporedno na skupni radijski oddajnik oziroma sprejemnik. Že pri debelini plovila oziroma razdalji med antenama komaj $h = 10\lambda$ smerni diagram opisane skupine postane interferenčni vzorec z velikim številom ozkih snopov sevanja in globokimi minimumi med njimi. Smerni diagram s številnimi globokimi minimumi pomeni nezanesljivo radijsko zvezo s številnimi izpadi, pogosto celo slabše od tistega, kar bi dosegli z eno samo anteno...

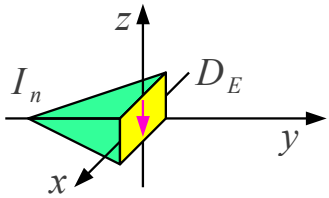


$F(\Theta,\Phi) \equiv$ *smerni diagram skupine anten*



$F_S(\Theta,\Phi) \equiv$ *smerni diagram skupine neusmerjenih virov*

Skupina neusmerjenih virov
(A) Enaka razporeditev h_{mn}
(B) Enako napajanje I_n



$F_E(\Theta,\Phi) \equiv$ *smerni diagram elementa*

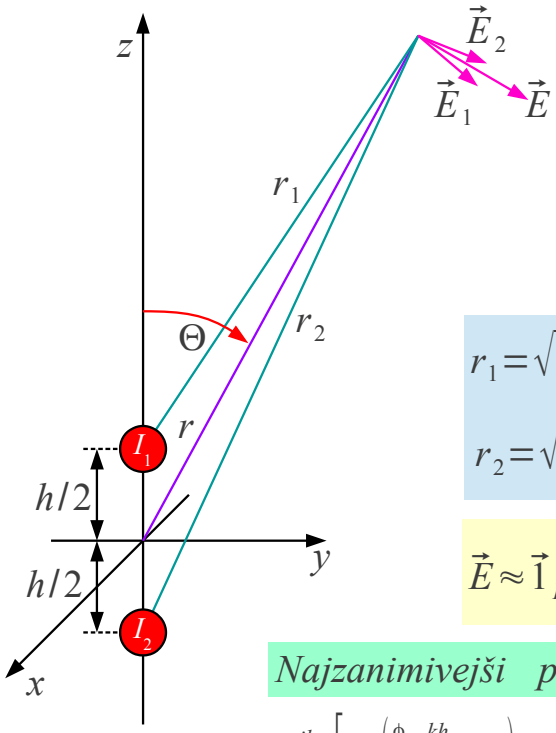
(1) Skupina samih enakih anten
(2) Vse antene enako orientirane
(3) Vse antene enako polarizirane

$$F(\Theta,\Phi) = F_S(\Theta,\Phi) \cdot F_E(\Theta,\Phi)$$

Pravilo o množenju smernih diagramov

$$D \neq D_S \cdot D_E$$

Običajno $D_E, D_S < D < D_S \cdot D_E$



$$\vec{E}=\vec{E}_1+\vec{E}_2=\vec{1}_{E_1}\alpha I_1\frac{e^{-jkr_1}}{r_1}+\vec{1}_{E_2}\alpha I_2\frac{e^{-jkr_2}}{r_2}$$

Fraunhofer $r>\dfrac{2h^2}{\lambda}$

$$\vec{1}_{E_1}\approx\vec{1}_{E_2}\approx\vec{1}_E \qquad \frac{1}{r_1}\approx\frac{1}{r_2}\approx\frac{1}{r}$$

$$r_1=\sqrt{r^2+(h/2)^2-rh\cos\Theta}\approx r-\frac{h}{2}\cos\Theta$$

$$r_2=\sqrt{r^2+(h/2)^2+rh\cos\Theta}\approx r+\frac{h}{2}\cos\Theta$$

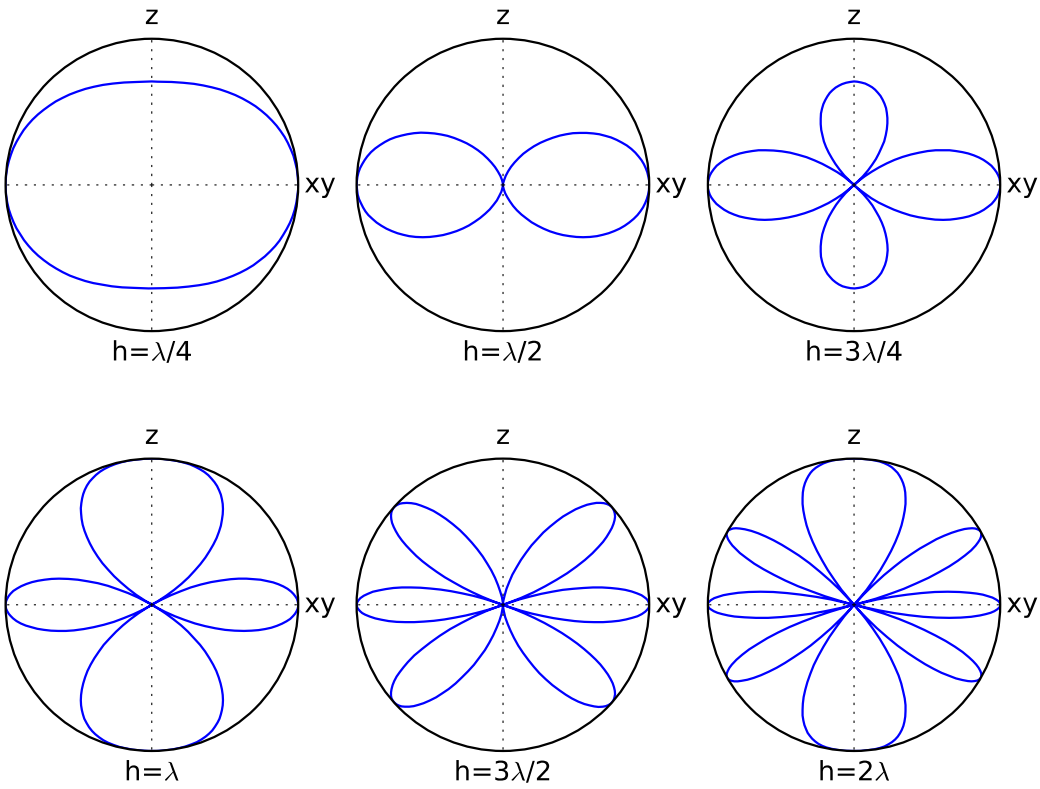
$$\vec{E}\approx\vec{1}_E\alpha\frac{e^{-jkr}}{r}\left[I_1e^{j\frac{kh}{2}\cos\Theta}+I_2e^{-j\frac{kh}{2}\cos\Theta}\right]$$

Najzanimivejši primer $|I_1|=|I_2|$ → $I_1=I\,e^{j\phi/2}$ $I_2=I\,e^{-j\phi/2}$

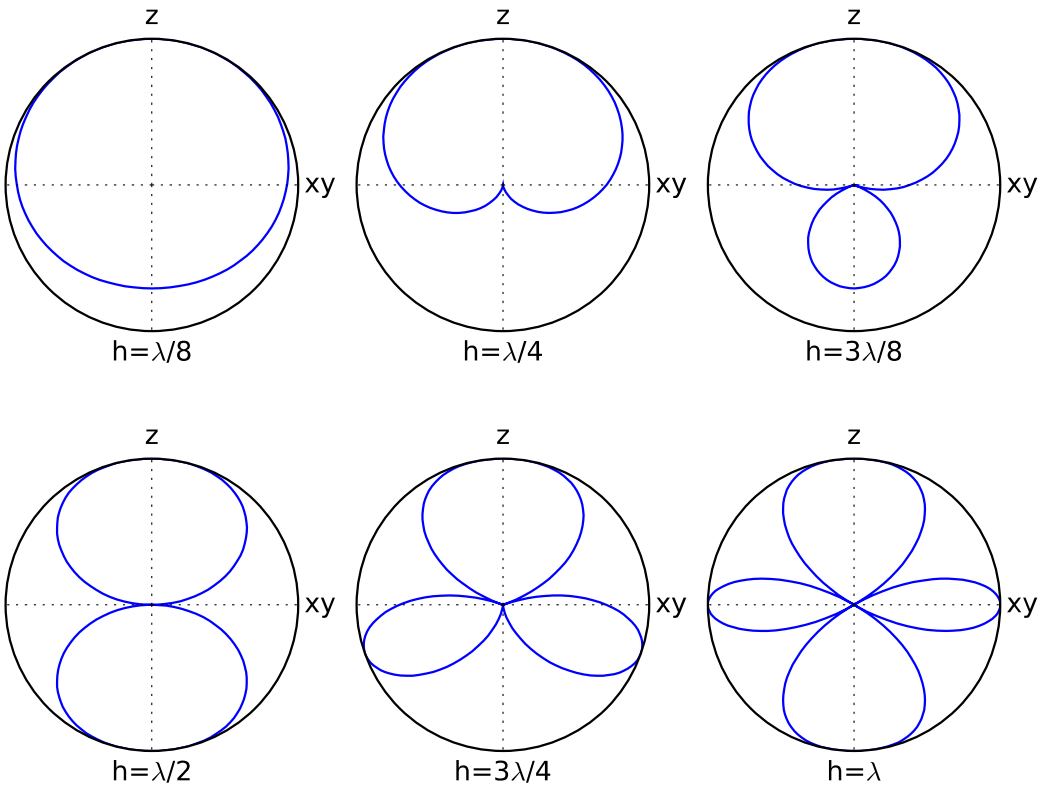
$$\vec{E}\approx\vec{1}_E\alpha I\frac{e^{-jkr}}{r}\left[e^{j\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)}+e^{-j\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)}\right]=\vec{1}_E\alpha I\frac{e^{-jkr}}{r}2\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)$$

$$F(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)$$

Dva neusmerjena (izotropna) vira



Smerni diagrami bočnih skupin $\phi = 0$



Smerni diagrami osnih skupin $\phi = -kh$

$$D=\frac{4\pi\left|F\left(\Theta_{MAX},\Phi_{MAX}\right)\right|^2}{\iint\limits_{4\pi}\left|F\left(\Theta,\Phi\right)\right|^2 d\,\Omega}$$

$$F\left(\Theta,\Phi\right)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)$$

$$\iint\limits_{4\pi}\left|F\left(\Theta,\Phi\right)\right|^2 d\,\Omega=\int_0^{\pi}\int_0^{2\pi}\left|F\left(\Theta,\Phi\right)\right|^2\sin\Theta\,d\,\Theta\,d\,\Phi=$$

$$=\int_0^{\pi}\int_0^{2\pi}\left|\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)\right|^2\sin\Theta\,d\,\Theta\,d\,\Phi=2\pi\int_0^{\pi}\left|\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)\right|^2\sin\Theta\,d\,\Theta=$$

$$=2\pi\int_{-1}^{1}\left[\cos\left(\frac{\phi}{2}+\frac{khu}{2}\right)\right]^2 du=\pi\int_{-1}^{1}\left[1+\cos\left(\phi+khu\right)\right]du=$$

$$=\pi\left[2+\frac{\sin\left(\phi+kh\right)-\sin\left(\phi-kh\right)}{kh}\right]=2\pi\left[1+\frac{\sin\left(kh\right)}{kh}\cos\phi\right]$$

$$D=\frac{2\left|F\left(\Theta_{MAX},\Phi_{MAX}\right)\right|^2}{1+\frac{\sin\left(kh\right)}{kh}\cos\phi}$$

Smernost dveh virov

$F\left(\Theta_{MAX}=\pi/2,\Phi_{MAX}\right)=1$

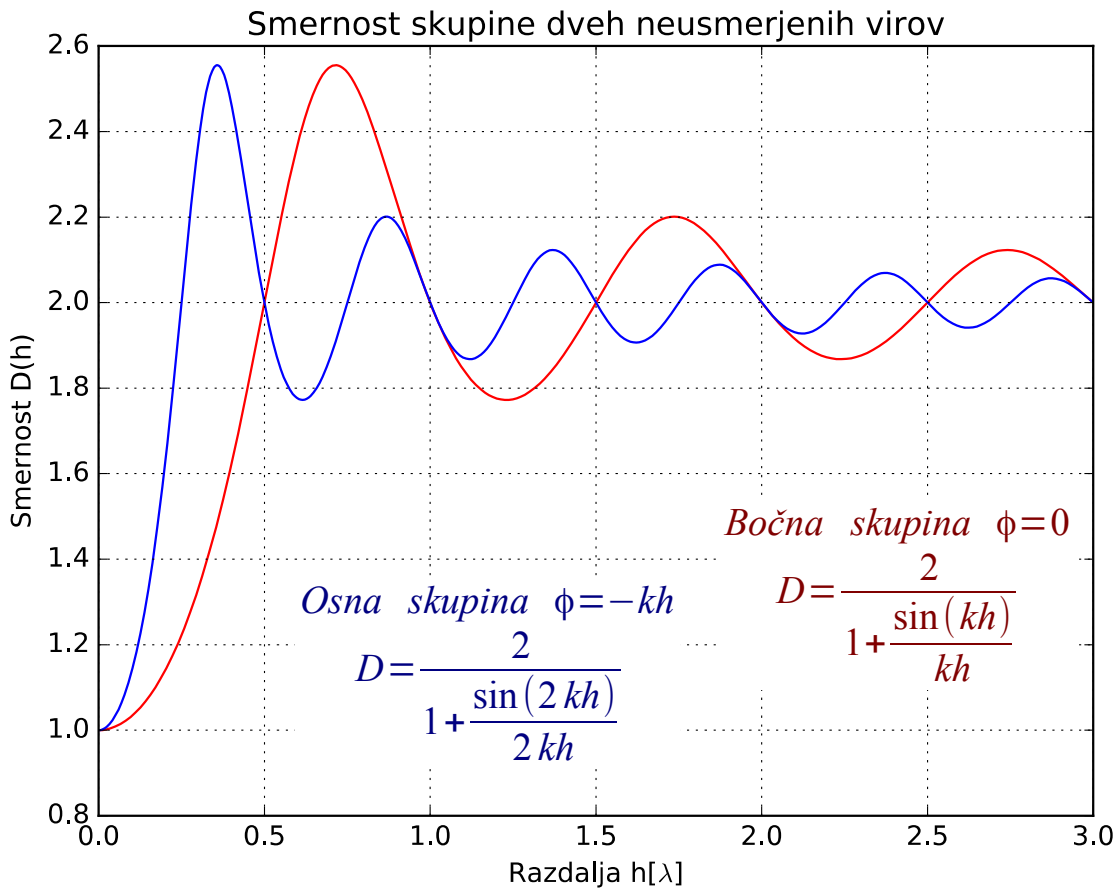
Bočna skupina → $\phi=0$

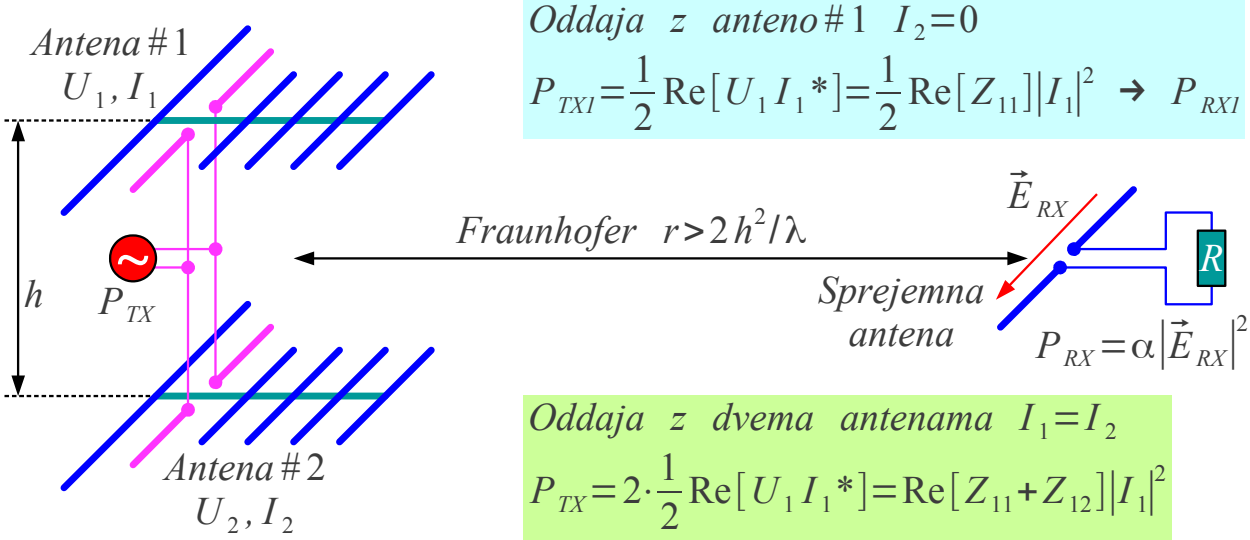
$$D=\frac{2}{1+\frac{\sin\left(kh\right)}{kh}}$$

$F\left(\Theta_{MAX}=0,\Phi_{MAX}\right)=1$

Osna skupina → $\phi=-kh$

$$D=\frac{2}{1+\frac{\sin\left(2\,kh\right)}{2\,kh}}$$


Smernost skupine dveh neusmerjenih virov
Smernost D(h)
Razdalja h[λ]
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Osna skupina ϕ=−kh
D=2/(1+sin(2kh)/(2kh))
Bočna skupina ϕ=0
D=2/(1+sin(kh)/(kh))



Oddaja z anteno #1 $I_2 = 0$

$$P_{TX1} = \frac{1}{2}\mathrm{Re}[U_1 I_1^*] = \frac{1}{2}\mathrm{Re}[Z_{11}]|I_1|^2 \rightarrow P_{RX1}$$

Oddaja z dvema antenama $I_1 = I_2$

$$P_{TX} = 2 \cdot \frac{1}{2}\mathrm{Re}[U_1 I_1^*] = \mathrm{Re}[Z_{11} + Z_{12}]|I_1|^2$$

$$\vec{E}_{RX} = 2\vec{E}_{RX1} \rightarrow P_{RX} = 4 P_{RX1}$$

Medsebojni vpliv v skupini

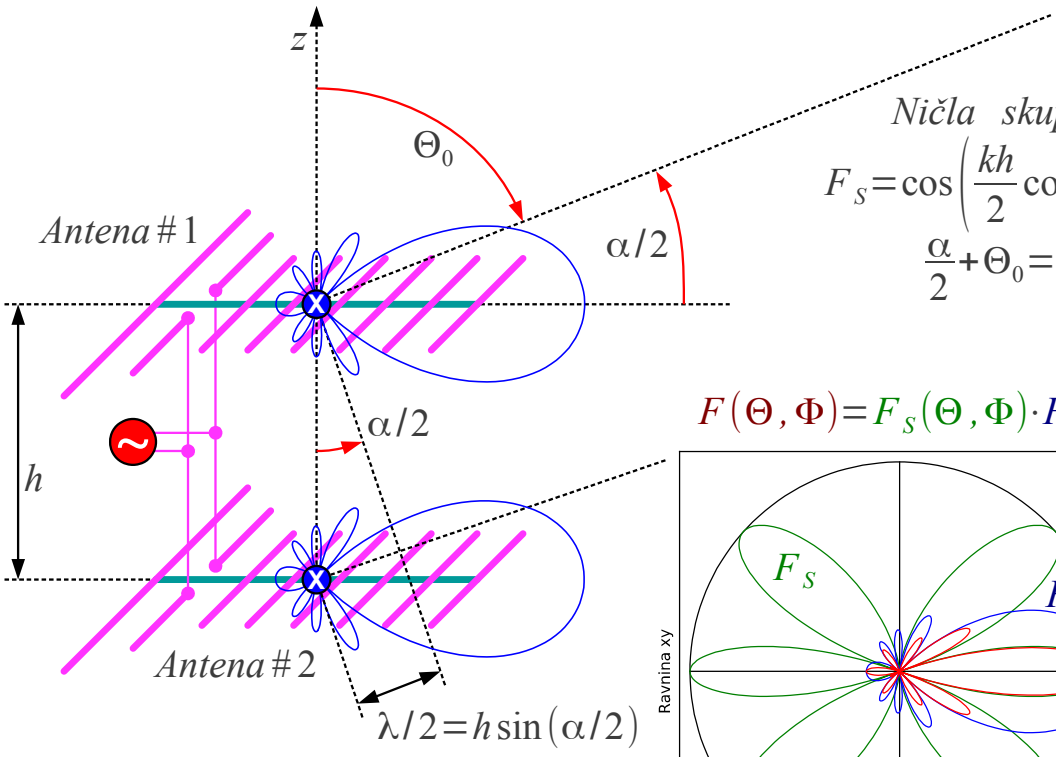
$$\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} . \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

Recipročnost $Z_{12}(h) = Z_{21}(h)$

Enaki anteni $Z_{11} = Z_{22}$

$$\Delta D = \frac{\left(\frac{P_{RX}}{P_{RX1}}\right)}{\left(\frac{P_{TX}}{P_{TX1}}\right)} = \frac{4}{\frac{\mathrm{Re}[Z_{11} + Z_{12}]|I_1|^2}{\frac{1}{2}\mathrm{Re}[Z_{11}]|I_1|^2}} = \frac{2\,\mathrm{Re}[Z_{11}]}{\mathrm{Re}[Z_{11} + Z_{12}]}$$

Medsebojna impedanca v bočni skupini



Ničla skupine

$$F_S = \cos\left(\frac{kh}{2}\cos\Theta_0\right) = 0$$

$$\frac{\alpha}{2} + \Theta_0 = \frac{\pi}{2}$$

$$F(\Theta,\Phi) = F_S(\Theta,\Phi)\cdot F_E(\Theta,\Phi)$$

$$h \approx \frac{\lambda}{2\sin(\alpha_{-3\mathrm{dB}}/2)}$$

Približno pravilo za bočno skupino

Osna skupina $|F(\Theta_{MAX}=0,\Phi_{MAX})|<1$

$$F(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta\right)$$

$$D=\frac{2|F(\Theta_{MAX},\Phi_{MAX})|^2}{1+\frac{\sin(kh)}{kh}\cos\phi}=\frac{2\left|\cos\left(\frac{\phi}{2}+\frac{kh}{2}\right)\right|^2}{1+\frac{\sin(kh)}{kh}\cos\phi}=\frac{1+\cos(\phi+kh)}{1+\frac{\sin(kh)}{kh}\cos\phi}$$

$$\frac{\partial D}{\partial\phi}=0=\frac{-\sin(\phi+kh)\left[1+\frac{\sin(kh)}{kh}\cos\phi\right]-\left[1+\cos(\phi+kh)\right]\left[-\frac{\sin(kh)}{kh}\sin\phi\right]}{\left[1+\frac{\sin(kh)}{kh}\cos\phi\right]^2}$$

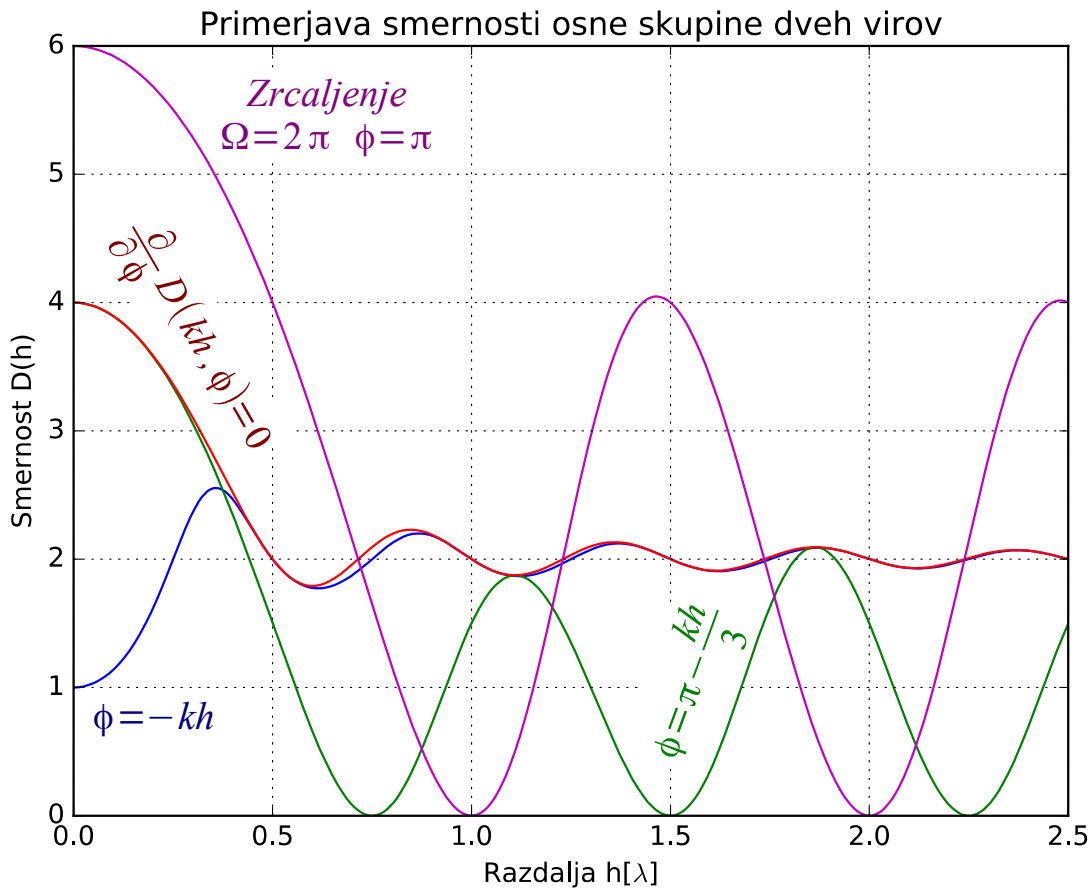
$$0=\left[\frac{\sin^2(kh)}{(kh)^2}-2\frac{\sin(kh)}{kh}\cos(kh)+1\right]\sin^2\phi-$$

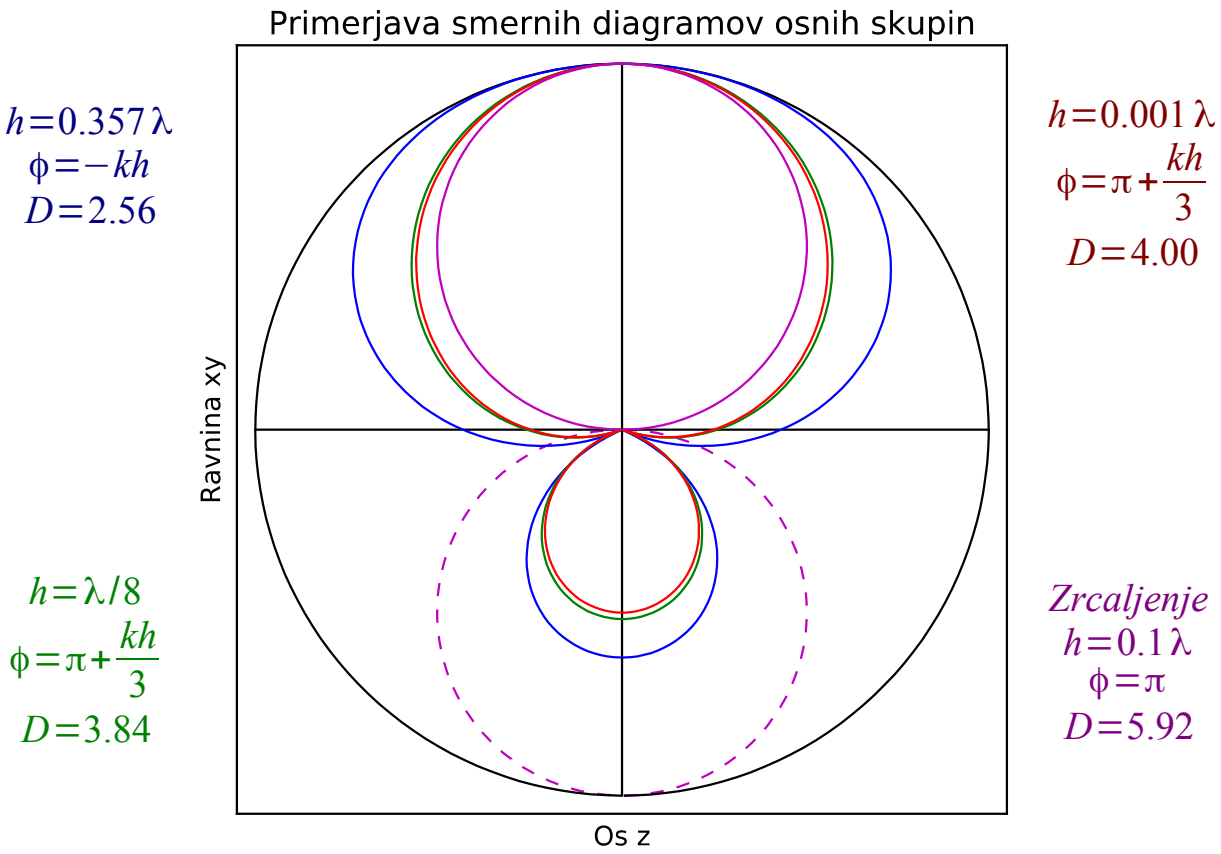
$$-2\frac{\sin^2(kh)}{kh}\left[\frac{\sin(kh)}{kh}-\cos(kh)\right]\sin\phi+\left[\frac{\sin^4(kh)}{(kh)^2}-\sin^2(kh)\right]$$

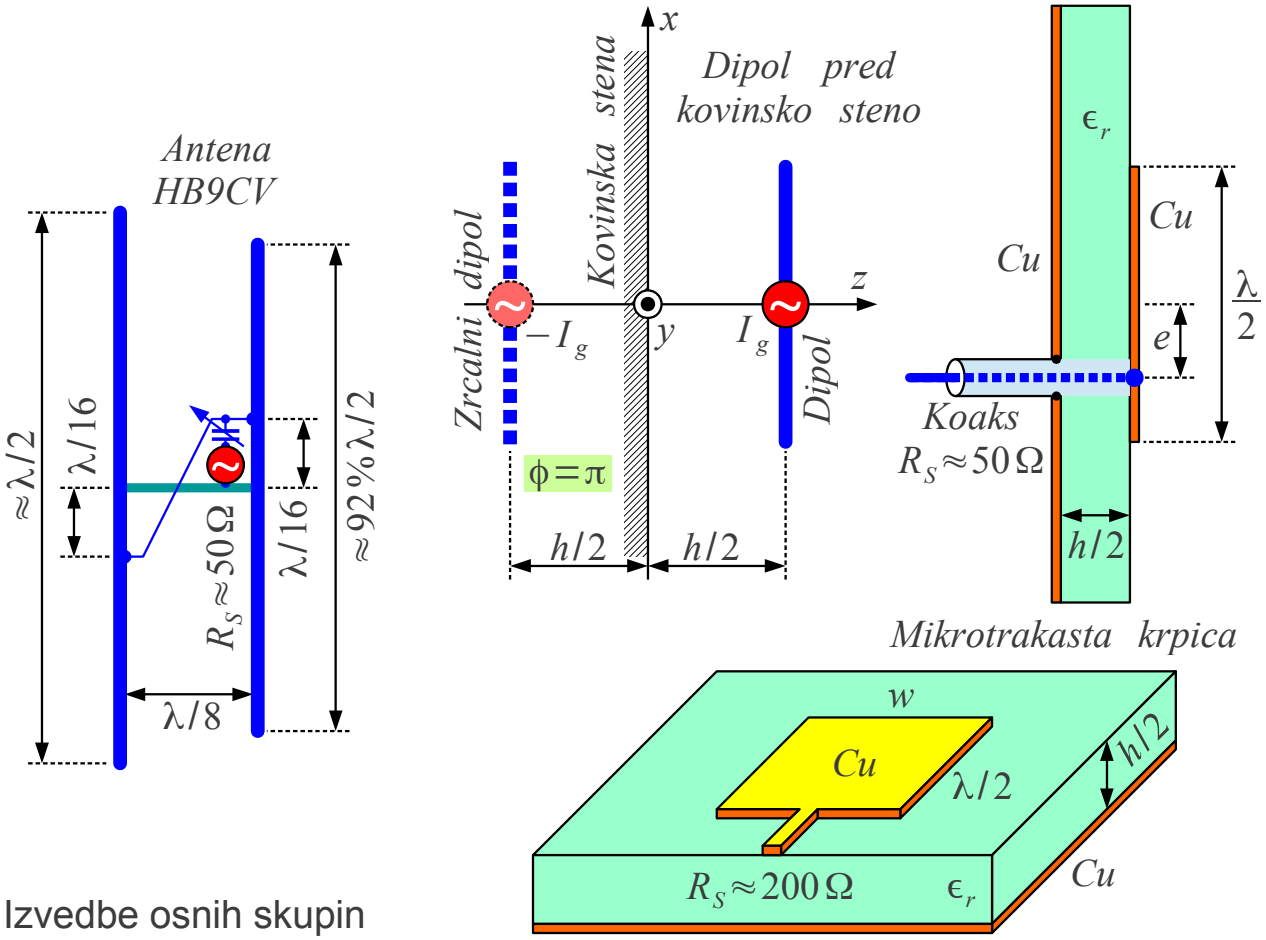
$u=\sin\phi \rightarrow \phi=\arcsin u$ *ali* $\phi=\pi-\arcsin u$

Približek $h<\frac{\lambda}{4} \rightarrow \phi\approx\pi+\frac{kh}{3}$

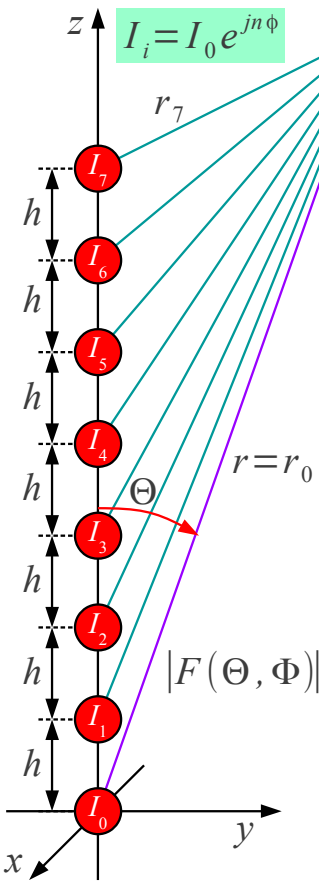
Največja smernost osne skupine


Primerjava smernosti osne skupine dveh virov
Zrcaljenje
Ω=2π ϕ=π
∂/∂ϕ D(kh,ϕ)=0
ϕ=−kh
ϕ=π−kh/3
Smernost D(h)
Razdalja h[λ]
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0
2.5


Primerjava smernih diagramov osnih skupin
$h=0.357\lambda$
$\phi=-kh$
$D=2.56$
$h=0.001\lambda$
$\phi=\pi+\frac{kh}{3}$
$D=4.00$
$h=\lambda/8$
$\phi=\pi+\frac{kh}{3}$
$D=3.84$
Zrcaljenje
$h=0.1\lambda$
$\phi=\pi$
$D=5.92$
Ravnina xy
Os z



Izvedbe osnih skupin



$$\vec{E} = \sum_{n=0}^{m-1} \vec{E}_i$$

$$\vec{E}_i = \vec{1}_{E_i}\, \alpha\, I_i \frac{e^{-jkr_i}}{r_i} \approx \vec{1}_E \frac{\alpha\, I_0}{r} e^{jn\phi} e^{-jkr_n}$$

$$r_i = \sqrt{r^2 + (ih)^2 - 2\, rih \cos\Theta} \approx r - ih\cos\Theta$$

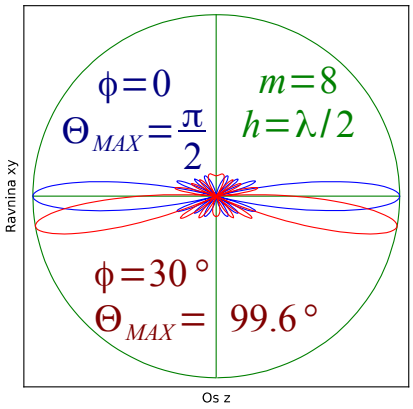
$$\vec{E} \approx \vec{1}_E \frac{\alpha\, I_0}{r} \sum_{n=0}^{m-1} e^{-j(kr_n - n\phi)} \approx \vec{1}_E\, \alpha\, I_0 \frac{e^{-jkr}}{r} \sum_{n=0}^{m-1} e^{jn(\phi + kh\cos\Theta)}$$

$$b = e^{j(\phi + kh\cos\Theta)}$$
$$|b| = 1$$

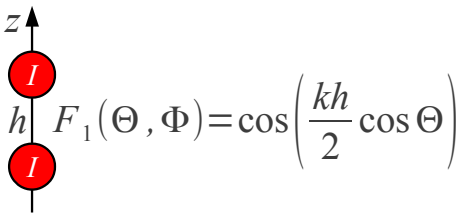
$$\sum_{n=0}^{m-1} b^n = \frac{b^m - 1}{b - 1} = \left(b^{\frac{m-1}{2}}\right) \frac{\sin\left(m\frac{\phi + kh\cos\Theta}{2}\right)}{\sin\left(\frac{\phi + kh\cos\Theta}{2}\right)}$$

$$|F(\Theta, \Phi)| = \frac{1}{m} \left| \frac{\sin\left(m\frac{\phi + kh\cos\Theta}{2}\right)}{\sin\left(\frac{\phi + kh\cos\Theta}{2}\right)} \right|$$

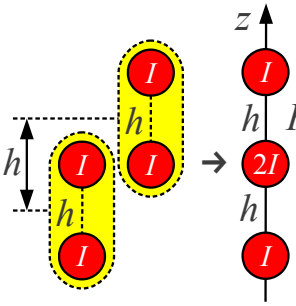
$$\Theta_{MAX} = \arccos\left(\frac{-\phi}{kh}\right)$$



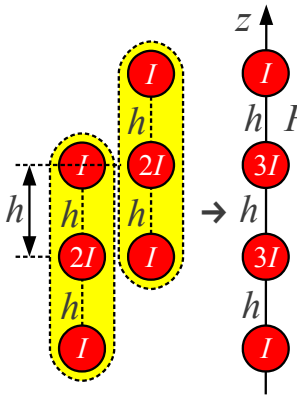
Enakomerna skupina izvorov



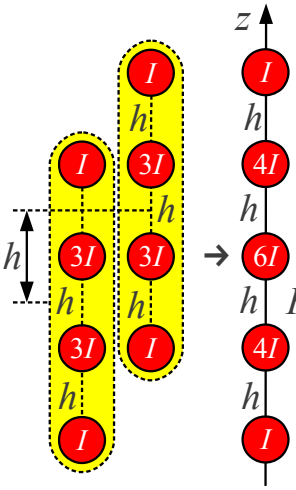
$$F_1(\Theta,\Phi)=\cos\left(\frac{kh}{2}\cos\Theta\right)$$



$$F_2(\Theta,\Phi)=\cos^2\left(\frac{kh}{2}\cos\Theta\right)$$



$$F_3(\Theta,\Phi)=\cos^3\left(\frac{kh}{2}\cos\Theta\right)$$



$$F_4(\Theta,\Phi)=\cos^4\left(\frac{kh}{2}\cos\Theta\right)$$

$$F_N(\Theta,\Phi)=\cos^N\left(\frac{kh}{2}\cos\Theta\right)$$

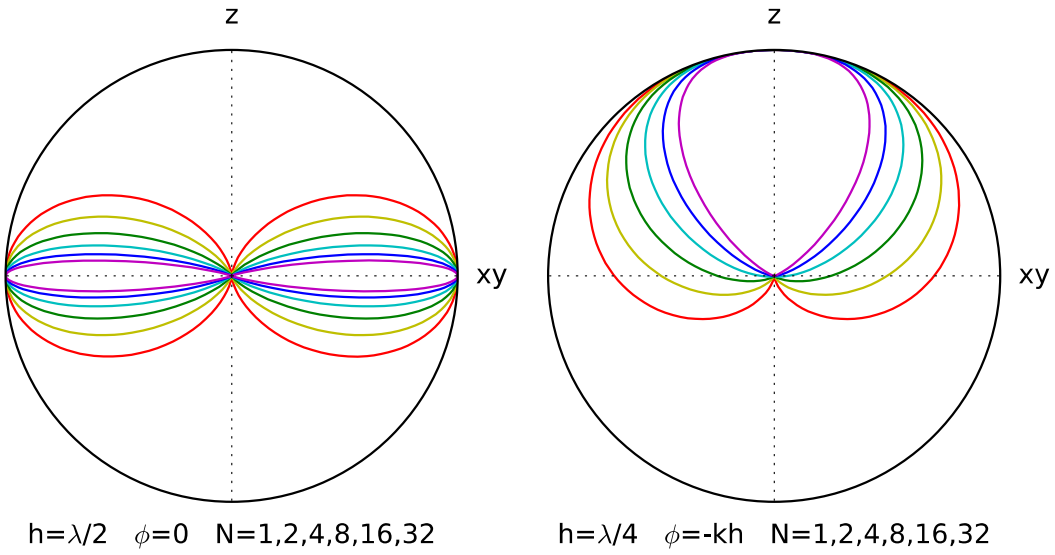
Binomska bočna skupina

Bočna binomska skupina

$$F_N(\Theta,\Phi)=\cos^N\left(\frac{kh}{2}\cos\Theta\right)$$

Osna binomska skupina

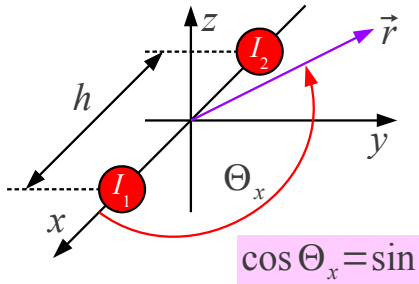
$$F_N(\Theta,\Phi)=\cos^N\left(\frac{kh}{2}(\cos\Theta-1)\right)$$



h=λ/2 ϕ=0 N=1,2,4,8,16,32 h=λ/4 ϕ=-kh N=1,2,4,8,16,32

Smerni diagrami binomskih skupin

$$F_S(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta_x\right)$$



$$\cos\Theta_x=\sin\Theta\cos\Phi$$

$$F_S(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\sin\Theta\cos\Phi\right)$$

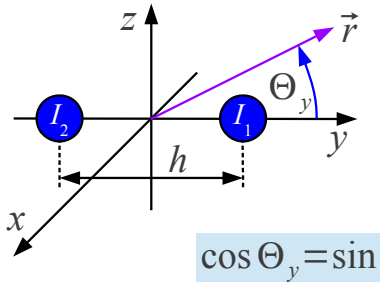
Polvalovni dipol v smeri x

$$F_D(\Theta,\Phi)=\frac{\cos\left(\frac{\pi}{2}\sin\Theta\cos\Phi\right)}{\sqrt{1-\sin^2\Theta\cos^2\Phi}}$$

$$\sin\Theta_x=\sqrt{1-\sin^2\Theta\cos^2\Phi}$$

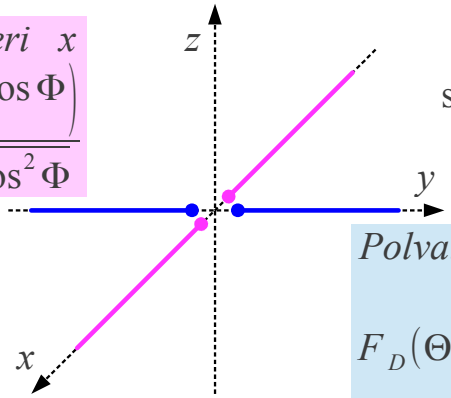
Obračanje anten

$$F_S(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\cos\Theta_y\right)$$



$$\cos\Theta_y=\sin\Theta\sin\Phi$$

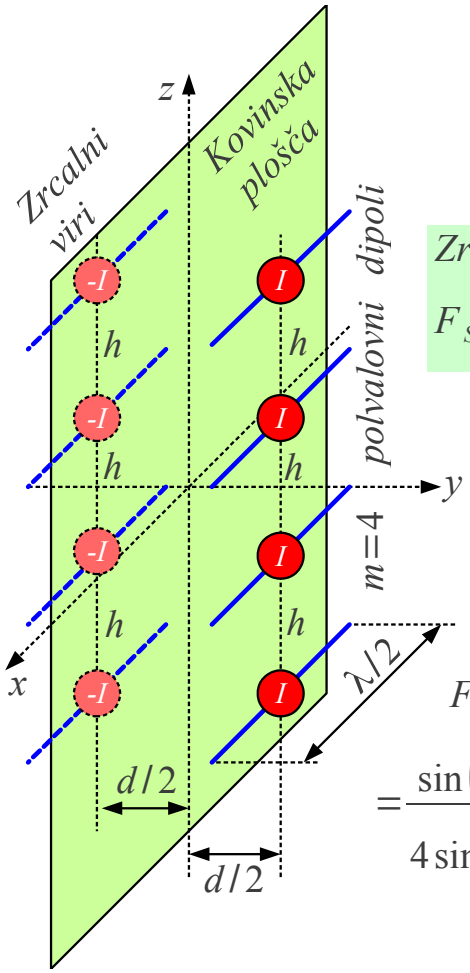
$$F_S(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kh}{2}\sin\Theta\sin\Phi\right)$$



$$\sin\Theta_y=\sqrt{1-\sin^2\Theta\sin^2\Phi}$$

Polvalovni dipol v smeri y

$$F_D(\Theta,\Phi)=\frac{\cos\left(\frac{\pi}{2}\sin\Theta\sin\Phi\right)}{\sqrt{1-\sin^2\Theta\sin^2\Phi}}$$



Polvalovni dipol v smeri osi x

$$F_E(\Theta,\Phi)=\frac{\cos\left(\frac{\pi}{2}\cos\Theta_x\right)}{\sin\Theta_x}=\frac{\cos\left(\frac{\pi}{2}\sin\Theta\cos\Phi\right)}{\sqrt{1-\sin^2\Theta\cos^2\Phi}}$$

Zrcaljenje v smeri osi y → $\phi=-\pi$

$$F_{S1}(\Theta,\Phi)=\cos\left(\frac{\phi}{2}+\frac{kd}{2}\cos\Theta_y\right)=\sin\left(\frac{kd}{2}\sin\Theta\sin\phi\right)$$

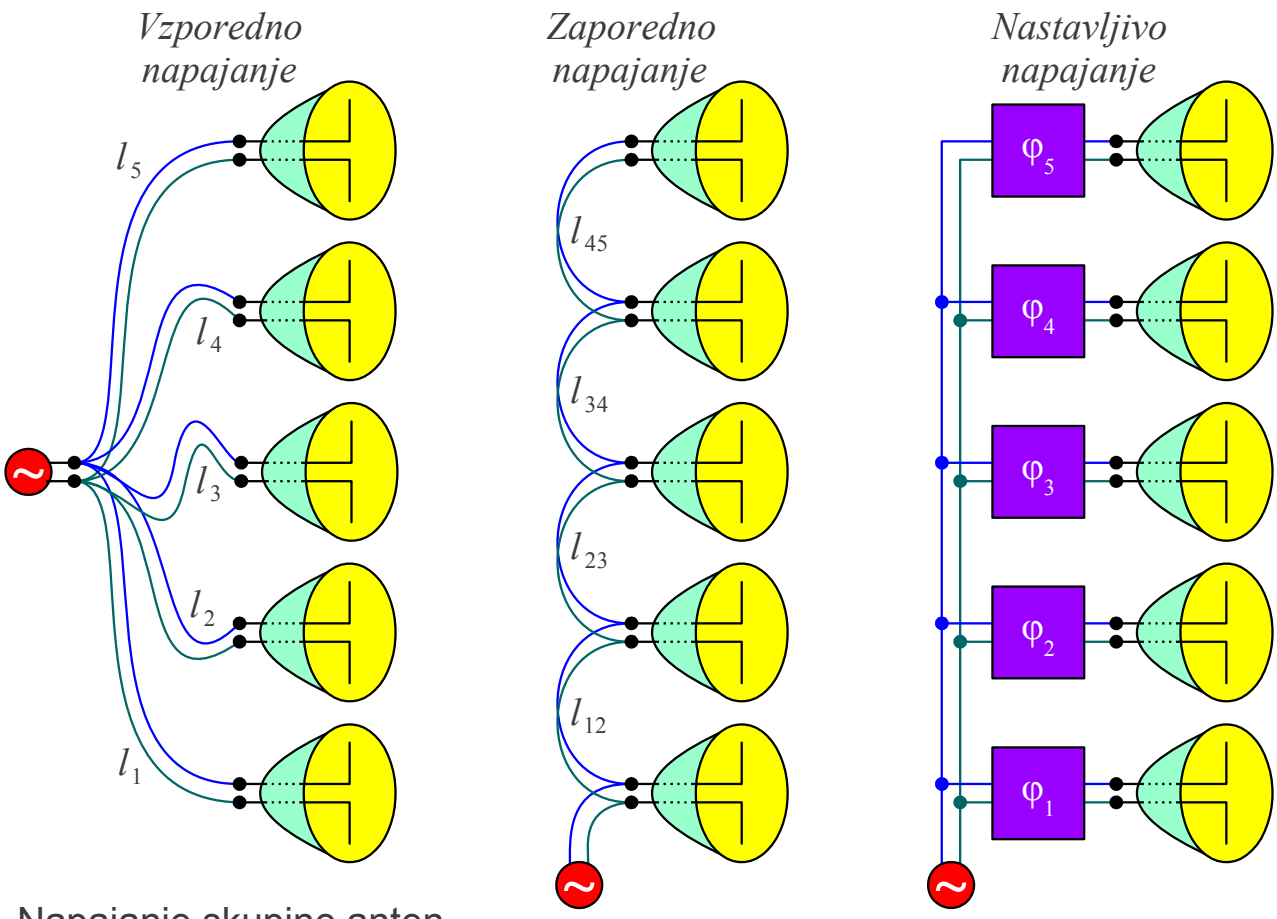
Enakomerna bočna skupina v smeri osi z

$$F_{S2}(\Theta,\Phi)=\frac{\sin\left(m\frac{kh}{2}\cos\Theta\right)}{m\sin\left(\frac{kh}{2}\cos\Theta\right)}=\frac{\sin\left(2\,kh\cos\Theta\right)}{4\sin\left(\frac{kh}{2}\cos\Theta\right)}$$

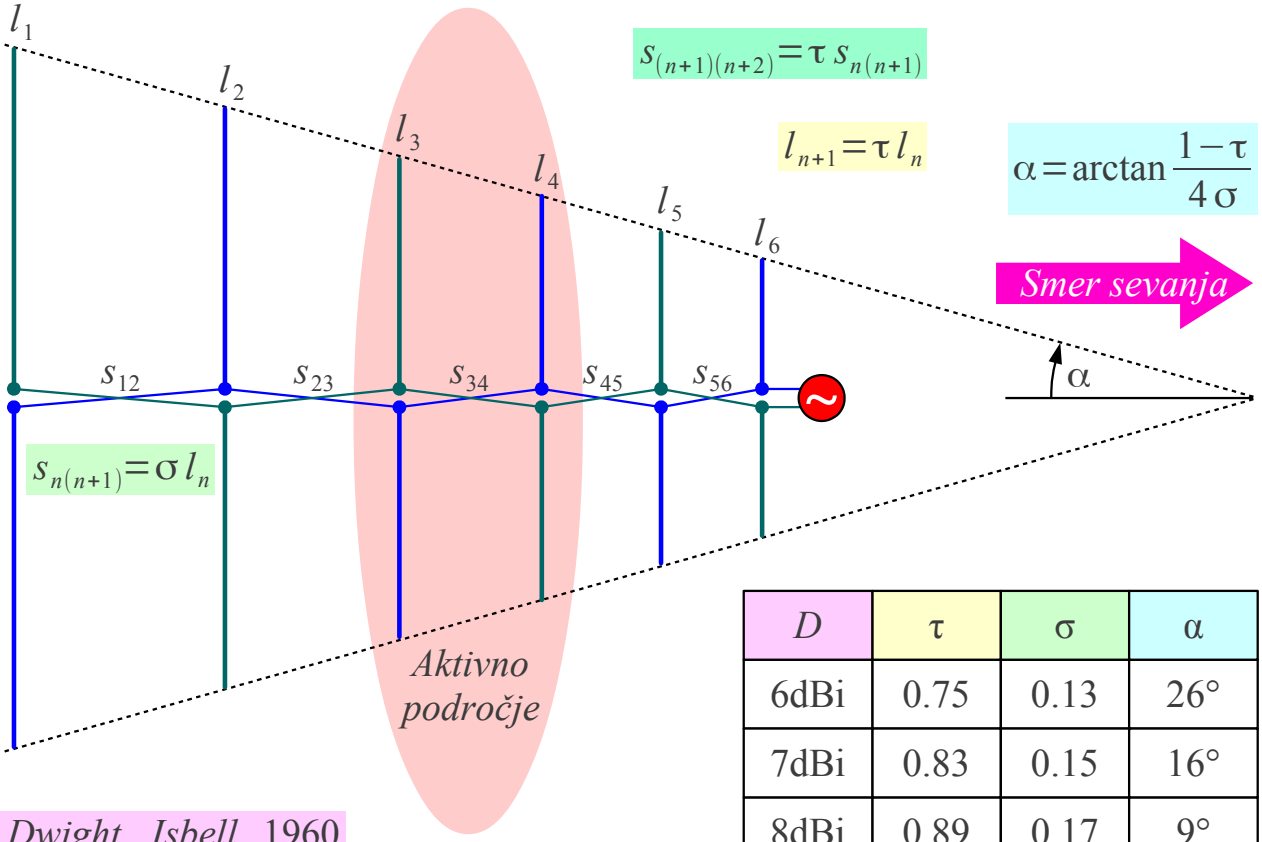
$$F(\Theta,\Phi)=F_{S2}(\Theta,\Phi)\cdot F_{S1}(\Theta,\Phi)\cdot F_E(\Theta,\Phi)=$$

$$=\frac{\sin\left(2\,kh\cos\Theta\right)}{4\sin\left(\frac{kh}{2}\cos\Theta\right)}\sin\left(\frac{kd}{2}\sin\Theta\sin\phi\right)\frac{\cos\left(\frac{\pi}{2}\sin\Theta\cos\Phi\right)}{\sqrt{1-\sin^2\Theta\cos^2\Phi}}$$

Sestavljanje skupin



Napajanje skupine anten



Dwight Isbell 1960

Logaritmično-periodična skupina dipolov

D	τ	σ	α
6dBi	0.75	0.13	26°
7dBi	0.83	0.15	16°
8dBi	0.89	0.17	9°
9dBi	0.94	0.19	5°

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