Fizica III – Electromagnetism

Aplicatii # 6 – Propagare neghidata. Radiatie. Antene.

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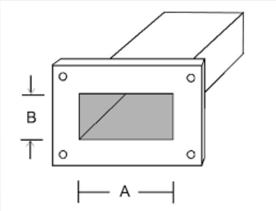
Propagare neghidata. Radiatie. Antene.

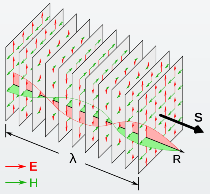
1. Concepte utile*
   - 1.1. Propagare neghidata. Radiatie. Antene.
   - 1.2. Sistem de 2 antene
   - 1.3. Principiul unui sistem de comunicatie radio
2. Experimente virtuale
3. Experiment real

*Pentru detalii vedeti cursul, cap 5 si cap6.

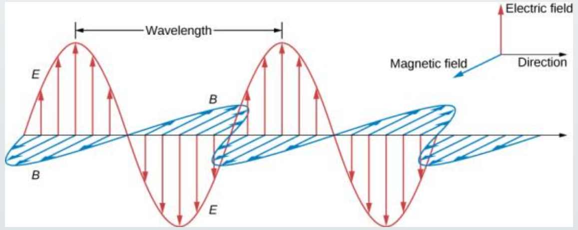
1. Concepte utile
1.1. a) Propagare neghidata

La P5 am studiat propagarea campului electromagnetic, **ghidat de linii** electrice.
Linia electrica poate fi inteleasa ca un circuit electric cu parametri distribuiti, caracterizabil local prin parametri lineici. Propagarea ghidata de-a lungul liniilor electrice este cel mai simplu mod de propagare a campului EM, ea poate fi modelata cu circuite cu parametri distribuiti si simulata in simulatoare de circuit, de tip SPICE.





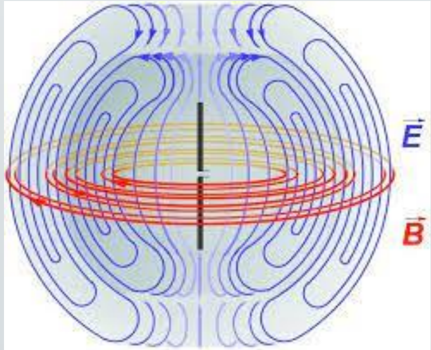
Propagarea campului EM in general poate fi
- Neghidata (in intreg spatiul)
- Ghidata de "ghiduri de unda"(nu neaparat linii)



In general, probleme de analiza a campului EM in regim general variabil sunt

- **Probleme de propagare** – in domenii nu exista surse interne de camp, campul EM se propaga in spatiul liber sau in domenii marginite de frontiere metalice (numite dispozitive de radio frecventa-RF sau de microunde-MW), datorita unor conditii initiale in domeniu, sau pe frontiera lui. Intereseaza modul in care campul se propaga.

- **Probleme de radiatie** – in domenii exista surse de camp – antene (de emisie). O unda EM poate fi si receptata de antena (prin curentii care se induc in ea, antenna fiind acum de receptie) sau poate fi reflectata (imprastiata) de diferite obiecte (de exemplu in radar), acest din urma caz nu face obiectul acestui curs.



1. Concepte utile
1.1. a) Propagare neghidata

- **Dielectric cu pierderi** = un dielectric in care unda EM isi pierde din putere pe masura ce se propaga, datorita de exemplu unor proprietati de conductie (slabe) ale mediului. $\sigma \neq 0$.
- **Dielectric fara pierderi**: $\sigma = 0$

Ipoteze de studiu: 1) mediu liniar, omogen, izotrop, neelectrizat

Materiale liniare din toate punctele de vedere: electric (ε), magnetic (μ), conductie (σ)

Proprietatile de material nu depind de punctul din spatiu, sunt aceleasi in toate punctele domeniului de stiudiu.

Proprietatile de material nu depend de directia campului. Constantele de material sunt scalari, nu tensori.

$\rho = 0$

2) Vom presupune un regim armonic permanent (r.a.p), de pulsatie ω

1. Concepte utile
1.1. a) Propagare neghidata

Ecuatii de ordinul I

$$\nabla \cdot \underline{\vec{E}} = 0 \qquad (1)$$

$$\nabla \cdot \underline{\vec{H}} = 0 \qquad (2)$$

$$\nabla \times \underline{\vec{E}} = -j\omega\mu\underline{\vec{H}} \qquad (3)$$

$$\nabla \times \underline{\vec{H}} = (\sigma + j\omega\varepsilon)\underline{\vec{E}} \qquad (4)$$

Ecuatii de ordinul II – in E sau H (ambele sunt de tip Helmholtz complex)

$$\Delta\,\underline{\vec{E}} - j\,\omega\,\mu(\sigma + j\omega\varepsilon)\underline{\vec{E}} = 0$$

$$\Delta\,\underline{\vec{E}} - \underline{\gamma}^2\,\underline{\vec{E}} = 0 \qquad (**E)$$

$$\Delta\,\underline{\vec{H}} - j\,\omega\,\mu(\sigma + j\omega\varepsilon)\underline{\vec{H}} = 0$$

$$\Delta\,\underline{\vec{H}} - \underline{\gamma}^2\,\vec{H} = 0 \qquad (**H)$$

$\underline{\vec{E}}$ si $\underline{\vec{H}}$ satisfac ecuatii identice de ordinul II, dar ele nu sunt independente, ci legate prin relatii de ordinul I.
*In rezolvare, se alege una din ecuatiile de ordinul II care se rezolva (de exemplu (**E)) iar cealalta marime se determina dintr-o ecuatie de ordinul I (de exemplu (3)).*

$\underline{\gamma}$ constanta de propagare complexa.

$$\underline{\gamma} = \sqrt{j\,\omega\,\mu\,(\sigma + j\,\omega\,\varepsilon)}$$

$$\underline{\gamma} = \alpha + j\,\beta$$

$\alpha = \mathrm{Real}\,(\gamma) > 0$ factor de atenuare [Np/m]

$\beta = \mathrm{Imag}\,(\gamma) > 0$ constanta de faza (numar de unda) [rad/m]

1. Concepte utile
1.1. a) Propagare neghidata

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α si β se pot calcula in functie de parametrii de material si frecventa:

α si β depinde de frecventa (prin ω explicit dar si proprietatile de material pot depinde de frecventa – materialele se numesc in acest caz "dispersive")

$$\alpha = \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[-1 + \sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2}\right]}$$

$$\beta = \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[+1 + \sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2}\right]}$$

OBS: daca $\sigma = 0$ atunci $\alpha = 0$

Similar cu

Obs: la linii in r.a.p. constanta de propagare complexa era

$$\underline{\gamma} = \sqrt{(R_l + j\,\omega\,L_l)\,(G_l + j\,\omega\,C_l)}$$

$L_l \sim \mu$

$G_l \sim \sigma$

$C_l \sim \varepsilon$

$R_l \sim$ Nu are correspondent, la linii e legat de conductorul care ghideaza

α si β se pot calcula in functie de parametrii lineici si de frecventa:

$$\alpha = \sqrt{\frac{1}{2}\left[R_l\,G_l - \omega^2 L_l C_l + \sqrt{(R_l\,G_l - \omega^2 L_l C_l)^2 + \omega^2 (L_l G_l + R_l C_l)^2}\right]}$$

$$\beta = \sqrt{\frac{1}{2}\left[-R_l\,G_l + \omega^2 L_l C_l + \sqrt{(R_l\,G_l - \omega^2 L_l C_l)^2 + \omega^2 (L_l G_l + R_l C_l)^2}\right]}$$

OBS: daca $R_l = 0$ si $G_l = 0$ atunci $\alpha = 0$

Intr-un mediu fara pierderi, undele se propaga fara atenuare.

1. Concepte utile
1.1. a) Propagare neghidata

- **Unda plana** = unda care depinde de o singura coordonata spatiala (de exemplu z) si de timp.

Obs: 1) Coordonata spatiala este cea de-a lungul careia are loc propagarea; 2) Intr-un plan perpendicular pe coordonata spatiala de care depinde, unda are aceeasi valoare la un moment de timp fixat.)

Undele plane nu exista in realitate (ar trebui generate de plane infinit extinse parcurse de curenti). Ele sunt importante pentru ca sunt simple si pot fi folosite ca aproximatii ale undelor reale la distante sufficient de departate de sursele care le genereaza - antene.

$$\vec{E}(x,y,z,t) = \vec{E}_x(x,y,z,t)\vec{\imath} + \vec{E}_y(x,y,z,t)\vec{\jmath} + \vec{E}_z(x,y,z,t)\vec{k}$$

Unda plana: $\vec{E}(z,t) = \vec{E}_x(z,t)\vec{\imath} + \vec{E}_y(z,t)\vec{\jmath} + \vec{E}_z(z,t)\vec{k}$

Unda plana in r.a.p – reprezentare in complex: $\underline{\vec{E}}(z) = \underline{E_x}(z)\vec{\imath} + \underline{E_y}(z)\vec{\jmath} + \underline{E_z}(z)\vec{k}$

Sa presupunem ca unda are doar componenta dupa directia Ox: $\underline{\vec{E}}(z) = \underline{E_x}(z)\vec{\imath}$

- **Polarizarea unei unde EM** = are legatura cu directia campului electric.

Unda polarizata liniar dupa Ox.

1. Concepte utile

1.1. a) Propagare neghidata

Ecuatiile si solutiile sunt similare cu cele de la linii, cu E si H in loc de u si i.

Unda plana polarizata dupa Ox:

$$\vec{\underline{E}}(z) = \underline{E}_x(z)\vec{\imath}$$

$$\Delta\vec{\underline{E}} - \underline{\gamma}^2\vec{\underline{E}} = 0$$

$$\Delta\vec{\underline{E}} = \Delta\,\underline{E}_x(z)\vec{\imath} = \left(\frac{\partial^2\underline{E}_x(z)}{\partial x^2} + \frac{\partial^2\underline{E}_x(z)}{\partial y^2} + \frac{\partial^2\underline{E}_x(z)}{\partial z^2}\right)\vec{\imath} = \frac{\mathrm{d}^2\underline{E}_x(z)}{\mathrm{d}^2 z}\vec{\imath}$$

$$\frac{\mathrm{d}^2\underline{E}_x(z)}{\mathrm{d}z^2}\vec{\imath} - \underline{\gamma}^2\underline{E}_x(z)\vec{\imath} = 0 \Rightarrow \boxed{\frac{\mathrm{d}^2\underline{E}_x(z)}{\mathrm{d}z^2} - \underline{\gamma}^2\underline{E}_x(z) = 0}$$

Ec.Helmholtz scalara complexa

$$\underline{E}_x(z) = \underline{C}_1 e^{-\underline{\gamma}z} + \underline{C}_2 e^{+\underline{\gamma}z}$$

$$\underline{E}_x(z) = \underline{E}_d(z) + \underline{E}_i(z)$$

$\underline{C}_1$ si $\underline{C}_2$ sunt constante de integrare care se determina din datele problemei

Si campul magnetic se determina din rel. de ord.I

$$\nabla \times \vec{\underline{E}} = -j\omega\mu\vec{\underline{H}} \Rightarrow \vec{\underline{H}}(z) = \underline{H}_y(z)\vec{\jmath}$$

Unda plana este TEM (transveral electromagnetica)!

$$\underline{H}_y(z) = \frac{1}{\underline{Z}_c}\left(\underline{E}_d(z) - \underline{E}_i(z)\right)$$

$$\boxed{\underline{Z}_c = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}}$$

Impedanța caracteristică complexă **a mediului**

$$\underline{Z}_c = \frac{\underline{E}_d}{\underline{H}_d} = -\frac{\underline{E}_i}{\underline{H}_i}$$

Raport de componente directe!

La linii am rezolvat ecuatia de gradul II

$$\boxed{\frac{\mathrm{d}^2\underline{U}(z)}{\mathrm{d}z^2} = \underline{\gamma}^2\underline{U}(z)}$$

$$\underline{U}(z) = \underline{C}_1 e^{-\underline{\gamma}z} + \underline{C}_2 e^{+\underline{\gamma}z}$$

$$\underline{U}(z) = \underline{U}_d(z) + \underline{U}_i(z)$$

unda elementara directa de tensiune = $\underline{U}_d(z)$

unda elementara inversa de tensiune = $\underline{U}_i(z)$

Si curentul a fost determinat din rel. de ord.I

$$-\frac{\mathrm{d}\underline{U}(z)}{\mathrm{d}z} = (R_l + j\omega L_l)\,\underline{I}(z)$$

$$\underline{I}(z) = \frac{1}{\underline{Z}_c}\left(\underline{U}_d(z) - \underline{U}_i(z)\right)$$

$$\underline{Z}_c = \frac{\underline{U}_d}{\underline{I}_d} = -\frac{\underline{U}_i}{\underline{I}_i}$$

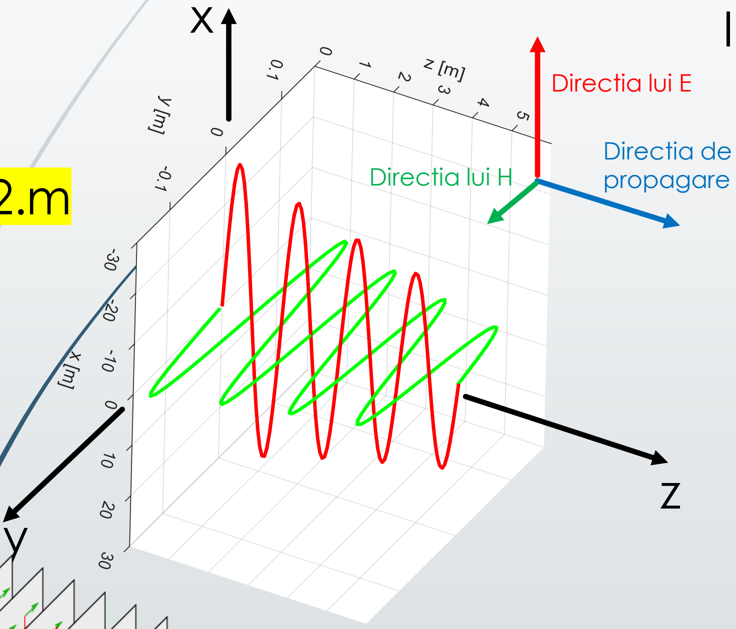
Impedanța caracteristică complexă **a liniei**

$$\boxed{\underline{Z}_c = \sqrt{\frac{R_l + j\omega L_l}{G_l + j\omega C_l}}}$$

1. Concepte utile
1.1. a) Propagare neghidata

$$E_x(z,t) = E_0 e^{-\alpha z}\sqrt{2}\,\sin(\omega t - \beta z + \varphi_0)$$

demo2.m



In general, pentru o unda plana

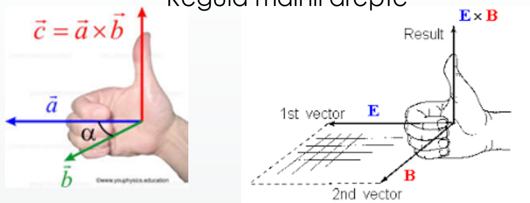
$$\boxed{\overline{u}_E \times \overline{u}_H = \overline{u}_{\text{propagare}}}$$

directia campului electric

directia campului magnetic

directia de propagare

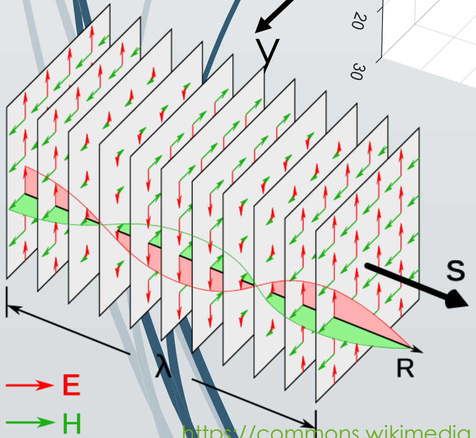
Regula mainii drepte



La T. energiei am definit

$$\vec{E} \times \vec{H} = \vec{S}$$

Directia vectorului Poynting indica directia de propagare a undei.



https://commons.wikimedia.org/wiki/File:Plane_electromagnetic_wave.svg

Modul de propagare a undei plane este **TEM – transversal electromagnetic**.

Unda plana

in **plane** perpendiculare pe directia de propagare, **campurile sunt uniforme**!

TEM

campul electric este perpendicular pe directia de propagare $\overline{u}_E \perp \overline{u}_{\text{propagare}}$

si

campul magnetic este perpendicular pe directia de propagare $\overline{u}_H \perp \overline{u}_{\text{propagare}}$

1. Concepte utile
1.1. a) Propagare neghidata

Cazuri particulare:

a1) **In medii fara pierderi**: $\sigma = 0,\ \varepsilon = \varepsilon_0 \varepsilon_r,\ \mu = \mu_0 \mu_r$

$$\underline{\gamma} = \sqrt{(j\omega\mu)(\sigma + j\omega\varepsilon)} = \sqrt{-\omega^2 \mu\varepsilon} = j\ \omega\ \sqrt{\mu\varepsilon}$$

$$\underline{\gamma} = \alpha + j\beta$$

$\alpha = 0$ Nu exista atenuare

$$\beta = \omega\ \sqrt{\mu\varepsilon}$$

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}}$$

Daca parametrii mediului nu depind de frecventa, atunci viteza de propagare nu depinde de frecventa. => Semnalele se propaga fara distorsiuni (toate armonicele se propaga cu aceeasi frecventa).

$$\underline{Z}_c = \sqrt{\frac{j\ \omega\mu}{\sigma + j\ \omega\varepsilon}} = \sqrt{\frac{\mu}{\varepsilon}} \in \mathrm{R}\ ;\ \underline{Z}_c \overset{\text{not}}{=} Z_0 \qquad \theta = 0$$

Impedanta caracterstica este un numar real.

Campul magnetic e in faza cu campul electric.

$\sim$

a) **Linia fara pierderi** $(R_l = 0; \mathrm{G}_l = 0)$

$$\underline{\gamma} = \sqrt{(R_l + j\omega L_l)(G_l + j\omega C_l)} = \sqrt{-\omega^2 L_l C_l} = j\ \omega\ \sqrt{L_l C_l}$$

$$\underline{\gamma} = \alpha + j\beta$$

$\alpha = 0$ Nu exista atenuare

$$\beta = \omega\ \sqrt{L_l C_l}$$

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{L_l C_l}}$$

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Impedanta caracterstica este un numar real.

1. Concepte utile
1.1. a) Propagare neghidata

Cazuri particulare:

a2) **In vid**: $\sigma = 0,\ \varepsilon = \varepsilon_0,\ \mu = \mu_0$

$$c = \frac{1}{4\,\pi\,10^{-7} \cdot 8.854 \cdot 10^{-12}} = 2.9979 \cdot 10^8 \approx 3 \cdot 10^8 \text{ m/s}$$

Viteza de propagare a luminii in vid.

Lumina este o unda electromagnetica.

In cazul anterior $\varepsilon_r = 1, \mu_r = 1$

$\alpha = 0$ Nu exista atenuare

$$\beta = \omega\,\sqrt{\mu_0 \varepsilon_0}$$

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \triangleq c$$

$$\underline{Z}_c = \sqrt{\frac{\mu_0}{\varepsilon_0}} \in \mathrm{R}\,;\ \underline{Z}_c \overset{\text{not}}{=} Z_0$$

Impedanta caracterstica este un numar real.

$$\theta = 0$$

Campul magnetic e in faza cu campul electric.

$$Z_0 = \sqrt{\frac{4\,\pi\,10^{-7}}{8.854 \cdot 10^{-12}}} \approx 377\ \Omega$$

Impedanta vidului.

$50\ \Omega$

Impedanta tipica a cablurilor.

Obs: in dielectrici fara pierderi

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\ \varepsilon_r}} < c$$

$\mu_r = 1$ (medii nemagnetice)
$\varepsilon_r > 1$ (medii dielectrice, nu vid)

$$\frac{c}{v} \overset{\text{def}}{=} n = \sqrt{\mu_r \varepsilon_r}$$

Indicele de refactie al unui mediu.

1. Concepte utile
1.1. a) Propagare neghidata

Cazuri particulare:

b) **In conductoare foarte bune**: $\sigma \neq 0, \sigma \gg \omega \varepsilon$

$$\alpha = \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[-1+\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}\right]} \approx \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[-1+\sqrt{\left(\frac{\sigma}{\omega\varepsilon}\right)^2}\right]} \approx \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[-1+\frac{\sigma}{\omega\varepsilon}\right]} \approx \omega\sqrt{\frac{\mu\,\varepsilon}{2}\frac{\sigma}{\omega\varepsilon}} = \sqrt{\frac{\omega\mu\,\sigma}{2}}$$

$$\boxed{\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}}}$$

$$\boxed{v = \frac{\omega}{\beta} = \sqrt{\frac{2\,\omega}{\mu\,\sigma}}}$$

Depinde de frecventa

$$\beta = \omega\sqrt{\frac{\mu\,\varepsilon}{2}\left[+1+\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}\right]} \approx \sqrt{\frac{\omega\mu\,\sigma}{2}}$$

Adancimea de patrundere in conductoare foarte bune:

$$\boxed{\delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}}}$$

$$\underline{Z}_c = \sqrt{\frac{j\,\omega\mu}{\sigma + j\,\omega\varepsilon}} \qquad Z_c = \left|\underline{Z}_c\right| = \sqrt{\frac{\omega\mu}{\sqrt{\sigma^2+(\omega\varepsilon)^2}}} \approx \sqrt{\frac{\omega\mu}{\sigma}}$$

$$2\theta = \frac{\pi}{2} - \operatorname{atan}\frac{\omega\,\varepsilon}{\sigma} \approx \frac{\pi}{2} \Rightarrow \theta = \frac{\pi}{4}$$

Campul magnetic e defazat in urma campului electric cu $\pi/4$.

1. Concepte utile
1.1. a) Propagare neghidata

Important!

Comportarea unui material in camp electromagnetic nu depinde numai de proprietatile lui electrice (ε), magnetice (μ) sau de conductie (σ) ci si de frecventa la care este folosit (ω).

$$\operatorname{tg}\delta = \frac{\sigma}{\omega\varepsilon} \gg 1$$

Materialul este un conductor foarte bun

$$\operatorname{tg}\delta = \frac{\sigma}{\omega\varepsilon} \ll 1$$

Materialul poate fi considerat fara pierderi.

1. Concepte utile
1.1. a) Propagare neghidata

- **Polarizarea unei unde plane** = se refera la modul de variatie in timp a directiei campului electric, mai precis la locul geometric al varfului vectorului $\vec{E}(z,t)$, vazut pe un plan perpendicular pe directia de propagare (front de unda).

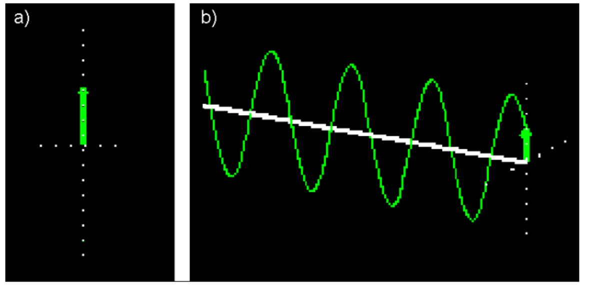
Poate fi: **liniara**, **circulara**, **eliptica**

- varful vectorului $\vec{E}$ descrie (in timp) un segment/cerc/elipsa intr-un plan perpendicular pe directia de propagare (frontul undei).

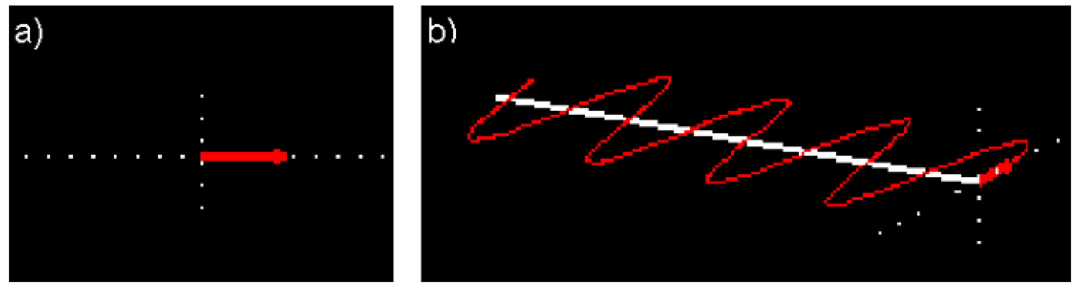
Pentru a putea comunica, doua antene trebuie sa produca unde polarizate similar.

radio AM (Vpol), radio FM (Vpol, Cpol, sau Epol), WiFi (Vpol), GPS (RHCP).

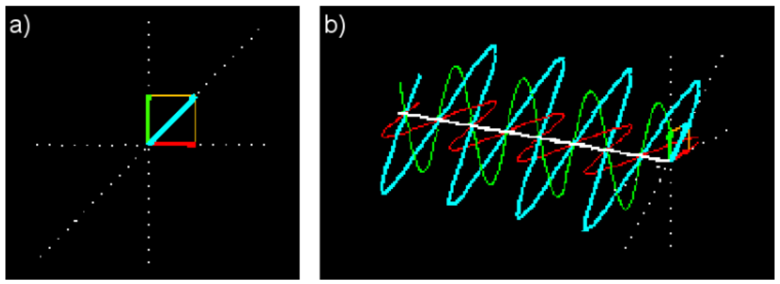
Polarizare liniara



Polarizare liniara - verticala
(folosita in radio AM si in WiFi)



Polarizare liniara - orizontala
(folosita la TV)



Polarizare liniara - oblica

Aici obtinuta din superpozitia a doua unde polarizate liniar (una verticala si una orizontala), de aceeasi frecventa, care sunt in faza si au aceeasi amplitudine (=> unghi de 45 de grade)

Vedeti animatii la https://shopdelta.eu/wave-polarisation_l2_aid893.html

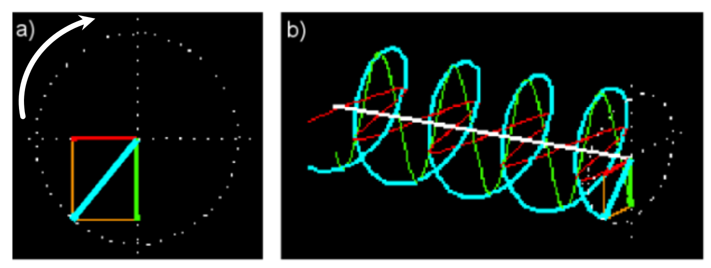
1. Concepte utile
1.1. a) Propagare neghidata

$$\overline{E}(z,t) = E_1 \sin(\omega t - \beta z)\,\overline{i} + E_2 \sin(\omega t - \beta z + \Phi)\,\overline{j}$$

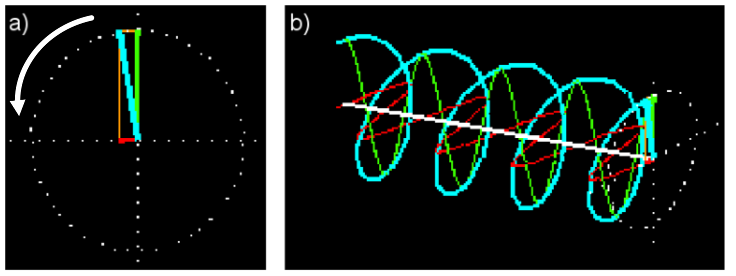
daca $\Phi = 0$ sau $\Phi = \pi$ **atunci**
$\overline{E}$ este polarizata liniar
altfel
daca $\Phi = \pm\frac{\pi}{2}$ si $E_1 = E_2$ **atunci**
$\overline{E}$ este polarizata circular
altfel
$\overline{E}$ este polarizata eliptic
*
*

Daca cele doua unde sunt in faza, polarizarea este liniara, verticala pentru E2=0, orizontala cand E1=0 si oblica atunci cand E1>0, si E2>0, diferite. In cazul general, eliptic, defazajul este nenul, polarizarea devine circulara cand E1=E2 si defazajul este de 90 grade (cele doua unde polarizate liniar de amplitudine egala sunt in cuadratura atat spatial cat si temporal).

Polarizare circulara

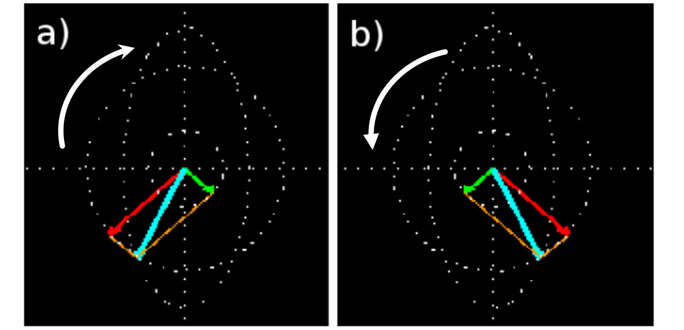


Left handed circular polarized
(LHCP)



Right handed circular polarized
(RHCP)
(folosite in GPS)

Polarizare eliptica
(folosita des in radio FM)



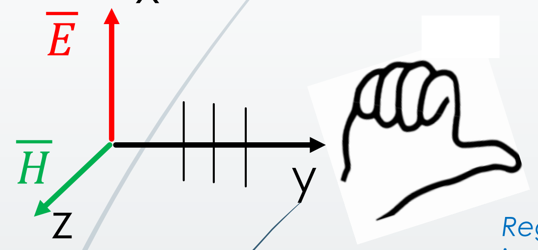
Left handed Right handed

In figurile 2D - directia de propagare iese din foaie.
Luati mana dreapta astfel incat degetul mare deschis la 90 de grade (fata de celelalte degete intinse) sa indice directia de propagare (indreptat spre dvs). Indoiti celelalte 4 degete, varful lor indica directia de rotatie pentru cazul RHCP (trigonometric).

Vedeti animatii la https://shopdelta.eu/wave-polarisation_l2_aid893.html

1. Concepte utile
1.1. a) Propagare neghidata - puteri

Unda plana polarizata liniar care se propaga dupa directia pozitiva a axei Oz (e o unda directa):



$\hat{x} \times \hat{y} = \hat{z}$

$$\overline{E}(z,t) = E_{xd}(z,t)\ \hat{x}$$

$$\overline{H}(z,t) = H_{xd}(z,t)\ \hat{y}$$

Regula mainii drepte poate fi folosita pentru a indica directia de transfer a puterii.

Vectorul Poynting

$$\overline{S}(z,t) = \overline{E} \times \overline{H} = E_{xd}(z,t) H_{xd}(z,t)\ \hat{z} = S(z,t)\hat{z}$$

Indica sensul transferului de energie.
Modulul lui reprezinta puterea transmisa de unda pe unitatea de arie, este deci o **densitate de putere**. [W/m²]

<u>Intr-un mediu fara pierderi.</u>

Campul electric si campul magnetic sunt in faza.
Nu exista atenuare. (In realitate, undele EM se atenueaza datorita raspandirii lor in spatiu, ele avand un front sferic si nu plan).
Impedanta caracteristica este un numar real.

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}} \qquad Z_0 = \frac{E_{xd}(z,t)}{H_{xd}(z,t)} \qquad \forall\, z, \forall t$$

Viteza de propagare a undei este $v = \dfrac{1}{\sqrt{\mu\varepsilon}}$

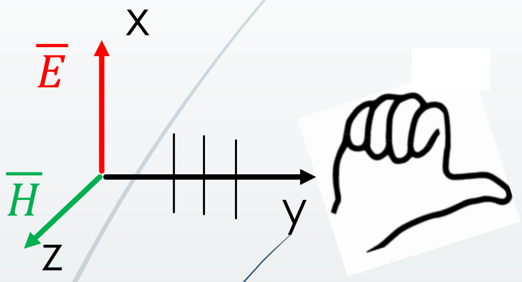
$$\boxed{S(z,t) = \frac{E_{xd}^2(z,t)}{Z_0} = Z_0\, H_{xd}^2\,(z,t)} = \sqrt{\frac{\varepsilon}{\mu}}\, E_{xd}^2(z,t) = \sqrt{\frac{\mu}{\varepsilon}}\, H_{xd}^2(z,t) = \frac{2}{\sqrt{\mu\varepsilon}} \frac{\varepsilon E_{xd}^2(z,t)}{2} = \frac{2}{\sqrt{\mu\varepsilon}} \frac{\mu\, H_{xd}^2(z,t)}{2} = 2\, v w_e = 2 v w_m$$

$$\Rightarrow w_e(z,t) = w_m(z,t) \Rightarrow w(z,t) = 2w_e(z,t) = 2w_m(z,t) \Rightarrow \boxed{S(z,t) = v\, w(z,t)}$$

Unda plana, intr-un mediu fara pierderi, e tot timpul la rezonanta.

Densitatea de energie totala.

1. Concepte utile
1.1. a) Propagare neghidata - puteri



$\hat{x} \times \hat{y} = \hat{z}$

Regula mainii drepte poate fi folosita pentru a indica directia de transfer a puterii.

Intr-un mediu cu pierderi.

Rationamentul se face in r.a.p.

$\underline{\overline{S}} = \underline{\overline{E}} \times \underline{\overline{H}}^*$ Marimile depind de z.

$$\underline{\overline{E}}(z) = \underline{E}_0\, e^{-\underline{\gamma} z}\, \hat{x} = \underline{Z}_c \underline{H}_0\, e^{-\underline{\gamma} z}\, \hat{x}$$

$$\underline{\overline{H}}(z) = \frac{\underline{E}_0}{\underline{Z}_c}\, e^{-\underline{\gamma} z}\, \hat{y} \Rightarrow \underline{\overline{H}}^*(z) = \frac{\underline{E}_0^*}{\underline{Z}_c^*}\, e^{-\underline{\gamma}^* z}\, \hat{y} = \underline{H}_0^*\, e^{-\underline{\gamma}^* z}\, \hat{y}$$

$$\underline{\overline{S}} = \underline{\overline{E}} \times \underline{\overline{H}}^* = \underline{E}_0\, e^{-\underline{\gamma} z}\, \frac{\underline{E}_0^*}{\underline{Z}_c^*}\, e^{-\underline{\gamma}^* z}\, \hat{k} = \underline{S}\hat{k}$$

$$\underline{\overline{S}} = \underline{\overline{E}} \times \underline{\overline{H}}^* = \underline{Z}_c \underline{H}_0 e^{-\underline{\gamma} z}\, \underline{H}_0^*\, e^{-\underline{\gamma}^* z}\, \hat{k} = \underline{S}\hat{k}$$

$$\underline{S}(z) = \frac{\underline{E}_0 \underline{E}_0^*}{\underline{Z}_c^*} e^{-(\underline{\gamma}+\underline{\gamma}^*)z} = \frac{E_0^2}{\underline{Z}_c^*} e^{-2\,\alpha z}$$

$$\underline{S}(z) = \underline{Z}_c \underline{H}_0 \underline{H}_0^* e^{-(\underline{\gamma}+\underline{\gamma}^*)z} = \underline{Z}_c\, H_0^2\, e^{-2\,\alpha z}$$

Pentru a afla media pe o perioada a densitatii de putere transmise:

$$\boxed{\widetilde{S(z,t)}^T = \frac{1}{T}\int_0^T S(z,t)\ \mathrm{d}t = \mathrm{Real}\,(\underline{S}(z))}$$

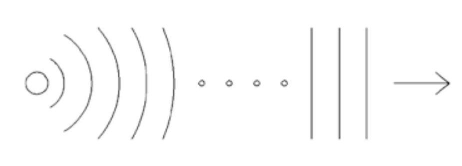
1. Concepte utile
1.1. a) Propagare neghidata - ex.1

1) Campul electric (unda sferica) produs de o statie de baza dintr-o retea de telefonie mobila.

Sa presupunem ca o statie de baza dintr-o retea de telefonie mobila are o putere de emisie de P=10 kW. Vom estima valoarea maxima a intensitatii campului electric la o distanta de 1 metru de antena (de fapt valorea medie a acestei marimi pe sfera de raza 1metru).

Pp. ca mediul este vid (fara pierderi, de impedanta $Z_0 = 377\ \Omega$) si presupunem ca sursa emite izotrop (la fel in toate directiile), produce o unda sferica. In aceste conditii puterea transmisa de antena trebuie sa se regaseasca pe o sfera de raza r, centrata in antena. Fiind unda sferica, directia de propagare este radiala, si datorita simetriei, valoarea densitatii de putere este aceeasi pe sfera.

$$P = P(r) = -\oint_{\Sigma} \bar{S} \cdot \bar{n}\ dA = \mathrm{S}_{\mathrm{mediu}}(\mathrm{r})\ 4\ \pi r^2 \;\Rightarrow\; S_{\mathrm{mediu}}(r) = S(r) = \frac{P}{4\ \pi r^2} \quad \left[\frac{W}{m^2}\right]$$



Aproximand local unda sferica cu o unda plana, putem estima modulul intensitatii campului electric

Atunci

$$S = \frac{E^2}{Z_0}$$ unde E este valoare efectiva $\Rightarrow$ $$S(r) = \frac{E_{\max}^2(r)}{2\ Z_0} \;\Rightarrow\; E_{\max}(r) = \sqrt{2\ Z_0\ S(r)} = \sqrt{Z_0 \frac{P}{2\ \pi r^2}}$$

$$E_{\max}(1) = \sqrt{377\ \frac{10^4}{2\ \pi}} = 775 \quad [\mathrm{V/m}]$$

$$E_{\max}(1000) = \sqrt{377\ \frac{10^4}{2\ \pi\ 10^6}} = 775 \quad [\mathrm{mV/m}]$$

1. Concepte utile
1.1. a) Propagare neghidata-ex.2

2) Campul electric produs de un telefon mobil.

Sa presupunem ca un telefon mobil are o putere de emisie de P = 1W. Vom estima valoarea maxima a intensitatii campului electric la o distanta de 10 cm de telefon (de fapt valorea medie a acestei marimi pe sfera de raza 10 cm).

Am putea sa reluam ipotezele si calculul din exemplu anterior. Rezultatul ar fi

$$E_{\max}(r) = \sqrt{2\,Z_0\,S(r)} = \sqrt{Z_0 \frac{P}{2\,\pi r^2}}$$

$$E_{\max}(0.1) = \sqrt{377\,\frac{1}{2\,\pi\,0.01}} = 77.5 \quad \text{[V/m]}$$

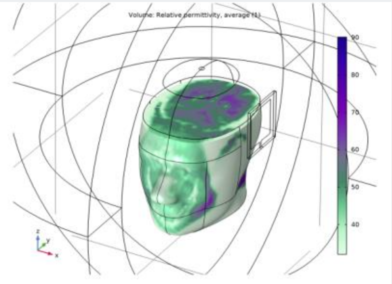


Figure 1: This plot shows how the average relative permittivity varies inside the head. The permittivity is calculated from the imported MRI image data.

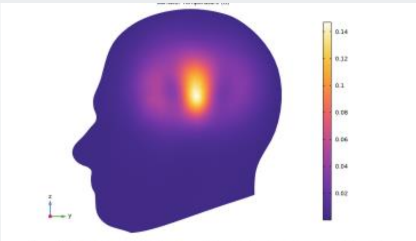


Figure 3: The local increase in temperature at the surface has the maximum right beneath the antenna.

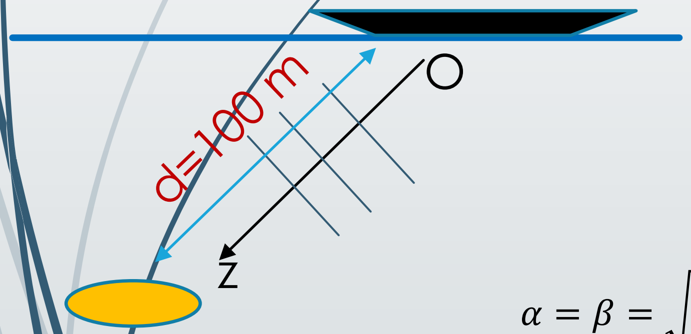
https://www.comsol.com/model/download/1093691/models.rf.sar_in_human_head.pdf

In realitate un astfel de model nu este potrivit la o distanta mica de antena, nu putem presupune mediul omogen si fara pierderi, nici aproximatia de unda plana nu este potrivita.
Pentru a calcula campul EM intr-un astfel de scenario, trebuie folosite model numerice care sa include tipul de radiatie al antenei si forma si proprietatile EM ale capului.

1. Concepte utile
1.1. a) Propagare neghidata-ex.3

3) Comunicarea dintre un vapor si un submarin.

Sa presupunem ca un submarin se afla scufundat la 100 m fata de un vapor aflat pe mare. Personalul aflat pe vapor doreste sa comunice cu submarinul, folosind frecventa $f = 3\,\mathrm{kHz}$. Sa se calculeze puterea (densitatea pe unitatea de suprafata) necesara emitatorului (pe vapor) astfel inca receptorul (submarin) sa primeasca un semnal cu o amplitudine de minimum $E_{\min} = 1\mu\mathrm{V/m}$.



Este necesara folosirea unor frecvente mici pentru comunicare deoarece apa marii este conductoare. Tangenta unghiului de pierderi este

$$\operatorname{tg}\delta_c = \frac{\sigma}{\omega\,\varepsilon} \approx 10^5 \gg 1$$

Apa marii poate fi considerate foarte bun conductor, chiar si la aceasta frecventa forte mica.

Vom folosi formulele demonstrate la conductoarele foarte bune (sectiunea 5.3.).

Proprietatile apei de mare

$\sigma = 4\,\mathrm{S/m}$, $\varepsilon_r = 81, \mu_r = 1$

$$\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}} \approx 0.2$$

$$\lambda = \frac{2\,\pi}{\beta} = 29\ \mathrm{m}$$

$$\delta = \frac{1}{\alpha} = 4.6\ \mathrm{m}$$

$$Z_c = \sqrt{\frac{\omega\mu}{\sigma}} \approx 0.08\ \Omega \qquad \theta = 45^o$$

$$E(z,t) = E_0\sqrt{2}e^{-\alpha z}\sin(\omega t - \beta z)$$

$$H(z,t) = \frac{E_0}{Z_c}\sqrt{2}e^{-\alpha z}\sin(\omega t - \beta z - \theta)$$

La receptor: $E_0 e^{-\alpha d}\sqrt{2} \geq E_{\min}$ $\qquad E_0 \geq \frac{E_{\min}}{\sqrt{2}} e^{\alpha d}$

La sursa: $\underline{S}(0) = \frac{E_0^2}{Z_c^*} = \frac{E_0^2}{Z\_c} e^{j\theta}$

$$P(0) = \mathrm{Real}\left(\underline{S}(0)\right) \geq \frac{E_{\min}^2\, e^{2\alpha d} \cos\theta}{2\, Z_c} = 37\ \frac{\mathrm{MW}}{\mathrm{m^2}}$$

Enorm!

La receptor densitatea de putere este

$$\underline{S}(d) = \frac{E_0^2}{Z_c^*} e^{-2\alpha d}$$

$$P(d) = \mathrm{Real}\left(\underline{S}(d)\right) = P(0)e^{-2\alpha d} = 4.5 \cdot 10^{-12}\,\frac{\mathrm{W}}{\mathrm{m^2}} = 4.5\ \frac{\mathrm{pW}}{\mathrm{m^2}}$$

La d = 10 m, $P(0) = 0.35\frac{\mathrm{nW}}{\mathrm{m^2}}$, $P(d) = 4.5\frac{\mathrm{pW}}{\mathrm{m^2}}$

Cod matlab disponibil

1. Concepte utile
1.1. b) Radiatie

Ipoteze de studiu: 1) mediu liniar electric si magnetic, afin dpdv al conductiei, omogen din pdv electric si magnetic, izotrop

$\bar{D} = \varepsilon \bar{E}$

$\bar{B} = \mu \bar{H}$

$\bar{J} = \sigma \bar{E} + \bar{J}_{\mathrm{i}} \approx \bar{J}_{\mathrm{i}}$

In conductoare vom neglija curentii indusi.
Dielectricii ii vom presupune fara pierderi.

Materiale liniare din punct de vedere si electric (ε), magnetic (μ), dpdv ak conductiei, relatia este afina, exista si un current imprimat (impus, de valoare cunoscuta)

Proprietatile de material electric si magnetic nu depind de punctul din spatiu, sunt aceleasi in toate punctele domeniului de stiudiu.

Proprietatile de material nu depend de directia campului. Constantele de material sunt scalari, nu tensori.

2) Vom presupune un regim armonic permanent (r.a.p), de pulsatie ω

Ecuatii de ordinul I

$$\nabla \cdot \underline{\vec{E}} = \frac{\rho}{\varepsilon} = 0$$

In ipoteza $\nabla \cdot \bar{J}_i = 0$.

$$\nabla \cdot \underline{\vec{H}} = 0$$

$$\nabla \times \underline{\vec{E}} = -j\omega\mu\underline{\vec{H}}$$

$$\nabla \times \underline{\vec{H}} = (j\omega\varepsilon)\underline{\vec{E}} + \underline{\vec{J}_i}$$

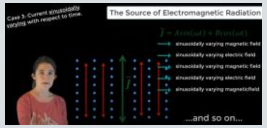
Ecuatii de ordinul II – in E sau H

(ambele sunt de tip Helmholtz complex)

$$\boxed{\begin{aligned} \Delta \underline{\vec{E}} - j\,\omega\,\mu(j\omega\varepsilon)\underline{\vec{E}} &= j\omega\mu\,\underline{\vec{J}_i} \\ \Delta \underline{\vec{H}} - j\,\omega\,\mu(j\omega\varepsilon)\underline{\vec{H}} &= -\nabla \times \underline{\vec{J}_i} \end{aligned}}$$

$$\Delta\,\bar{E} - \varepsilon\mu\frac{d^2\bar{E}}{dt^2} = \mu\frac{\mathrm{d}\bar{J}_i}{\mathrm{d}t}$$

$$\Delta\,\bar{H} - \varepsilon\mu\frac{d^2\bar{H}}{dt^2} = -\nabla \times \bar{J}_i$$



→ Unde EM

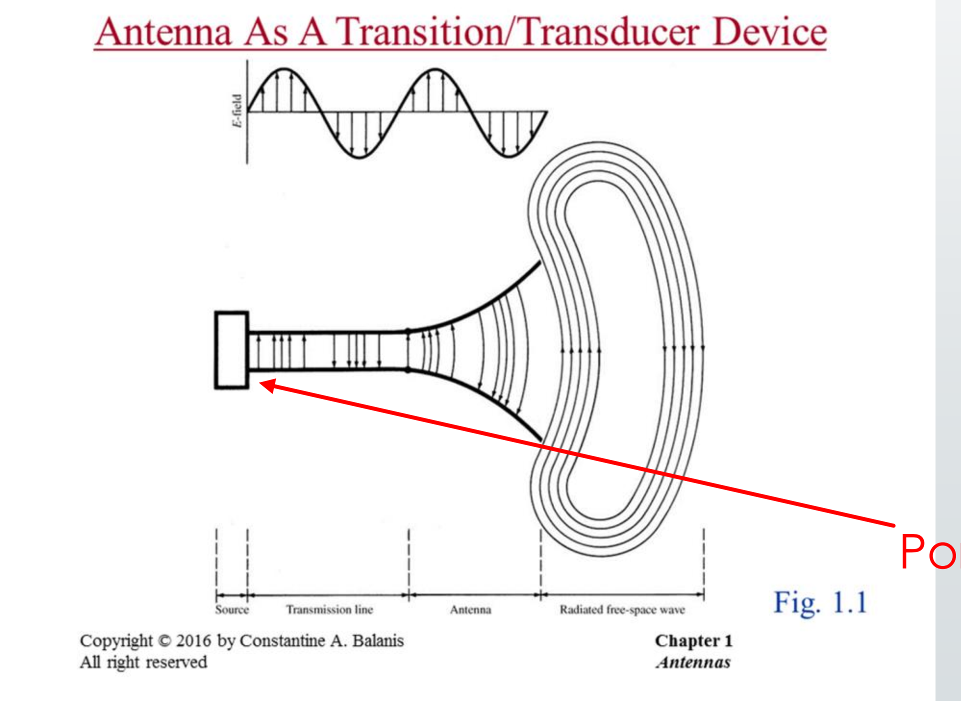
https://www.youtube.com/watch?v=FPf2ntK47xc&list=PL2fRCJxWQiS9oJqmnsV33GLf_zVNsCuSS&index=2

1. Concepte utile
1.1. c) Antene

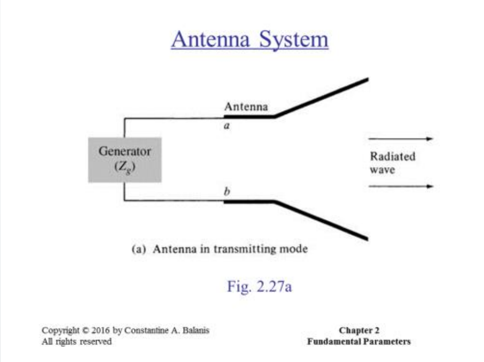
Antena = dispozitiv electromagnetic (EM) folosit pentru a trimite si receptiona unde EM.

(In ecuatiile anterioare, antena de emisie corespunde curentului fixat, sursa de camp.

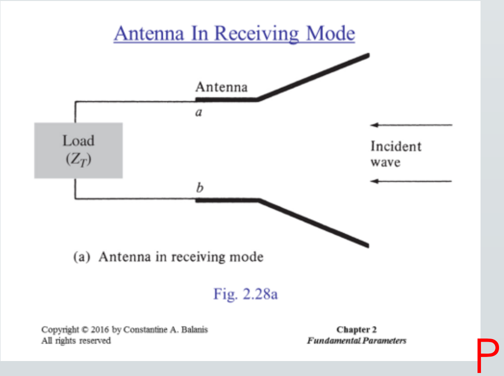
In mod tipic ele sunt dispositive care au un singur port. Un ghid de unda sau o linie de transmisie este conectat la antena intr-un singur punct.



Portul antenei



Antena in mod de emisie (TX)



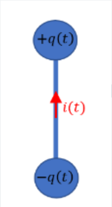
Antena in mod de receptie (RX)

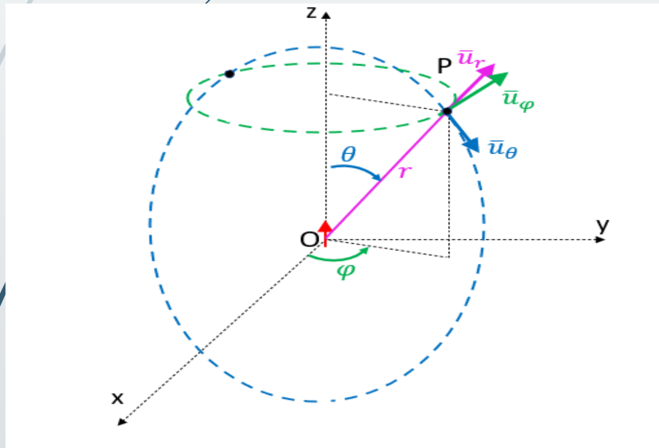
Portul antenei: a-b

Constantine Balanis, Anthena Theory. Analysis and Design, Wiley 2016

1. Concepte utile
1.1. c) Antene

Dipolul electric elementar = sistem radiant ideal, alcatuit din doua sarcini opuse, care variaza in timp $+q(t)$ si $-q(t)$, intre care exista un curent de conductie $i(t)$, astfel incat la orice moment de timp sa fie satisfacuta TCS (teorema conservarii sarcinii). Sistemul este plasat intr-un mediu dielectric liniar, omogen, izotrop.





$$\bar{p}(t) = \lim_{\substack{|q|\to\infty \\ l\to 0}} q(t)\,\bar{l}$$

$$-i(t) = -\frac{\mathrm{d}q(t)}{\mathrm{d}t}$$

$$i(t)\,\bar{l} = \frac{\mathrm{d}\,\bar{p}(t)}{\mathrm{d}t}$$

$$\boxed{\begin{aligned} E_r(\bar{r},t) &= \frac{1}{4\pi\varepsilon}\left(\frac{2\,[\dot{p}]}{c\,r^2} + \frac{2\,[p]}{r^3}\right)\cos\theta \\ E_\theta(\bar{r},t) &= \frac{1}{4\pi\varepsilon}\left(\frac{[\ddot{p}]}{c^2 r} + \frac{[\dot{p}]}{c\,r^2} + \frac{[p]}{r^3}\right)\sin\theta \end{aligned}}$$

$$E_\varphi(\bar{r},t) = 0$$

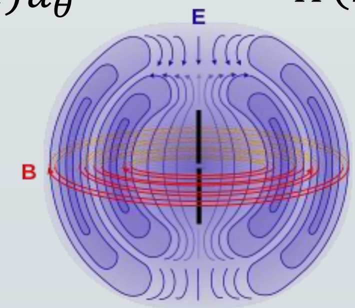
$$\bar{E}(\bar{r},t) = E_r(\bar{r},t)\bar{u}_r + E_\theta(\bar{r},t)\bar{u}_\theta$$

$$H_r(\bar{r},t) = 0$$

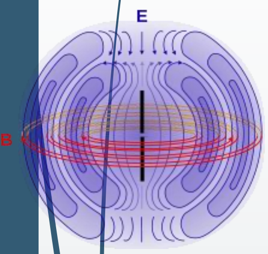
$$H_\theta(\bar{r},t) = 0$$

$$\boxed{H_\varphi(\bar{r},t) = \frac{1}{4\pi}\left(\frac{[\ddot{p}]}{cr} + \frac{[\dot{p}]}{r^2}\right)\sin\theta}$$

$$\bar{H}(\bar{r},t) = H_\varphi(\bar{r},t)\bar{u}_\varphi$$



1. Concepte utile
1.1. c) Antene



Relatiile anterioare arata ca vectorul $\bar{E}$ este situate in plane meridian ($E_\varphi(\bar{r},t)=0$), iar vectorul $\bar{H}$ in plane perpendicular pe axa oscilatorului ($H_r(\bar{r},t)=0,\ H_\theta(\bar{r},t)=0$).

Analizam doua zona importante:

a) **Zona apropiata** de oscilator, in care $r \ll \lambda$

Se pot retine numai termenii care il au pe r la puterea cea mai mare, iar campul se stabileste practice instantaneu (deoarce $\frac{r}{c} \ll t$):

$$E_r(\bar{r},t)=\frac{2\,p(t)}{4\pi\varepsilon\, r^3}\cos\theta$$

$$E_\theta(\bar{r},t)=\frac{p(t)}{4\pi\varepsilon r^3}\sin\theta$$

$$H_\varphi(\bar{r},t)=\frac{\dot{p}(t)}{4\pi r^2}\sin\theta$$

$$\boxed{\underline{E}_r(\bar{r})=\frac{2\,\underline{P}}{4\pi\varepsilon r^3}\cos\theta \qquad \underline{E}_\theta(\bar{r})=\frac{\underline{P}}{4\pi\varepsilon r^3}\sin\theta \qquad \underline{H}_\varphi(\bar{r})=\frac{j\omega\underline{P}}{4\pi r^2}\sin\theta}$$

$$p(t)=lq(t) \qquad \dot{p}(t)=li(t)$$

(*)

b) **Zona indepartata** de oscillator (**a undelor**), in care $r \gg \lambda$

Se pot retine numai termenii care il au pe r la puterea cea mai mica, campul se propaga (deoarce $\frac{r}{c} \gg t$):

$$E_r(\bar{r},t)=0$$

$$E_\theta(\bar{r},t)=\frac{1}{4\pi\varepsilon}\frac{[\ddot{p}]}{c^2 r}\sin\theta$$

$$H_\varphi(\bar{r},t)=\frac{1}{4\pi}\frac{[\ddot{p}]}{cr}\sin\theta$$

$$\underline{E}_r(\bar{r})=0$$

(**)

$$\boxed{\underline{E}_\theta(\bar{r})=\frac{1}{4\pi\varepsilon}\frac{\underline{I}lj\omega}{c^2 r}e^{j\left(-\frac{\omega r}{c}\right)}\sin\theta \qquad \underline{H}_\varphi(\bar{r})=\frac{1}{4\pi}\frac{\underline{I}lj\omega}{cr}e^{j\left(-\frac{\omega r}{c}\right)}\sin\theta}$$

Campurile au cate o singura componenta, sunt ortogonali si perpendicular pe directia de propagare de versor $\bar{u}_r$.

1. Concepte utile
1.1. c) Antene

Concluzii – dipolul electric elementar

- Spre deosebire de cazul undelor plane, amplitudinile campurilor radiate de dipolul electric elementar, pentru zona undelor, nu mai sunt constante ci variaza invers proportional cu distanta r, conform (**).
- In zona undelor, amplitudinile campurilor radiate sunt proportionale cu frecventa (**), de aceea in radiocomunicatii se lucreaza la frecvente inalte.
- Facand raportul modulelor in relatia (**) se obtine $\frac{E_\theta}{H_\varphi} = \frac{1}{\varepsilon c} = Z$, adica impedanta de unda a mediului (ca la unda plana). In cazul vidului aceasta impedanta este $120\pi = 377\ \Omega$.
- In zona undelor, componentele electrica si magnetica ale campului radiat sunt in faza, conform (**). In zona apropiata, fazele campurilor sunt in cuadratura, conform (*).
- In zona undelor, la un moment de timp fixat, componentele de faza egala au acelasi $\omega t - \frac{\omega r}{c}$, de unde componentele de faza egala au acelasi r. Undele radiate de dipolul electric elementar sunt unde sferice.
- Undele radiate de dipolul electric elementar sunt polarizate liniar, campul electric fiind orientat exclusiv dupa axa de coordonata θ.
- Intr-un punct in zona undelor, aflat la distanta r de dipolul plasat in origine si orientat dupa z, $\bar{E}$ are doar componenta dupa θ, $\bar{H}$ are doar componenta dupa φ, ambii vectori sunt tangenti la suprafata sferei de raza r, sistemul de vectori $(\bar{E}, \bar{H}, \bar{r})$ formeaza un triedru ortogonal drept.
- Din (**) se observa ca E_θ si H_φ sunt proportionale cu $\sin\theta$. Se spune ca dipolul electric elementar are **directivitate.** Valoarea maxima are loc in planul ecuatorial (definit de $\theta = \frac{\pi}{2}$). Dipolul nu radiaza dupa axa Oz ($\theta = 0$).

1. Concepte utile
1.1. c) Antene

$\theta \in [0, \pi]$

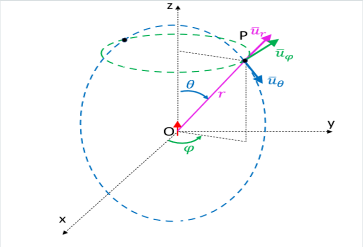
Parametri

$$\underline{E}_\theta(\bar{r}) = \frac{1}{4\pi\varepsilon} \frac{-\omega^2 P}{c^2 r} e^{j\left(-\frac{\omega r}{c}\right)} \sin\theta = \underline{E}_{\theta,\max}(\bar{r}) \sin\theta$$

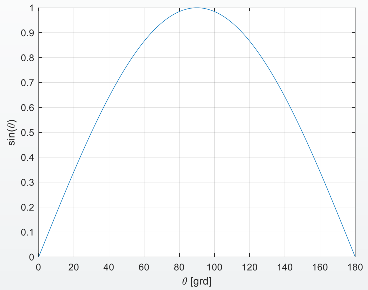
Raportul $\boxed{\dfrac{|\underline{E}_\theta(\bar{r})|}{|\underline{E}_{\theta,\max}(\bar{r})|}} = \sin\theta = f(\theta)$

Se numeste **caracteristica/rofilul de radiatie al campului** (*field radiation pattern*)

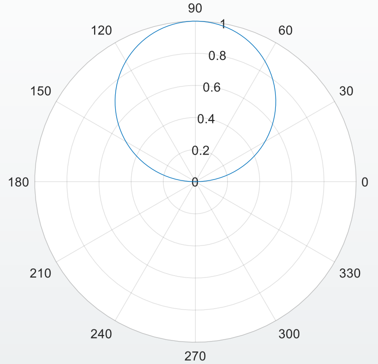
Se deseneaza de obicei intr-un sistem polar 2D, sau 3D.



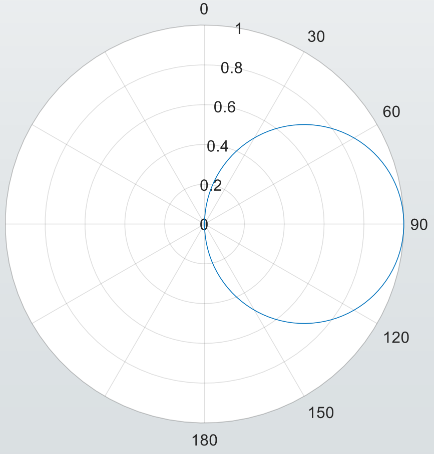
$\theta \in [0, \pi]$



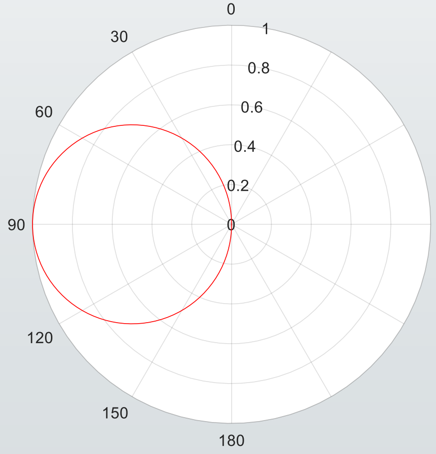
Polar plot, with θ - measured from the Ox axis (usual math representation)



Polar plot, with θ - measured from the Oz axis (antenna representation, ϕ = 0)



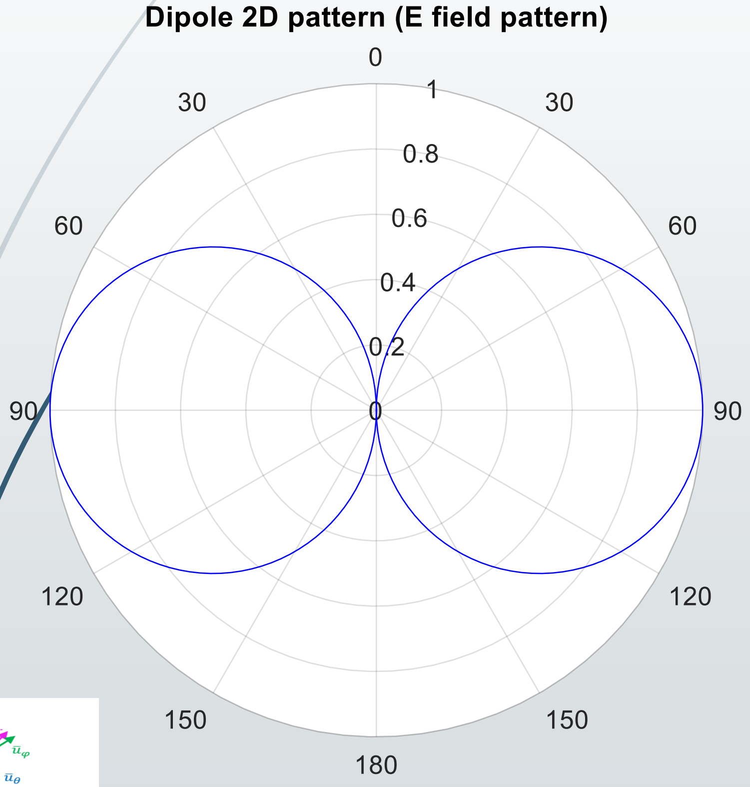
Polar plot, with θ - measured from the Oz axis (antenna representation, $\phi = \pi$)

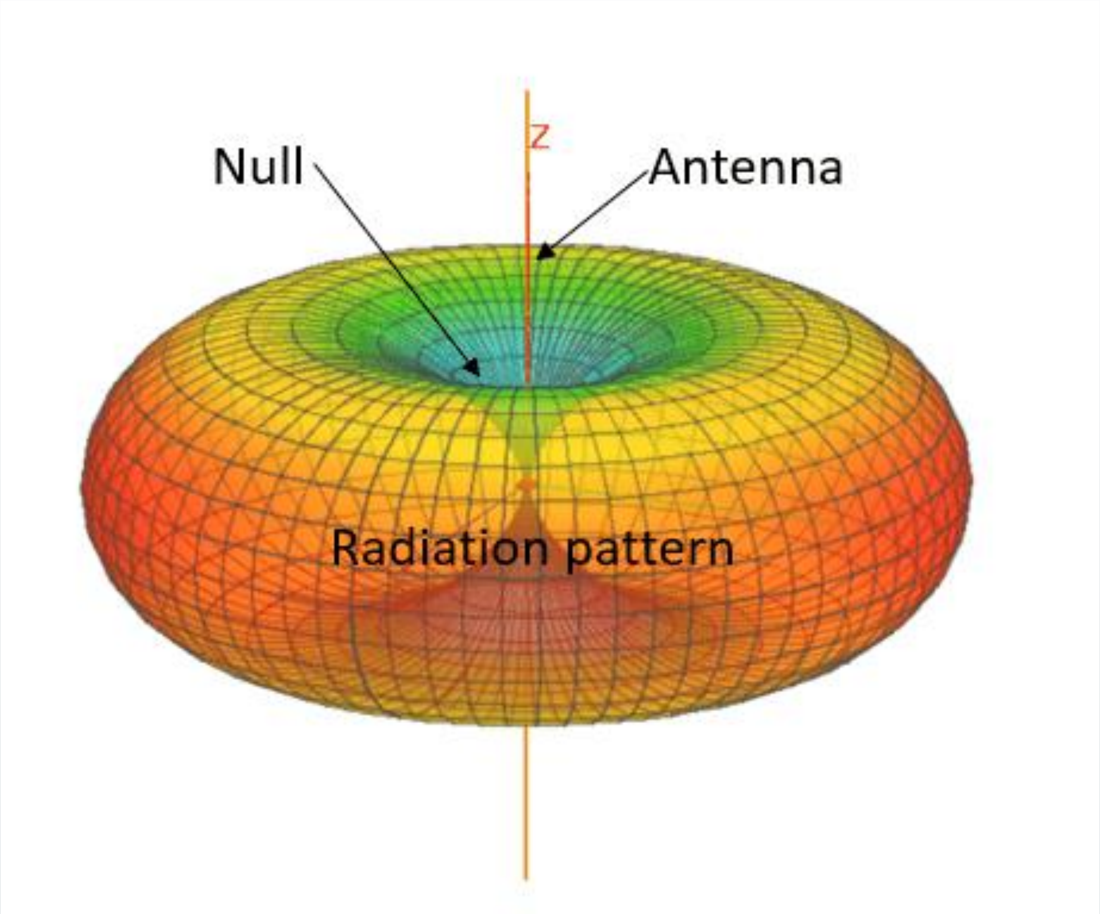


θ- unghiul de elevatie din sistemul sferic

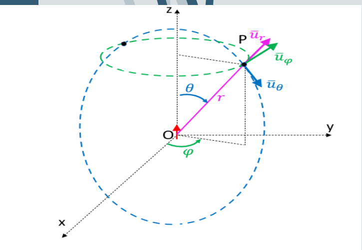
1. Concepte utile
1.1. c) Antene

Parametri – profilul de radiatie al campului





https://engibex.com/antennas-for-dummies



1. Concepte utile
1.1. c) Antene

Parametri – puterea radiata

Se calculeaza in zona undelor.
Se foloseste vectorul lui Poynting – care este o densitate superficiala de putere, marime locala si instantanee.

$$\bar{S}(\bar{r},t) = \bar{E}_\theta(\bar{r},t) \times \bar{H}_\varphi(\bar{r},t) = E_\theta(\bar{r},t) H_\varphi(\bar{r},t)\bar{u}_r = S_r(\bar{r},t)\bar{u}_r$$

Vectorul Poynting este radial, in sensul propagarii undei.

$$E_\theta(\bar{r},t) = \frac{1}{4\pi\varepsilon}\frac{[\ddot{p}]}{c^2 r}\sin\theta$$

$$H_\varphi(\bar{r},t) = \frac{1}{4\pi}\frac{[\ddot{p}]}{cr}\sin\theta$$

$$\Rightarrow \quad S_r(\bar{r},t) = \frac{1}{(4\,\pi)^2\varepsilon c^3}\frac{[\ddot{p}]^2}{r^2}\sin^2\theta$$

Modulul Poynting depinde de unghiul θ, radiatia se face directiv, fiind maxima in planul perpendicular pe dipol si nula pe axa dipolului. Densitatea de putere este invers proportionala cu patratul distantei.

Sa pp. variatii armonice in timp

$$\underline{E}_\theta(\bar{r}) = \frac{1}{4\pi\varepsilon}\frac{\underline{I}lj\omega}{c^2 r}e^{j\left(-\frac{\omega r}{c}\right)}\sin\theta$$

$$\underline{H}_\varphi(\bar{r}) = \frac{1}{4\pi}\frac{\underline{I}lj\omega}{cr}e^{j\left(-\frac{\omega r}{c}\right)}\sin\theta$$

$$\Rightarrow \quad \underline{\bar{S}}(\bar{r}) = \underline{E}_\theta(\bar{r}) \times \underline{H}_\varphi(\bar{r})^* = \frac{1}{(4\,\pi)^2\varepsilon c^3}\frac{I^2 l\,\omega^2}{r^2}\sin^2\theta\,\bar{u}_r$$

(are doar componenta reala)

1. Concepte utile
1.1. c) Antene

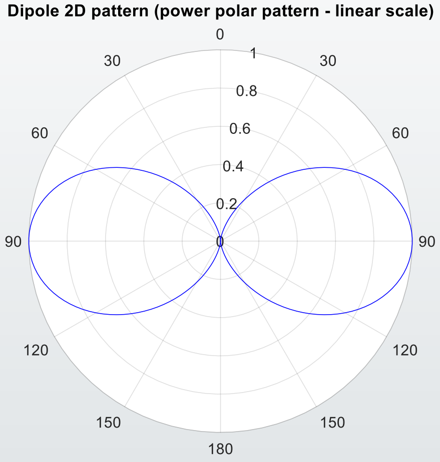
$$\underline{S}(r) = \frac{1}{(4\pi)^2 \varepsilon c^3} \frac{I^2 l\,\omega^2}{r^2} \sin^2\theta = \underline{S}_{\max}(r)\sin^2\theta$$

(***)

Raportul $\boxed{\dfrac{|\underline{S}(\bar{r})|}{|\underline{S}_{\max}(r)|}} = \sin^2\theta$

Se numeste **caracteristica de radiatie de putere** (profil de radiatie, *power radiation pattern*).

Se deseneaza de obicei intr-un sistem polar 2D, sau 3D.



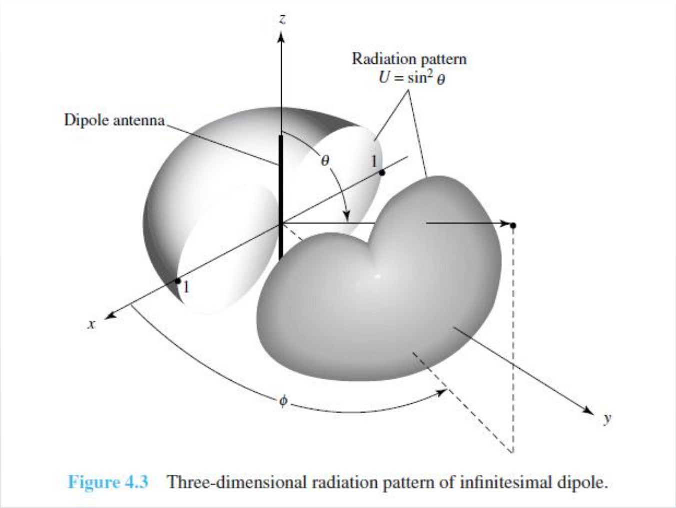
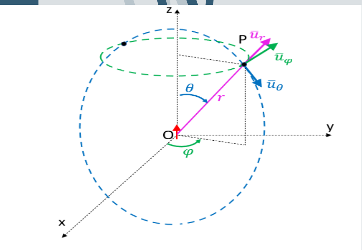


Figure 4.3 Three-dimensional radiation pattern of infinitesimal dipole.

Constantine Balanis, Anthena Theory. Analysis and Design, Wiley 2016

Caracteristicile de radiatie pentru putere se deseneaza uneori pentru valorile in decibel.



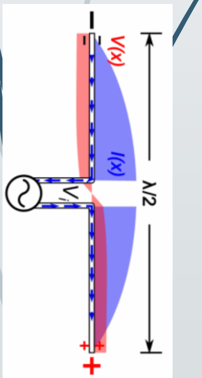
$\theta \in [0, \pi]$

1. Concepte utile
1.1. c) Antene

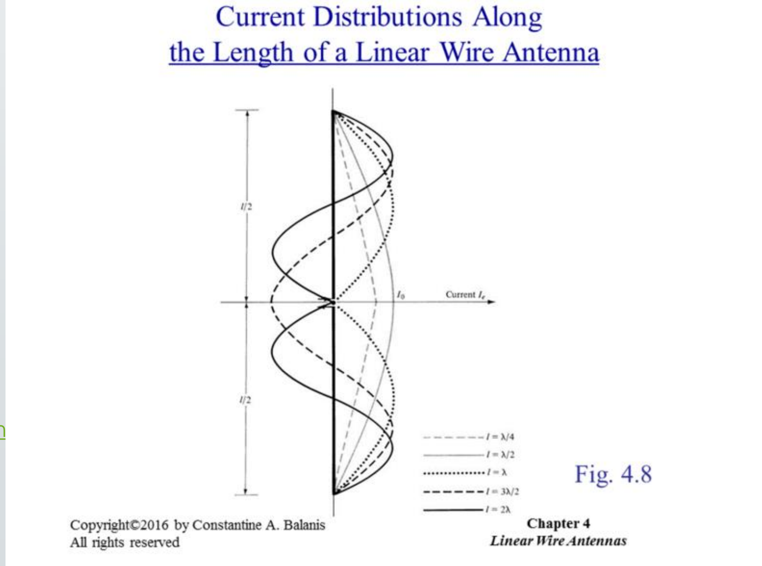
Dipolul electric = antena liniara, subtire, simetrica, alimentata central

Notam cu l – lungimea antenei

Obs: numai daca $l \ll \lambda$, dipolul electric este elementar. Studiul lui este foarte util pentru analiza unor sisteme radiante mai complexe, care pot fi considerate ca o inifinitate de dipoli elementari, si solutia se poate calcula prin superpozitie. Este cazul antenelor liniare subtiri (diametrul lor $d < \frac{\lambda}{100}$), formate din doua conductoare, de lungime $\frac{l}{2}$ fiecare. Se pp. ca alimentarea se face in partea centrala, printr-o linie de transmisie bifilara. Se pp. ca distributia de current este sinusoidala, aceasta aproximand destul de bine distributiile din antenele subtiri.



https://en.wikipedia.org/wiki/Dipole_antenna#/media/File:Standing_waves_animation_6_-_5fps.gif



Se poate demonstra ca functia de directivitate de amplitudine pentru aceste antene este

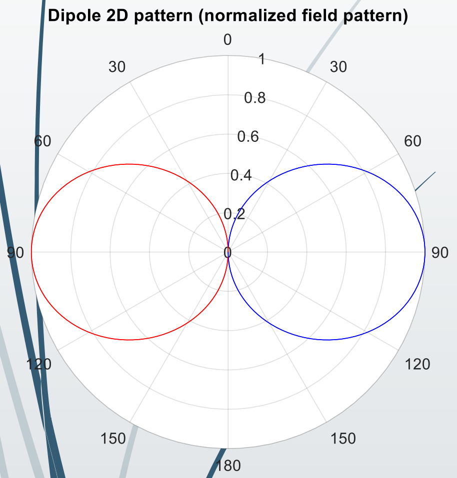
$$f(\theta) = \frac{\cos\left(\pi \frac{l}{\lambda} \cos\theta\right) - \cos\left(\pi \frac{l}{\lambda}\right)}{\sin\theta}$$

Pentru a putea compara directivitatea diferitor antene se normeaza aceasta valoare.

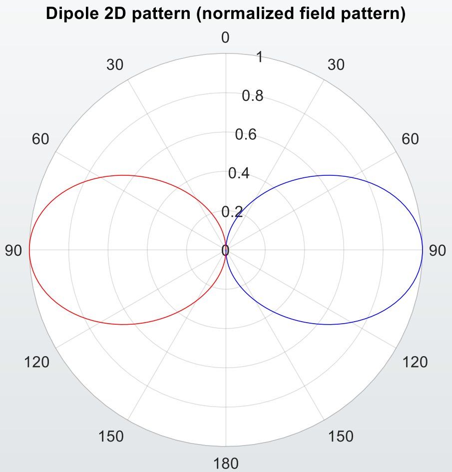
$$f_{\text{normat}}(\theta) = \frac{f(\theta)}{\max(|f(\theta)|)}$$

1. Concepte utile
1.1. c) Antene

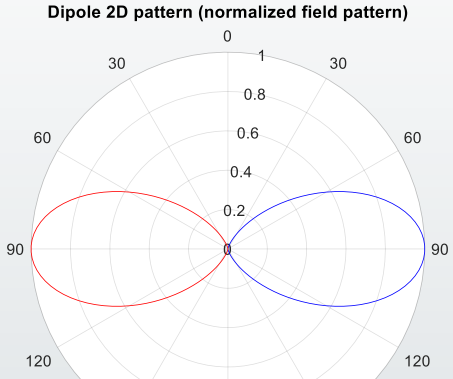
$$l = \frac{\lambda}{2}$$



$$l = \frac{3}{4}\lambda$$

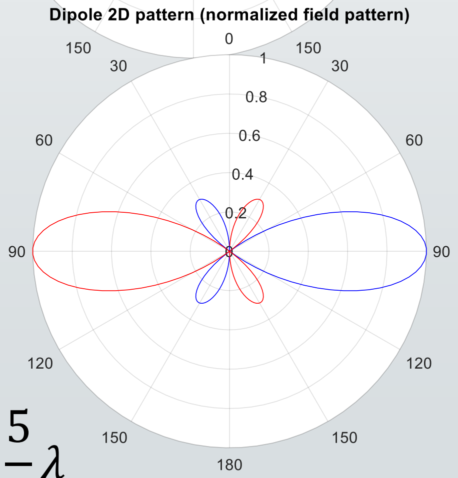


$$l = \lambda$$

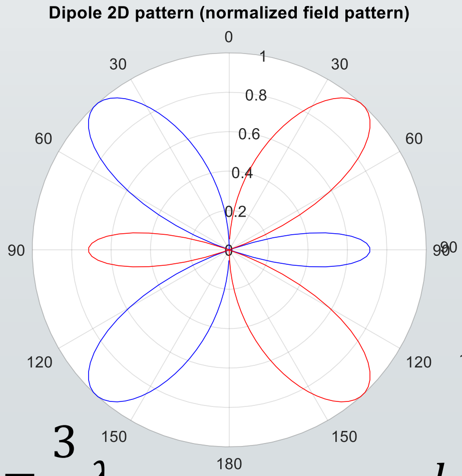


$$f_{\text{normat}}(\theta) = \frac{f(\theta)}{\max(|f(\theta)|)}$$

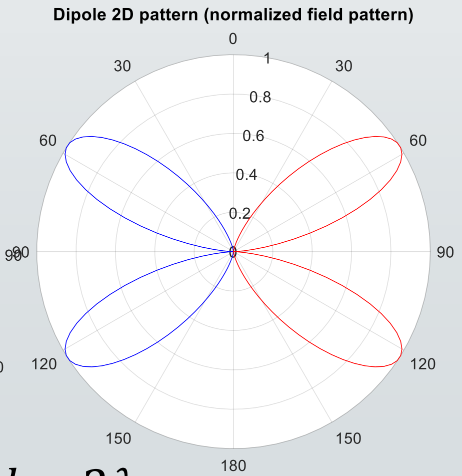
Profilul de radiatie normat, al campului.



$$l = \frac{5}{4}\lambda$$



$$l = \frac{3}{2}\lambda$$



$$l = 2\lambda$$

Cod Matlab disponibil

1. Concepte utile
1.1. c) Antene

Field Regions

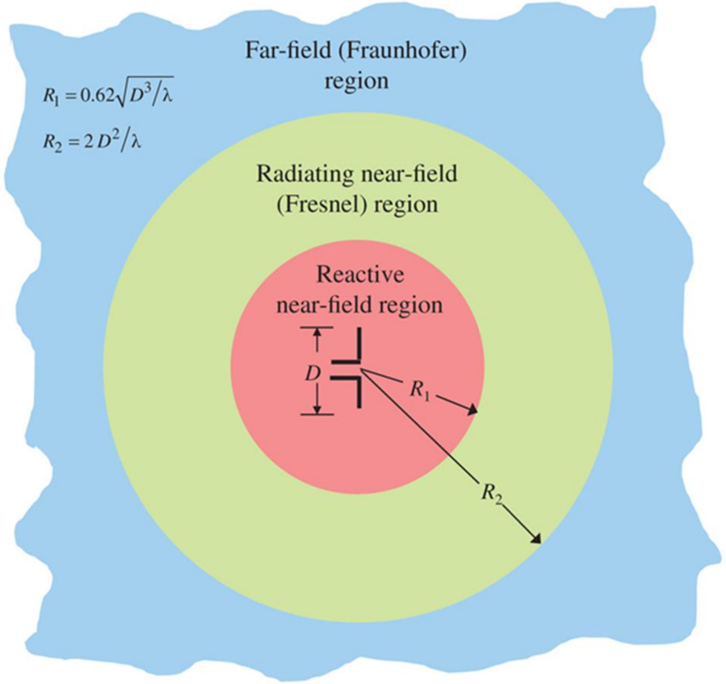


Fig. 2.7

Chapter 2
Fundamental Parameters

Constantine Balanis, Anthena Theory. Analysis and Design, Wiley 2016

Zona apropiata (reactive near-field)= la distante mici de antenna

- Fazele campurilor electrice si magntice sunt in cuadratura (defazate la 90 de grade). De aceea in aceasta zona impedanta undei este puternic reactiva. O mare parte din energia acumulata in aceasta zona nu contribuie la propagare.

Zona intermediara (radiating near-field, Fresnel) = la distante medii fata de antena

- Campurile sunt predominant in faza, dar nu au inca un front sferic. De aceea campul variaza cu distanta fata de antena. Este regiunea unde se fac masuratorile de camp apropiat (near-field measurements).

Zona departata (zona undelor, far-field, Fraunhofer) = la distante mari de antena

Campurile au front de unda sferic. In mod ideal campul nu depinde de distanta fata de antena. Campurile electric si magnetic sunt in faza. Impedanta de unda este, in mod ideal, reala. Puterea este predominant activa (reala), energia acumulata in aceasta zona contribuie la propagare.

1. Concepte utile
1.1. c) Antene

Parametrii antenelor sunt acele marimi care permit alegerea unui tip de antena pentru o aplicatie (vedeti si 6.8). Cei mai importanti parametri de performanta ai unei antene sunt:

- **Frecventa de operare**
- **Caracteristica de radiatie (camp/putere).**
  - **Intensitate maxima a campului electric** in puncte semnificative ale sistemului radiant, importanta mai ales in instalatiile radiante de mare putere, under ar putea fi induse fenomene corona sau strapungerea dielectricilor din vecinatate.
  - **Putere totala radiata** P_{rad}= atunci cand sistemul radiant este excitat de o distributie de current sau de sarcina cunoscuta.
  - **Intensitatea radiatiei** U
  - **Directivitate** D
- **Impedanta de intrare** a sistemului radiant $\underline{Z}_{in}$= importanta mai ales in problemele de adaptare a sistemului radiant la sistemul de alimentare al acestuia.
  - **Caracteristica de frecventa –** parametrii S
- **Eficienta (randament)** sistemului radiant e_{cd}= puterea radiata/puterea totala primita de la sistemul de alimentare (care este suma dintre puterea radiata si cea disipata in sistem). **Castig.**
- **Largime de banda**

Nu toti acesti parametri sunt independenti. Pentru a descrie complet performantele unei antene, numai unii dintre acesti parametri sunt suficienti.

1. Concepte utile
1.1. c) Antene

Caracteristica de radiatie *(radiation pattern)*

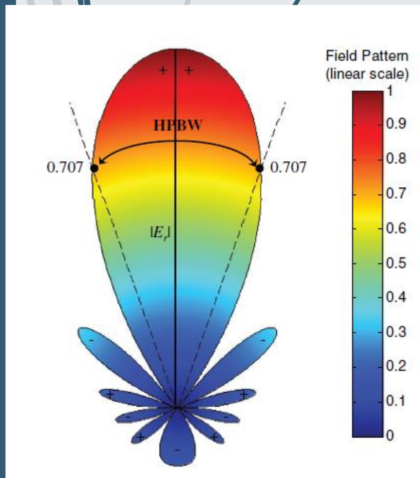
= o functie matematica sau o reprezentare grafica a proprietatilor de radiatie a antenei, ca o functie de coordonatele spatiale. In majoritatea cazurilor se determina in zona undelor si este o functie de coordonatele θ si φ.

Cea mai importanta proprietate legata de radiatie este distributia spatiala (2D sau 3D) a energiei radiate, in functie de pozitia unui observatory aflat pe o suprafata sferica, de raza constanta, cu centrul in antena.

Ea se poate referi la :

- Amplitudinea campului (electric sau magnetic) => caracteristica de radiatie a campului *(field radiation pattern)*
- Densitatea de putere (de obicei amplitudinea la patrat a campului electric sau magntic) => caracteristica de radiatie a puterii *(power radiation pattern).* Se reprezinta si in dB, pentru a pune in evidenta mai bine lobii minori (secundari).

De obicei aceste marimi sunt normate => *normalized field/power radiation pattern*



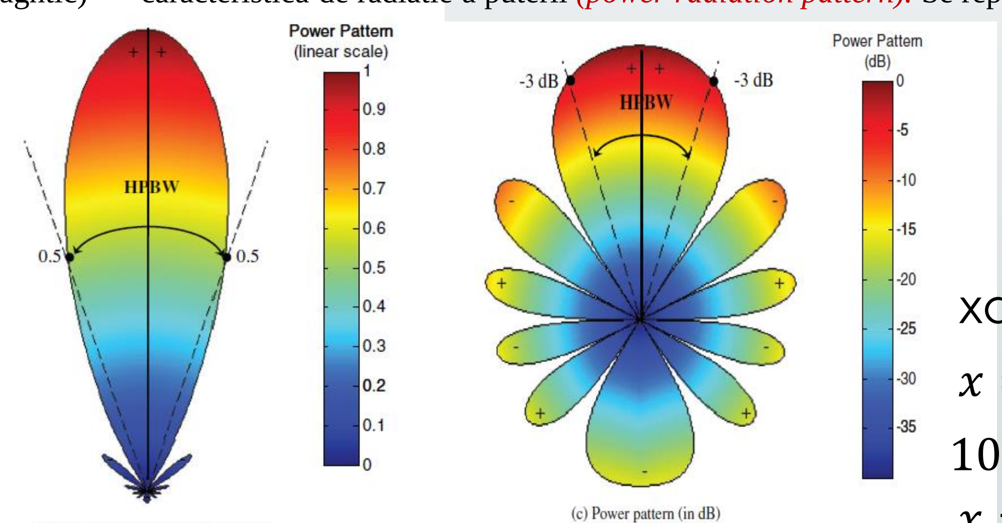
(a) Field pattern (in linear scale)

$$p \sim E^2$$

$$p_{\max} = C E_{\max}^2$$

$$0.5\, p_{\max} = C E_{0.5\mathrm{pmax}}^2$$

$$E_{0.5\mathrm{pmax}} = \frac{E_{\max}}{\sqrt{2}} = 0.707\, E_{\max}$$



(b) Power pattern (in linear scale)

(c) Power pattern (in dB)

Two-dimensional normalized *field* pattern (*linear scale*), *power* pattern (*linear scale*), and *power* pattern (*in dB*) of a 10-element linear array with a spacing of $d = 0.25\lambda$.

xdB = 10*log10(x)

$$x = 1$$

$$10 \log_{10} 1 = 0 \text{ dB}$$

$$x = 0.5$$

$$10 \log_{10} 0.5 = -3 \text{ dB}$$

Constantine Balanis, Anthena Theory. Analysis and Design, Wiley 2016

1. Concepte utile
1.1. c) Antene

Puterea radiata = puterea activa calculate prin integrarea vectorului Poynting pe o sfera centrata in antenna.

$$\boxed{P_{rad} = \int_{\Sigma} \mathrm{Re}\left(\bar{E} \times \bar{H}^*\right) \cdot \overline{\mathrm{dA}} = \int_{\Sigma} \bar{W}_{rad} \cdot \overline{\mathrm{dA}}}$$

Unde am notat densitatea de putere cu

$$\bar{W}_{rad} = \mathrm{Re}\left(\bar{E} \times \bar{H}^*\right) = W_{rad}\, \bar{u}_r$$

Deoarece in zona undelor, radiatia este dupa directia radiala. In aceasta zona, puterea reactiva e nula.

O antenna ideala, ar radia izotrop, la fel in toate directiile, caz in care densitatea de putere nu depinde decat de raza $W_{rad}(r)$. Rezulta ca

$$P_{rad} = 4\,\pi r^2 W_{rad\,(r)} \qquad W_{rad}(r) = \frac{P_{rad}}{4\pi r^2}$$

Aceasta marime, desi nu corespunde unei situatii reale, e folosita pentru normare.

Intensitatea radiatiei = puterea radiata de o antenna pe unitatea de unghi solid

Se defineste pentru zona undelor

$$\boxed{U = r^2\, W_{rad}} \qquad \text{[W/unitate de unghi solid]}$$

$$\boxed{U(\theta,\varphi) = B_0 F(\theta,\varphi)} \approx \frac{1}{Z}|E(\theta,\varphi)|^2$$

Pentru ca in zona undelor componenta radiala a campului se poate neglija.

unde B_0 este o constanta

Pentru rezonatorul ideal $U = \frac{P_{rad}}{4\,\pi} \triangleq U_0$

Valoarea maxima $U_{max} = B_0 F_{max}(\theta,\varphi)$

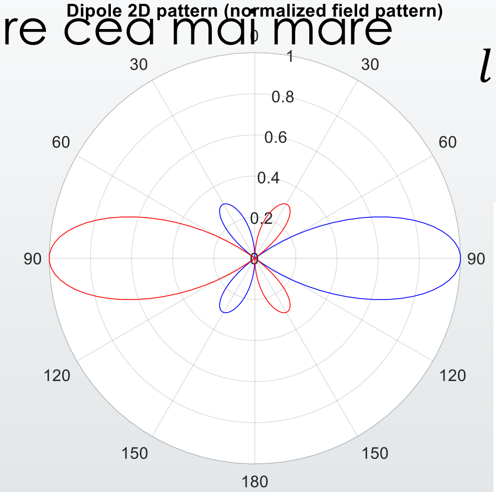
Puterea totala radiata devine

$$\boxed{P_{rad} = B_0 \int_0^{2\pi} \int_0^{\pi} F(\theta,\varphi) \sin\theta \; \mathrm{d}\theta \; \mathrm{d}\varphi}$$

1. Concepte utile
1.1. c) Antene

La dipolul electric, caracteristica de radiatie (camp sau putere) depinde numai de unghiul θ.

Directia (φ_0, θ_0) in care caract. de radiatie are cea mai mare valoare = **directie de radiatie maxima**.



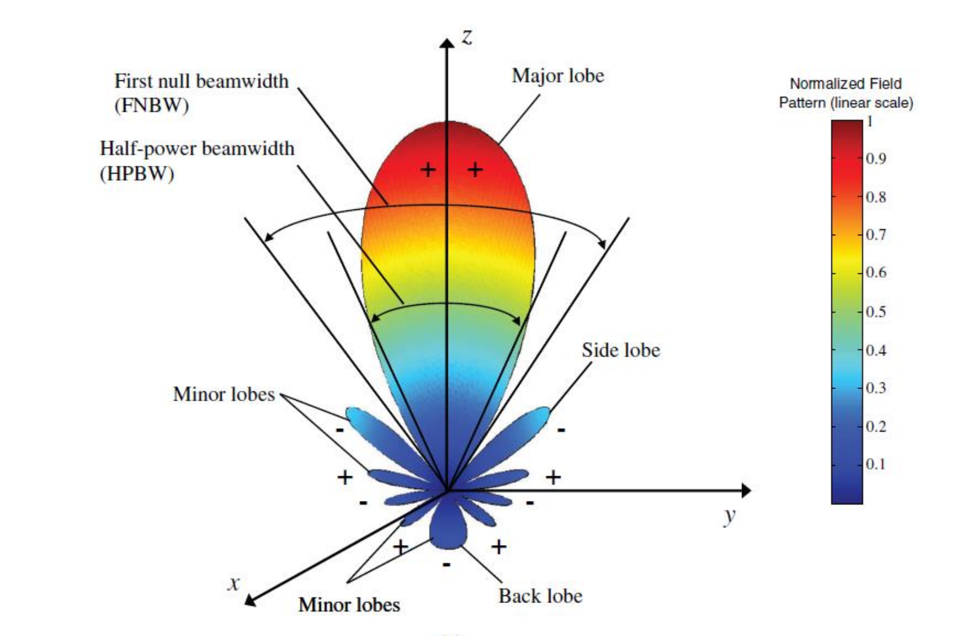
$$l = \frac{5}{4}\lambda$$

Directiile in care nu exista radiatie = **directii de radiatie nula**.

Totalitatea valorilor caracteristicii de directivitate cuprinse intre doua directii de radiatie nula = **lob**.

Lobul a carui maxim se suprapune pe directia de radiatia maxima = **lob principal**.

Ceilalti – **secundari (minori)**



(a)

Cu cat lobul principal este mai ingust, cu atat antenna este mai directiva. (La aceesi putere, distanta de actiune e mai mare - util pentru radar).

1. Concepte utile
1.1. c) Antene

Directivitate = raportul dintre intensitatea de radiatie intr-o directie data si intensitatea de radiatie mediata dupa toate directiile. Aceasta din urma este puterea totala radiata de antenna impartita la 4π. Daca nu se specifica nicio directive, implicit se considera directia de radiatie maxima.

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}}$$

$$D(\varphi, \theta) = 4\,\pi \frac{F(\theta, \varphi)}{\int_0^{2\pi}\int_0^{\pi} F(\theta, \varphi) \sin\theta \,\mathrm{d}\theta \,\mathrm{d}\varphi}$$

$$D_{max} = D_0 = \frac{4\,\pi U_{\max}}{P_{rad}}$$

$$D_0 = 4\,\pi \frac{F(\theta, \varphi)|_{\max}}{\int_0^{2\pi}\int_0^{\pi} F(\theta, \varphi) \sin\theta \,\mathrm{d}\theta \,\mathrm{d}\varphi}$$

D-directivitate [adimensionala]
D_0-directivitate maxima
U-intensitatea radiatiei [W/unitate de unghi solid]
$U_{\max}$-valoarea maxima a intensitatii radiatiei
U_0-intensitatea radiatiei unei surse care radiaza izotrop
P_{rad}-puterea totala radiata [W]

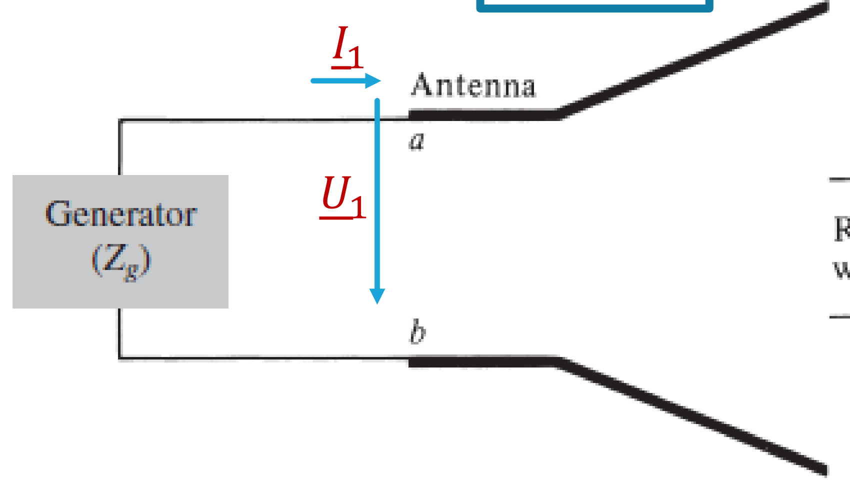
O directivitate mai mare inseamna o antenna mai directiva. De exemplu $D = 2$ inseamna ca antenna transmite de 2 ori mai multa putere in directia de radiatie maxima decat o antenna ideala (numita si izotropa).

Antenele telefoanelor mobile trebuie sa aiba o directivitate mica, deoarce semnalul poate veni din orice directie, si antenna trebuie sa il receptioneze.

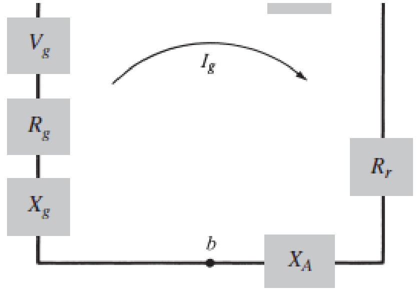
O antenna de satelit trebuie sa aiba o directivitate mare, pentru ca ea receptioneaza semnalele dintr-o directie fixa.
De regula, antenele care au o dimensiune mai mica decat lungimea de unda au o directivitate mica.

1. Concepte utile
1.1. c) Antene

Impedanta de intrare $\underline{Z}_{\text{in}} = \frac{\underline{U}_1}{\underline{I}_1}$



(a) Antenna in transmitting mode



(b) Thevenin equivalent

$\underline{Z}_{\text{in}} = R_A + j\,X_A$

Impedanta antenei la terminalele a-b

Rezistenta

Reactanta

In general, rezistenta antenei are doua componente

$R_A = R_L + R_{rad}$

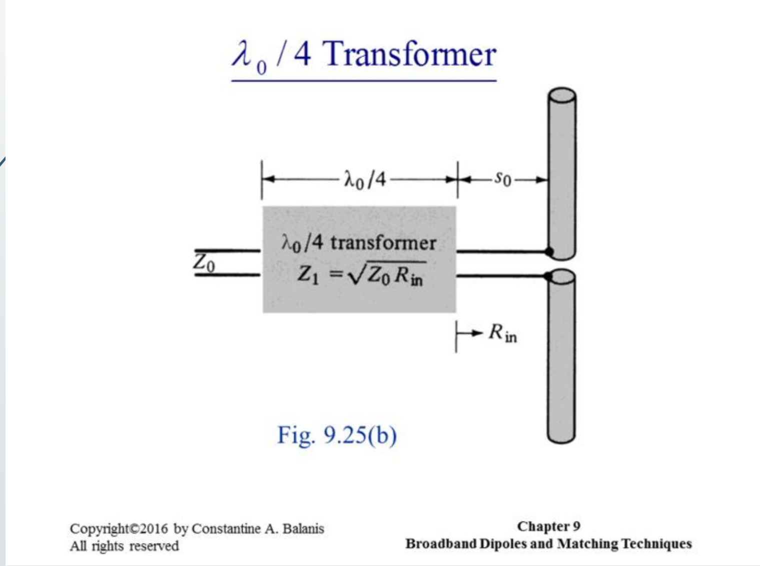
Rezistenta de pierderi (*loss*)

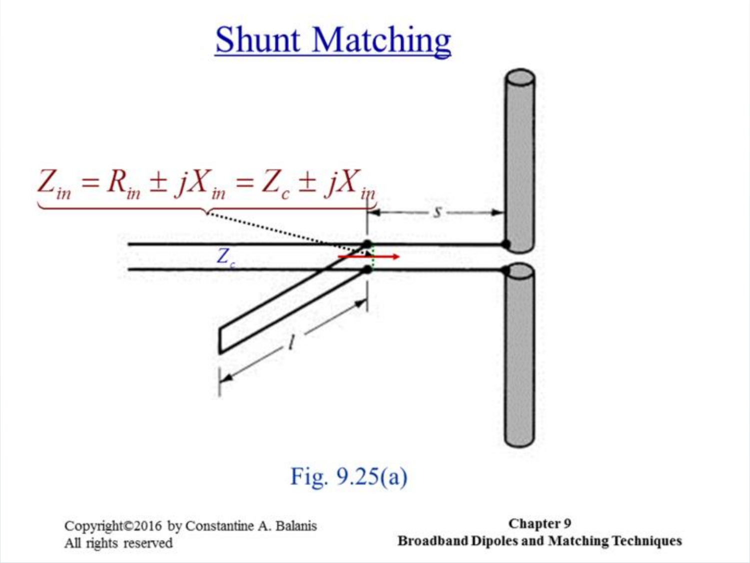
$R_{rad} = R_r$ Rezistenta de radiatie

Constantine Balanis, Anthena Theory. Analysis and Design, Wiley 2016

1. Concepte utile
1.1. c) Antene

Adaptarea antenelor la liniile de alimentare





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1. Concepte utile
1.1. c) Antene

Eficienta (randamentul)

E o masura a cat de bine o antenna primeste puterea primita in putere radiata.

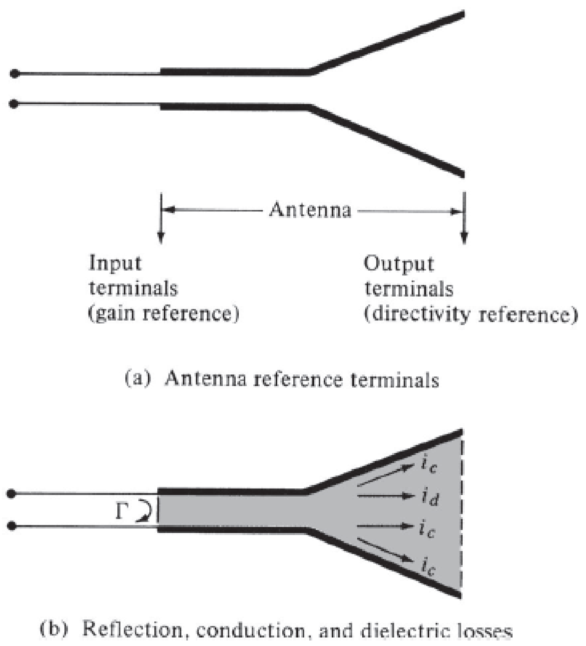

Figure 2.22 Reference terminals and losses of an antenna.

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$$e_0 = e_r e_{cd}$$

e_0- eficienta (randamentul) totala [adimensionala]

e_r- eficienta datorata reflexiei $e_r = 1 - |\Gamma|^2$ $\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$

e_{cd}- eficienta de radiatie, include fenomenele de conductie-c si fenomenele in dielectrici-d

Daca notam P_p- puterea furnizata antenei de catre generator.

$$e_r = \frac{P_{in}}{P_p}$$

Daca antenna este adaptata: $P_{in} = P_p, e_r = 1.$

Daca antenna nu este adaptata: $P_{in} < P_p, e_r < 1.$

$$e_{cd} = \frac{P_{rad}}{P_{in}} = \frac{P_{rad}}{P_{rad} + P_L}$$

P_L= putere disipata prin conductie in antena

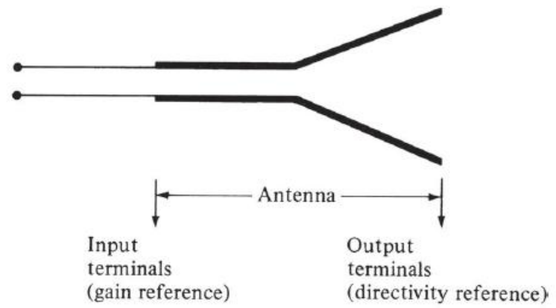
1. Concepte utile
1.1. c) Antene

Castigul antenei

Este un numar de performanta (*figure of merit*) strans legat de directivitate, dar care ia in considerare si eficienta antenei (e_{cd}).

$$\boxed{G(\theta,\varphi) = e_{cd}D(\theta,\varphi)}$$

Considerand valoarea maxima $\boxed{G_0 = e_{cd}D_0}$

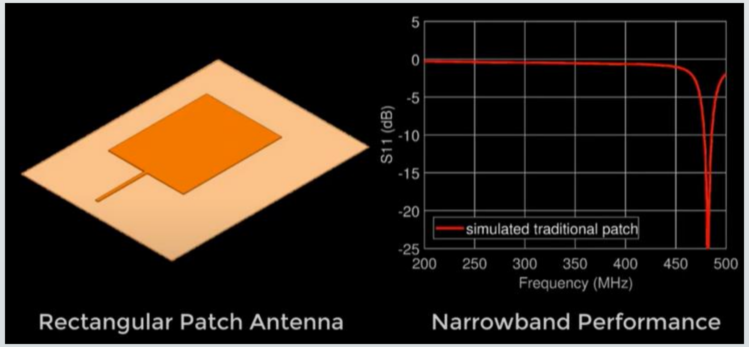


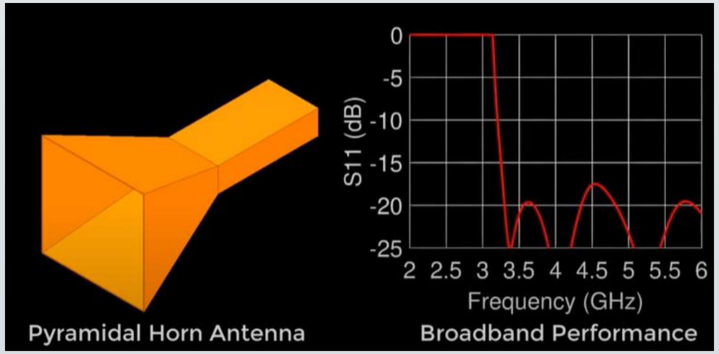
Lartimea de banda – gama de frecvente in care performantele antenei, in raport anumite caracteristici (de exemplu, impedanta de intrare, profilul de ratiatie, latimea lobului principal (beamwidht), polarizarea, latimea lobilor secundari, castigul, directia fascicolului, eficienta de radiatie) sunt conforme cu specificatiile dorite.

https://www.youtube.com/watch?v=_WuVv4tWVd8&list=PL2fRCJxWQiS916POeW3xkF5AU0H7lmNis&index=3

Ex:

$$BW = \frac{f_{\max,-10\text{dB}} - f_{min,-10dB}}{f_{\text{rez}}}$$





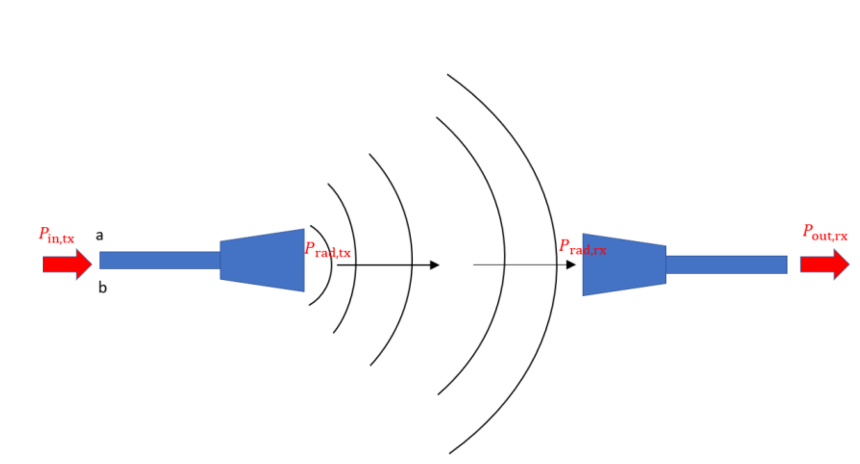
Se considera acceptabil

$$S_{11}(\text{dB}) \leq -10\text{ dB}$$

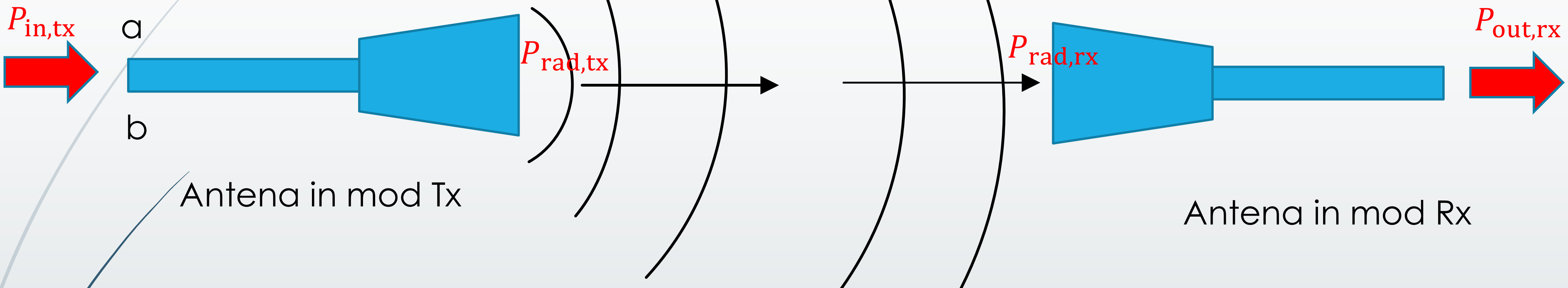
1. Concepte utile
1.2. Sistem de 2 antene

Sistemele de comunicatie fara fir (*wireless*) transmit informatia dintre doua antene:
- O antenna care emite (transmitator – Tx)
- O antenna care receptioneaza (receptor – Rx)

Puterea receptionata de antenna Rx depinde de:
- Puterea trimisa de antenna Tx
- Tipul antenelor (geometrie, materiale) – determina parametrii lor de performanta (e.g. castigul, largimea de banda)
- Pozitia relativa a antenelor
- Mediul prin care se propaga
- Compatibilitatea dintre cele 2 antene



1. Concepte utile
1.2. Sistem de 2 antene



Castigul sistemului $\boxed{G_s = \frac{P_{\mathrm{out,Rx}}}{P_{\mathrm{in,Tx}}}}$

A nu se confuda cu castigul antenei!

$P_{\mathrm{out,Rx}}$ Puterea generata de portul antenei Rx

$P_{\mathrm{out,Tx}}$ Puterea primita de portul antenei Tx

Formula Friis

$$\boxed{G_s = G_{Tx}(\theta_{Tx}, \varphi_{Tx})\, G_{Rx}(\theta_{Rx}, \varphi_{Rx}) \left(\frac{\lambda}{4\pi r}\right)^2}$$

Castigul antenei Tx   Castigul antenei Rx

(dep. de orientarea antenelor, care trebuie orientate corespunzator pentru un transfer maxim)

λ – lungimea de unda a semnalului

r – distanta dintre cele 2 antene

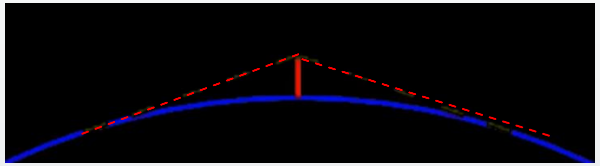
1. Concepte utile
1.2. Sistem de 2 antene

Formula Friis este valabila in urmatoarele ipoteze:

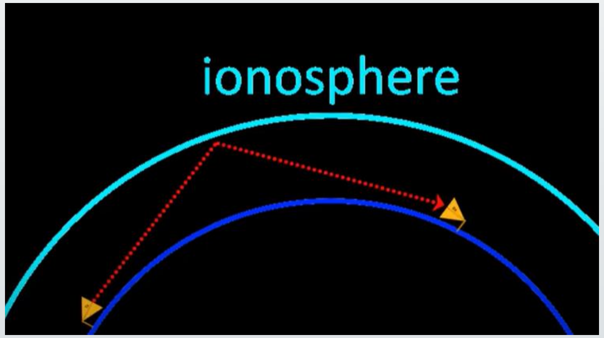
1. Se neglijeaza neadapatarea datorata unor **polarizari diferite**, se pp. ca antenele au acelasi fel de polarizare;
2. Se neglijeaza posibilele obstructii (mediul dintre cele doua antene se pp. omogen);
3. Se pp. ca intre cele 2 antene exista o linie dreapta (de exemplu semnalul nu s-ar putea transmite direct daca antena receptoare este dincolo de linia orizontului);
4. Se pp. mediul fara pierderi (nu exista atenuare datorata unor proprietati conductoare ale mediului);
5. Se pp. ca ambele antene sunt **perfect adaptate** circuitelor la care sunt conectate.

Chiar daca sunt multe ipoteze, formula Friis este utila pentru ca ea permite calulul puterii maxime care poate fi transmita, datorata limitarilor fizice ale sistemului (2,3,4). Ipotezele 1 si 5 sunt la indemana proiectantilor de antene.

Antena plasata la inaltimea de 2 m => transmite pana la 5 km
30 m => 21 km



Remediu

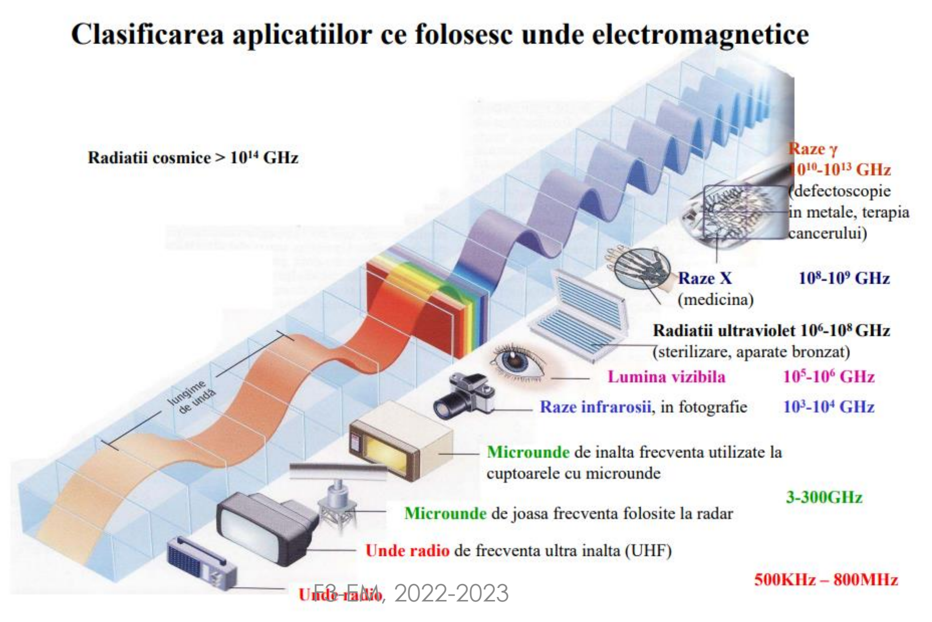


La frecventa mari, ionosfera se comporta ca un reflector.

https://www.youtube.com/watch?v=EdvbgZo2MNg&list=PL2fRCJxWQiS8AbtAcdDF1AoB3q3ghZ57c&index=2

1. Concepte utile
1.3. Principiul unui sistem de comunicatie RF (radio-frequency)

RF = frecventele cele mai joase ale spectrului EM, folosite in sistemele de comunicatii analoge si digitale. Cuprinde gama de frecvente dintre 3 kHz and 300 GHz. Aplicatii: radio analog, sistemele de navigatie ale aeronabelor, navelor maritive, radio de amatori, transmisii TV, retele mobile si sisteme de sateliti.



Radio Frequency Spectrum: Ranges

Designation	Abbreviation	Frequencies	Wavelengths
Very Low Frequency	VLF	3 kHz - 30 kHz	100 km - 10 km
Low Frequency	LF	30 kHz - 300 kHz	10 km - 1 km
Medium Frequency	MF	300 kHz - 3 MHz	1 km - 100 m
High Frequency	HF	3 MHz - 30 MHz	100 m - 10 m
Very High Frequency	VHF	30 MHz - 300 MHz	10 m - 1 m
Ultra High Frequency	UHF	300 MHz - 3 GHz	1 m - 100 mm
Super High Frequency	SHF	3 GHz - 30 GHz	100 mm - 10 mm
Extremely High Frequency	EHF	30 GHz - 300 GHz	10 mm - 1 mm

www.rfpage.com

https://www.rfpage.com/what-are-radio-frequency-bands-and-its-uses/

1. Concepte utile
1.3. Principiul unui sistem de comunicatie RF (radio-frequency)

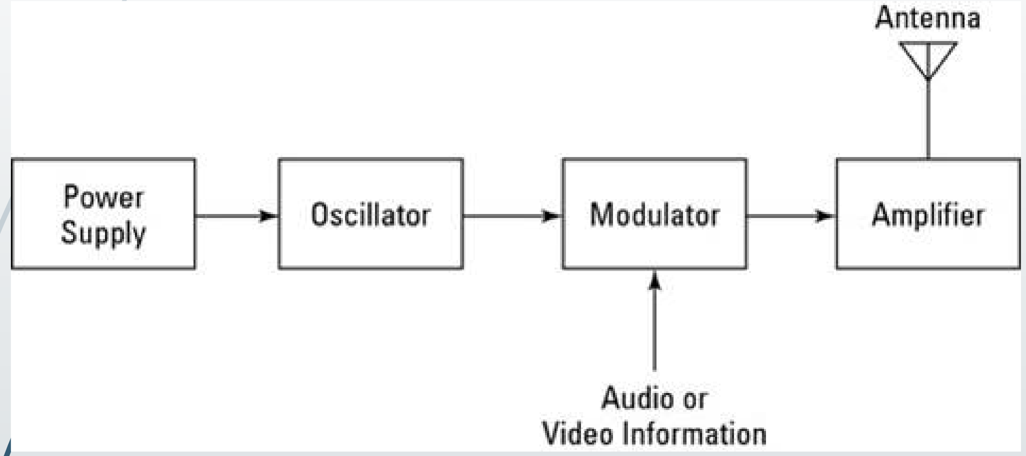


Diagrama bloc a unui sistem de emisie (Tx)

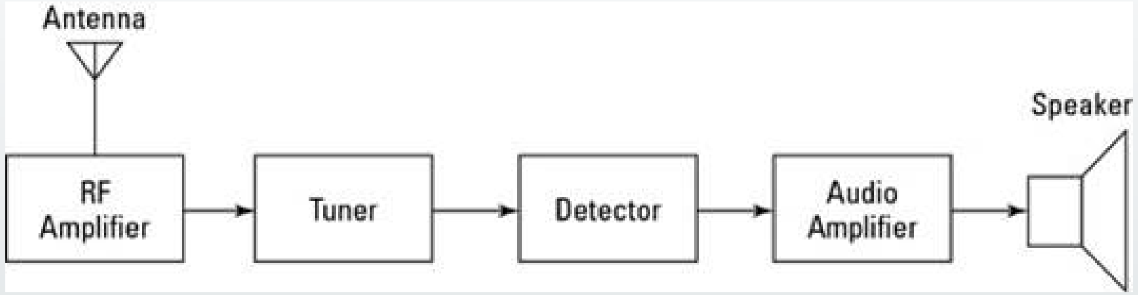


Diagrama bloc a unui sistem de receptie (Tx)

1. Concepte utile
1.3. Principiul unui sistem de comunicatie RF (radio-frequency)

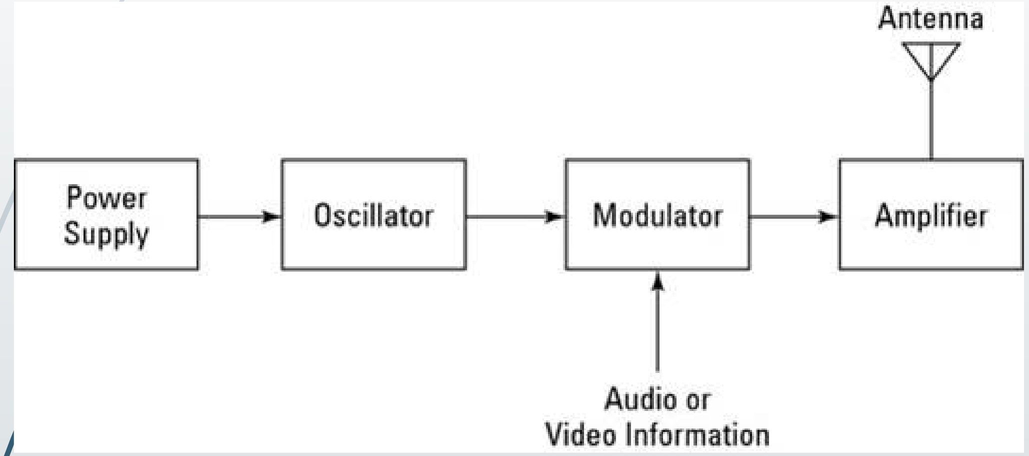


Diagrama bloc a unui sistem de emisie (Tx)

Semnalul util (de exemplu audio sau video) va fi combinat cu un semnal de frecventa inalta (semnal purtator) generat de un oscilator. Modulatorul este blocul care realizeaza aceasta combinare a semnalelor. De exemplu, in cazul modulatiei in amplitudine (AM- amplitude modulation), invasuratoarea (anvelopa) semnalului modulat va fi proportionala cu semnalul util, de transmis. Semnalul rezultat este amplificat, el alimenteaza antenna de emisie, care genereaza undele EM.

1. Concepte utile
1.3. Principiul unui sistem de comunicatie RF (radio-frequency)

Sistemul de receptie incepe cu antenna care receptioneaza undele EM, la portul ei se induce un semnal, care este apoi preluat de un filtru (tuner) care extrage semnalul de frecventa dorita, din combinatia de semnale receptionate. Detectorul este blocul care separa semnalul purtator de semnalul util. Semnalul rezultat este amplificat si redat.

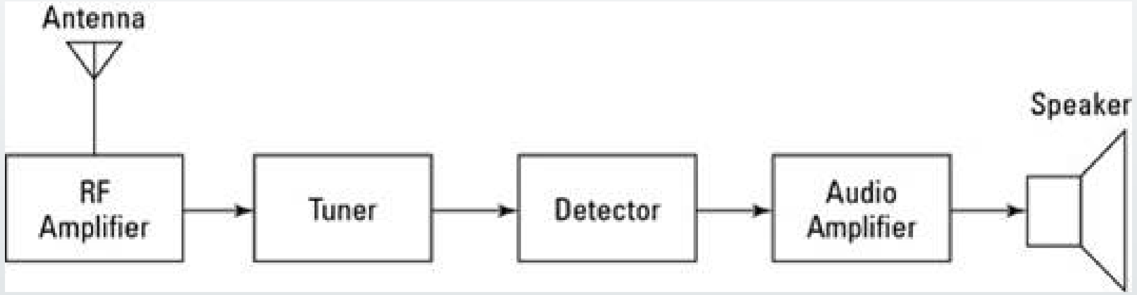


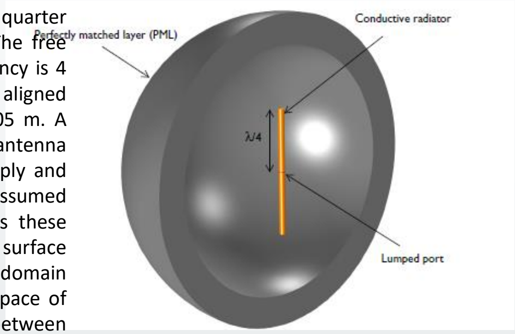
Diagrama bloc a unui sistem de receptie (Tx)

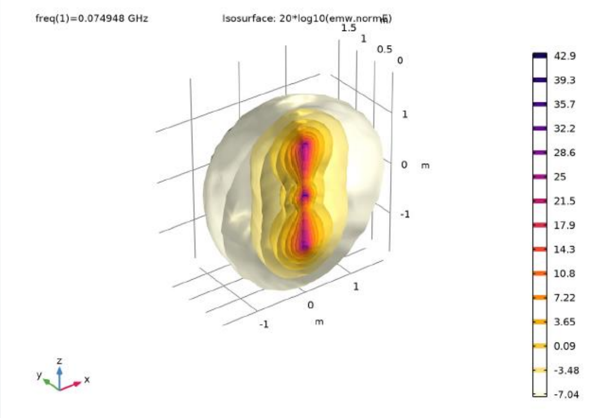
2. Experimente virtuale

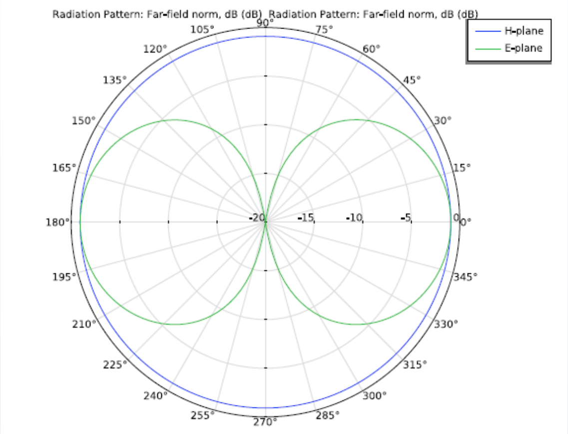
https://www.comsol.com/model/dipole-antenna-8715

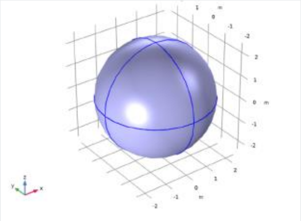
The length of the rods is chosen such that they are quarter wavelength elements at the operating frequency. The free space wavelength at the antenna's operating frequency is 4 m. Thus, each of the antenna arms is 1 m long and aligned with the *z*-axis. The arm radius is chosen to be 0.05 m. A small cylindrical gap of size 0.01 m between the antenna arms represents the voltage source. The power supply and feed structure are not modeled explicitly, and it is assumed that a uniform voltage difference is applied across these faces. This source induces electromagnetic fields and surface currents on the adjacent conductive faces. The air domain around the antenna is modeled as sphere of free space of radius 2 m, which is approximately the boundary between the near-field and the far-field. This sphere of air is truncated with a perfectly matched layer (PML) that acts as an absorber of outgoing radiation. The far-field pattern is computed on the boundary between the air and the PML domains. The mesh is manually adjusted such that there are five elements per free space wavelength and that the boundaries of the antenna are meshed more finely. The PML is swept with a total of five elements along the radial direction. The real part of the impedance as seen by the port is evaluated to be about 120 Ω which agrees reasonably with expectations. With further tuning of the antenna length, radius and gap height to have the resonance at which the reactance is zero, the result approaches the well known value for a half-wave (0.48 λ_0) dipole antenna, which is 73 Ω.

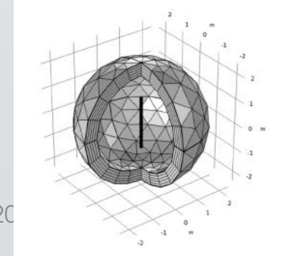
$$f = \frac{c}{\lambda} = \frac{3 \cdot 10^8 \mathrm{m/s}}{4\ \mathrm{m}} = 75\ \mathrm{MHz}$$

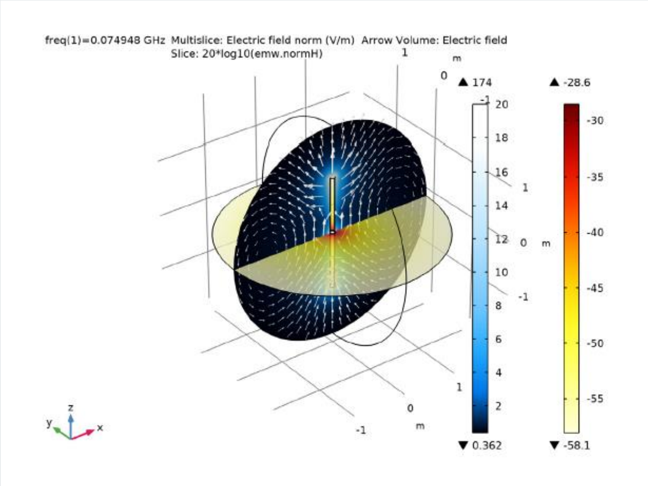


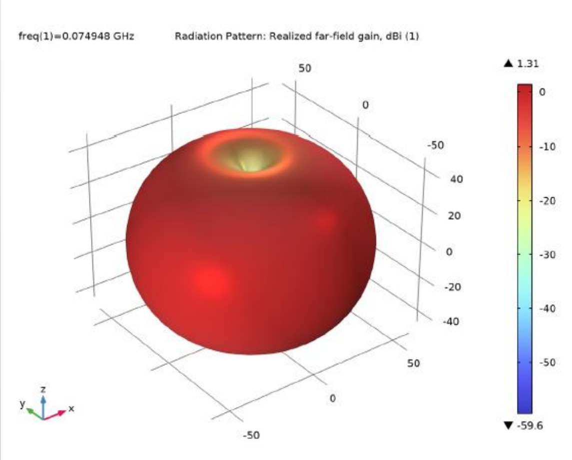






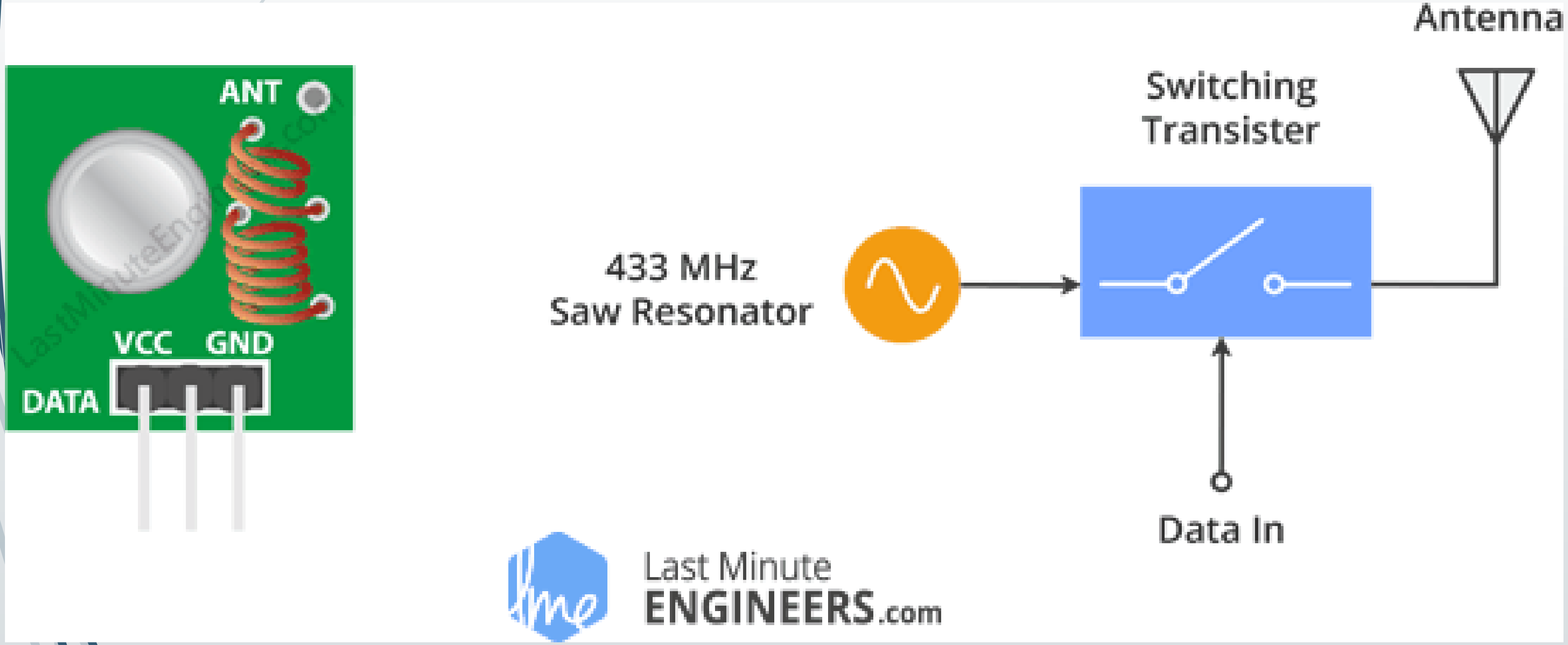






3. Experiment real - Modulul RF Tx-Rx 433MHz

Diagrama bloc a sistem de emisie (Tx)



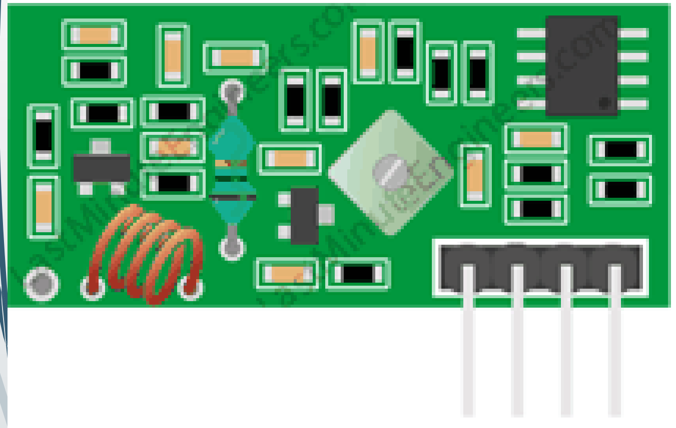
Specificatii:

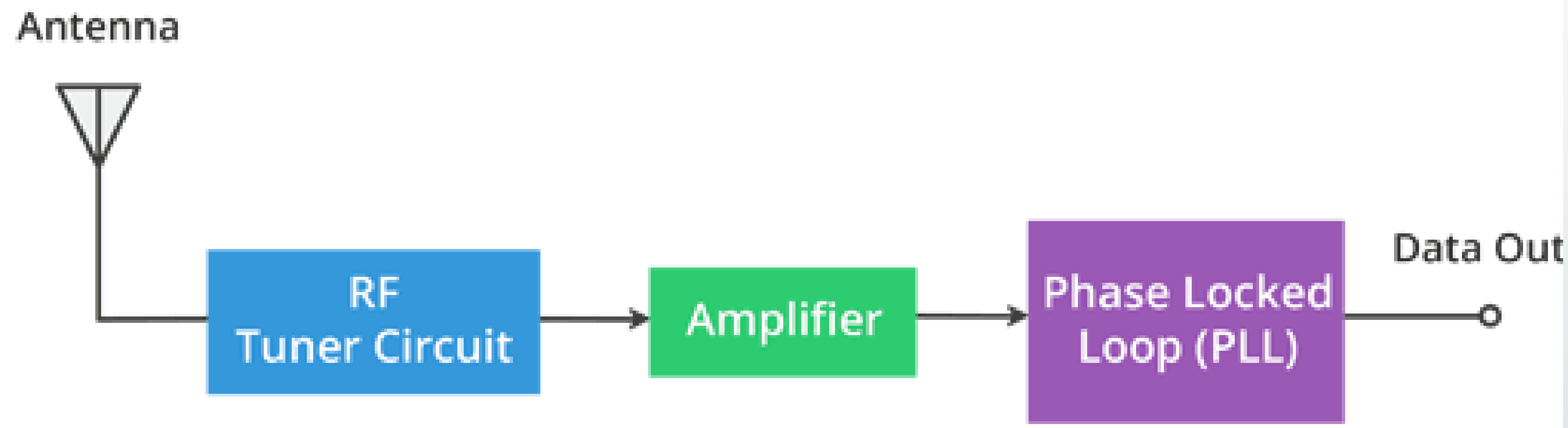
- Launch distance :20-200 meters (different voltage - different results)
- Operating voltage :3.5-12V
- Dimensions: 19 * 19mm
- Operating mode: AM
- Transfer rate: 4KB / S
- Transmitting power: 10mW
- Transmitting frequency: 433M

https://lastminuteengineers.com/433mhz-rf-wireless-arduino-tutorial/

3. Experiment real - Modulul RF Tx-Rx 433MHz

Diagrama bloc a sistem de receptie (Rx)





https://lastminuteengineers.com/433mhz-rf-wireless-arduino-tutorial/

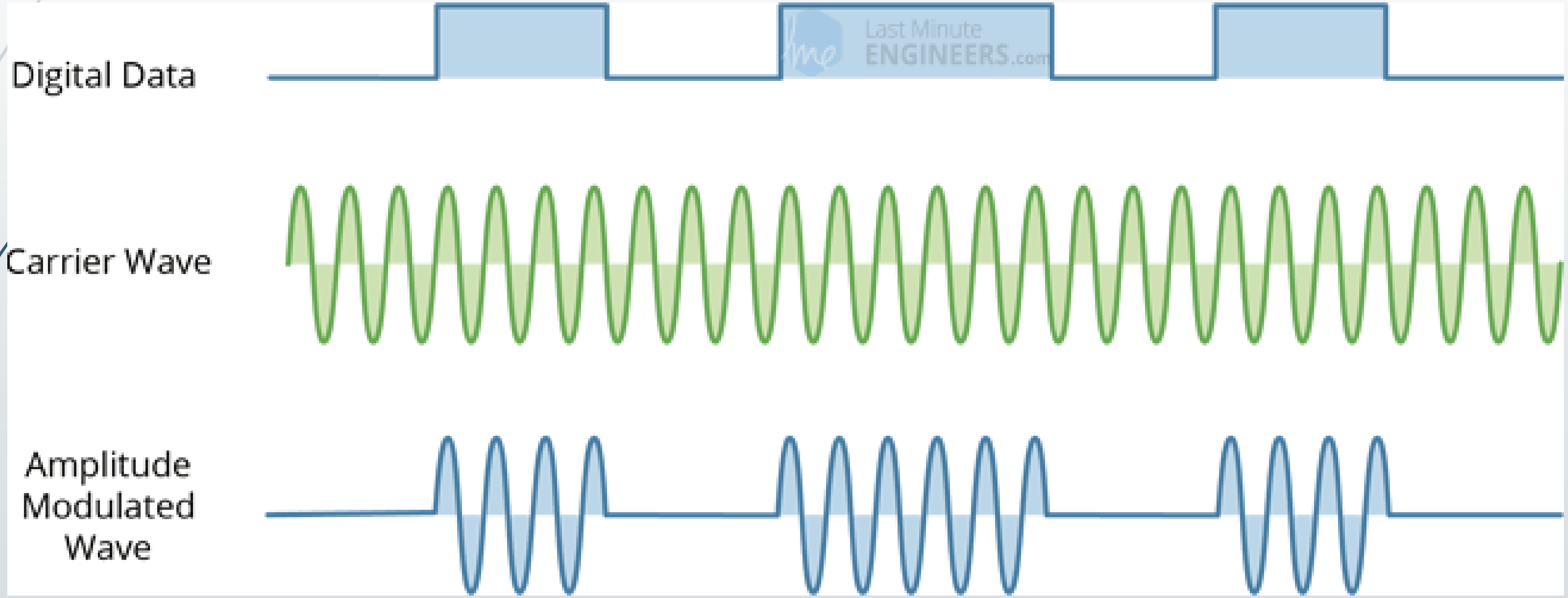
Specificatii:

- Operating mode: AM
- Operating voltage: DC5V
- Quiescent Current: 4mA
- Receiver sensitivity:-105DB
- Receivieng frequency: 433M
- Size: 30 * 14 * 7mm

3. Experiment real - Modulul RF Tx-Rx 433MHz

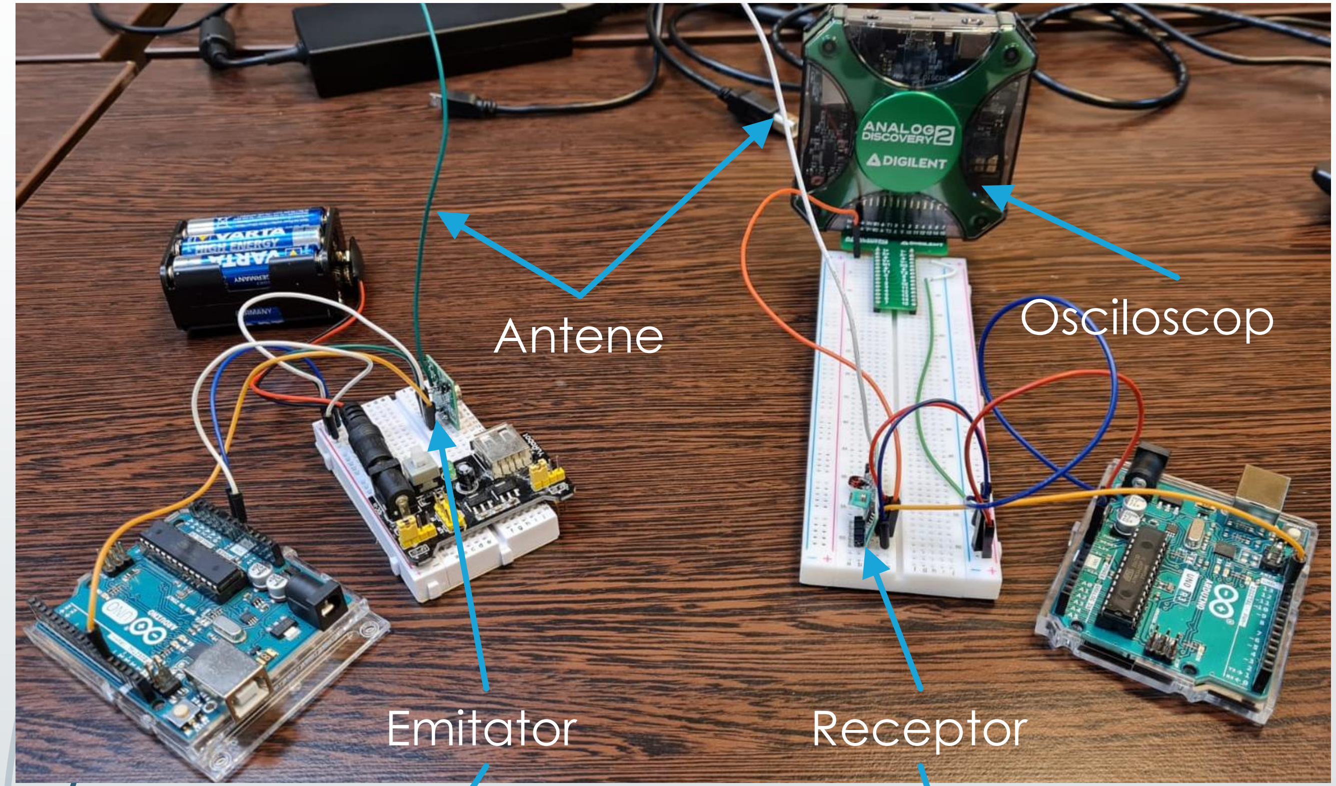
Mod de functionare

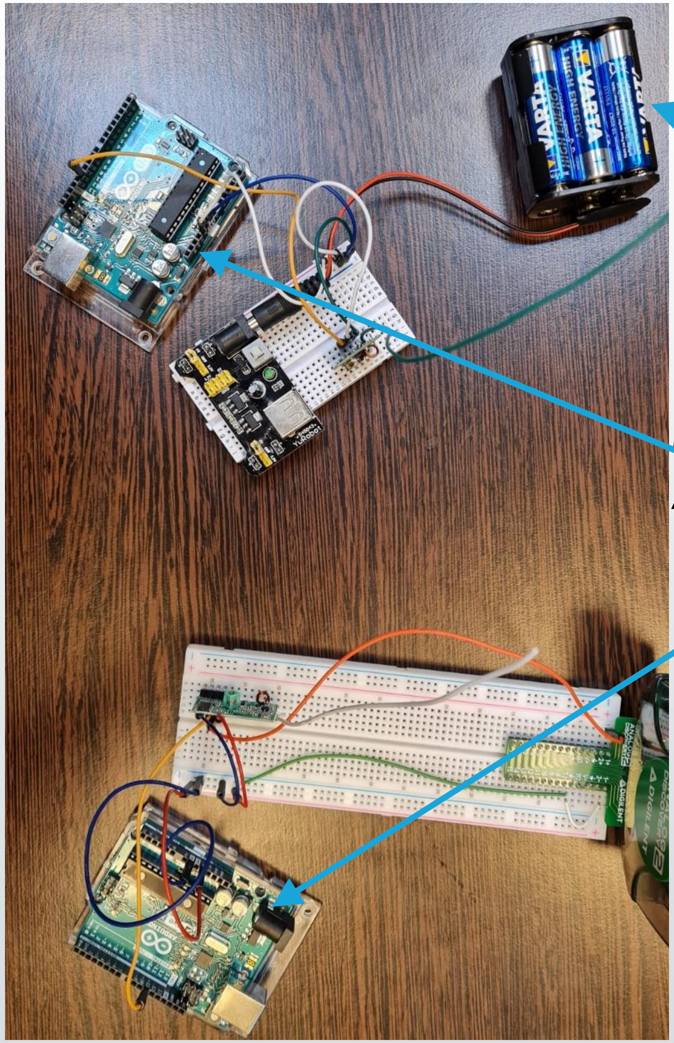
- Utilizeaza tehnici de modulatie digitala – ASK (Amplitude-shift keying) pentru a transimitere de date

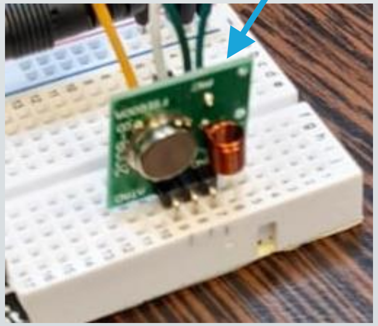


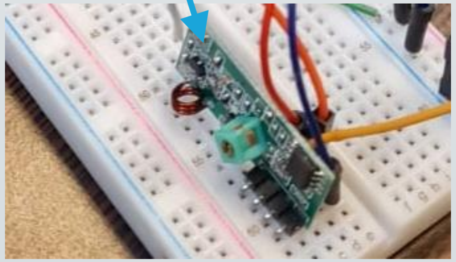
https://electronicscoach.com/amplitude-shift-keying.html

3. Experiment real – montaj experimental





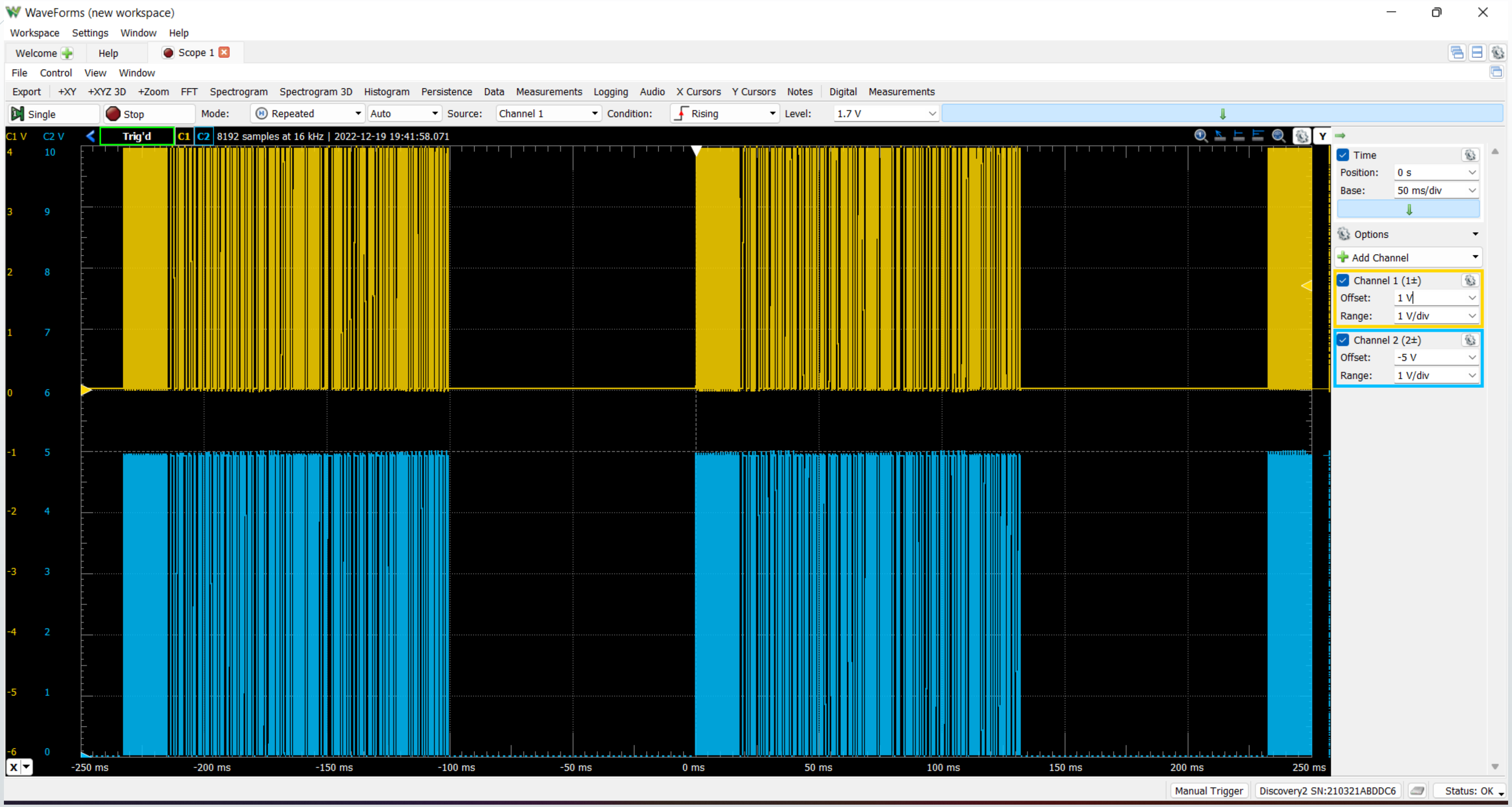




3. Experiment real - rezultate

Semnal receptat

Semnal emis



Take home message

Folosirea tehnologiei wireless in locul cablurilor:

- Avantaje: costul mai redus, mobilitatea, instalarea mai simpla, robustetea (se defecteaza mai greu decat reteau de cabluri), poate fi folosita si dupa dezastre (cutremure, inundatii, incendii).
- Dezavantaje,: interferente nerdorite cu alte sisteme wireless, securitate mai slaba decat cea oferita de cabluri, ingrijorarile privind efectul undelor (mai ales cele de are putere) asupra sanatatii.

In secolul XXI, comunicatiile bazate pe unde electromagnetice au avut o dezvoltare exploziva, care a generat profunde modificari sociale si culturale: posta electronica (email, prin Gmail sau alte servere), telefonia celulara, retelele de calculatoare, in general internetul (Chrome), cu multiplele sale aplicatiile. Smartphonurile au tot mai multa putere de calcul, memorie, dar si de comunicatii (au nu numai functii GSM, ci si Wi-Fi, Blootooth si RFID), la fel si laptopurile. Criza pandemica a contribuit si ea la folosirea tot mai intensiva a telemuncii si a scolii online, ambele bazate pe comunicatii fara fir. Infrastructura hardware, retele de calculatare si solutiii software dediate, cum sunt Team, Moodle, sau alte tehnici digitale colaborative.

Toate acestea ar fi fost imposibile fara telecomunicatiile prin unde electromagnetice. Si revolutia nu se termina aici.

https://ioe.org/

Notare

- Rezolvati quiz-ul P6.

- Pentru bonus (pana in saptamana 14)
  - – crearea unor figuri/animatii proprii illustrative pentru cursul de EM, folosind coduri proprii si instrumente software mai performante, de exemplu https://vtk.org/, https://www.paraview.org/
  - - realizarea unor experimente virtuale/reale care sa ilustreze conceptele discutate.