
Elektromagnetski valovi - od bežičnih komunikacija do elektromagnetskog smoga

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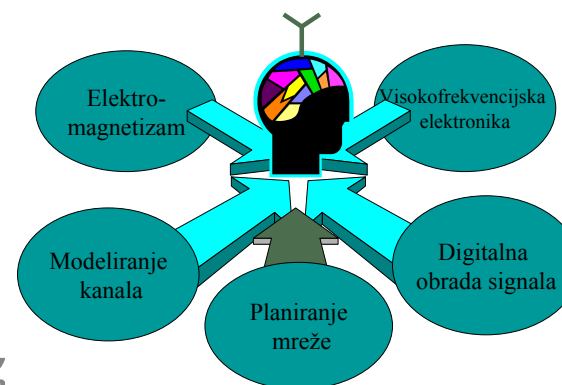


Sažetak

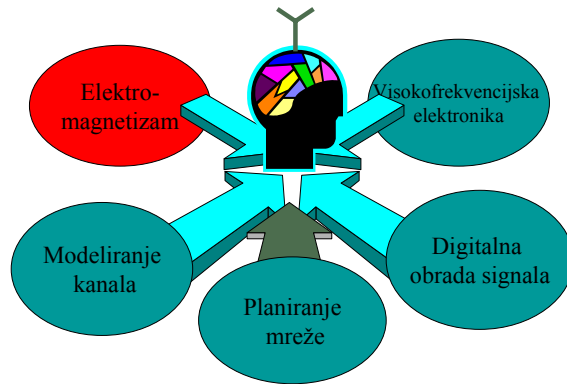
- Osnovna svojstva antena
- Konformne antene
- Mala priča iz povjesti
- usporedba znanstvenika i inženjera



Komunikacijski sustavi - ključne tehnologije



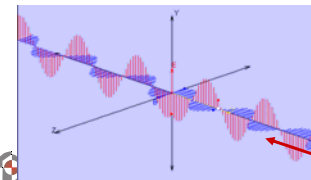
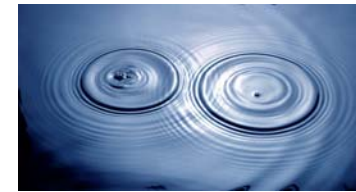
Komunikacijski sustavi - ključne tehnologije



Valovi

U svakidašnjem životu susrećemo se sa:

- vodenim valovima
- zvučnim valovima
- elektromagnetskim valovima

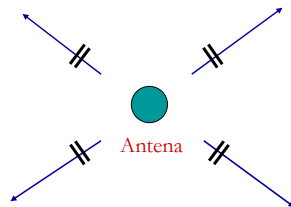


PROBLEM: Ne možemo vidjeti elektromagnetske valove!



Elektromagnetski valovi

- Elektromagnetski koncept:

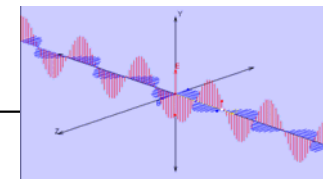
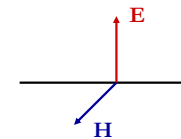


- Antena je struktura sastavljena od vodiča električne struje, koja zrači elektromagnetske valove, odnosno elektromagnetsku energiju.



Elektromagnetski valovi

- Planarni val – aproksimacija elektromagnetskog vala kojeg zrači antena:



$$E_x = E_0 \cos(\omega t - kz)$$

$$H_y = \frac{E_0}{\eta} \cos(\omega t - kz)$$

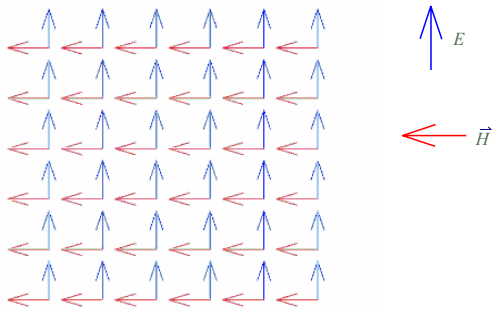
$$k = \frac{\omega}{v} = \frac{2\pi}{\lambda}, \quad \eta = \sqrt{\frac{\mu}{\epsilon}}$$

k – koeficijent rasprostiranja
 η – valna impedancija
 (u slobodnom prostoru
 $\eta \approx 377\Omega$).



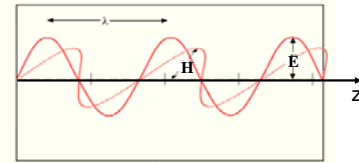
Planarni val

- Izgled planarnog vala u ravnini okomitoj na smjer širenja:

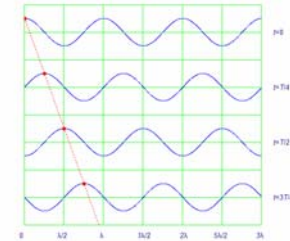


Planarni val

- Izgled planarnog vala:

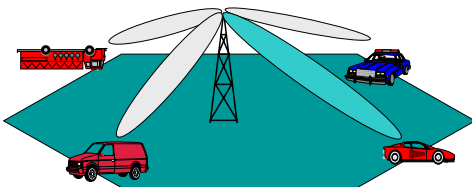


- Širenje planarnog vala u vremenu:



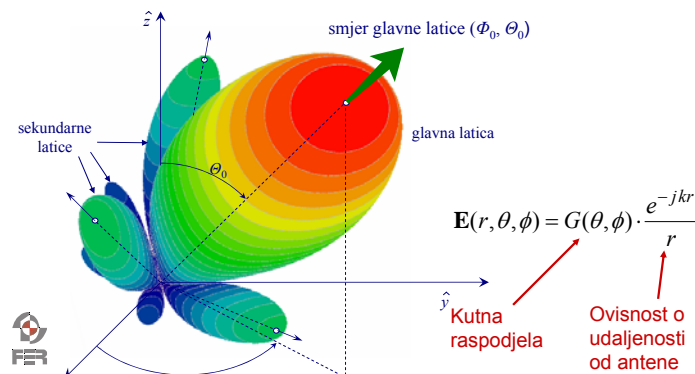
Elektromagnetski valovi

- Glupo je rasipati energiju – idealno bi bilo svu energiju fokusirati u smjeru prijammika.
- Antena – komponenta koja služi za usmjeravanje izračene elektromagnetske energije:



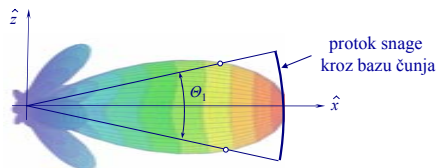
Antena – dijagram zračenja

3-D dijagram zračenja



Antene – dijagram zračenja

- *Dijagram zračenja* – opisuje kako antena zrači u promatranim smjerovima.
- *Usmjerenost antene* - kazuje koliko puta više antena zrači u željenom smjeru u odnosu na slučaj kada antena jednako zrači u svim smjerovima.
- *Kut usmjerenosti* – kut oko glavnog smjera zračenja unutar kojeg gustoća snage ne pada ispod polovice gustoće snage u glavnom smjeru.



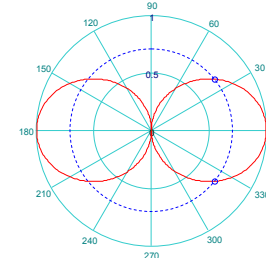
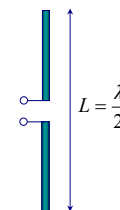
Uočiti - postoje dva kuta usmjerenosti:

- θ_1 (u xz ravnini)
- θ_2 (u xy ravnini)

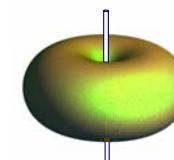


Dijagram zračenja električnog dipola

Dijagram zračenja u E -ravnini



3-D dijagram zračenja



Potrebna veličina antene

- Pri odabiru antene obično krećemo od kutova usmjerenosti θ_1 i θ_2
- Usmjerenost antene (broj koji kazuje koliko puta više antena zrači u željenom smjeru u odnosu na slučaj kada antena jednako zrači u svim smjerovima):

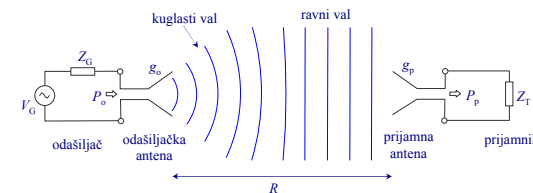
$$D \approx \frac{32400}{\theta_1 \theta_2}$$

- Potrebna površina antene:

$$A_{ef} = \frac{\lambda^2}{4\pi} D$$



Koliku snagu dobivamo na prijamniku?



Gustoća snage na mjestu prijamne antene: $S_{\text{sred}} = \eta_0 \frac{D_o P_o}{4\pi R^2}$ [W/m²]

$$P_p = A_{ef} S_{sr} = \eta_0 \eta_p \frac{D_o P_o A_{ef}}{4\pi R^2} \quad \text{ili} \quad P_p = \eta_p \eta_0 D_p D_o P_o \left(\frac{\lambda}{4\pi R} \right)^2 \quad [\text{W}]$$



Koliku snagu dobivamo na prijammniku?

$$P_p = \eta_p \eta_o D_p D_o P_o \left(\frac{\lambda}{4\pi R} \right)^2$$

← Udaljenost između antena
 (u valnim duljinama)

↖ Gubici antena
 (u metalu, dielektriku)

↗ Usmjerenost antena

Da bi dobili što veću snagu na prijemu potrebno je:

- Imati što veću usmjerenost D_o i D_p
- Imati što manje gubitke η_o i η_p
- Udaljenost (u valnim duljinama) treba biti što manja



Antene – osnovna svojstva

- **Primjer:** antena za mobilni telefon – budući da ne znamo gdje se nalazi bazna stanica, poželjno je da antena podjednako zrači u svim smjerovima.



- **Primjer:** antena za komunikaciju sa satelitom – poželjno je da antena većinu energije usmjeri u željenom smjeru.



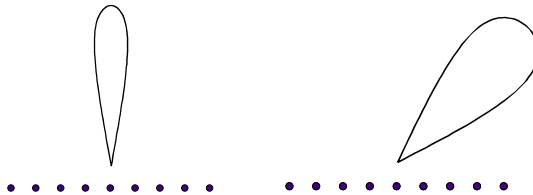
Potrebna veličina antene

- Ako želimo antenu s velikom usmjerenošću, tada možemo:

- Izabrati veliku antenu:
(u valnim duljinama)



- Formirati antenski niz:



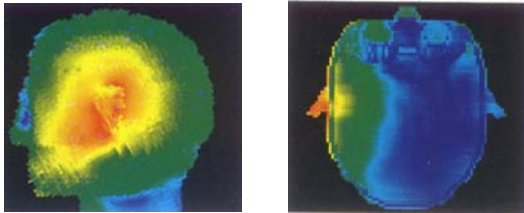
Antene – neželjena svojstva

- **Primjer:** mobilni telefon – budući da antena podjednako zrači u svim smjerovima, polovica snage se apsorbira u glavi.
- Posljedica: dolazi do lokalnog zagrijavanja tkiva.
- Pitanje: da li je to štetno?
- Dio smo globalnog eksperimenta, premalo vremena je prošlo da bi sa sigurnošću mogli reći što je štetno i u kojoj mjeri je štetno.



Antene – neželjena svojstva

- Primjer - lokalno zagrijavanje tkiva u glavi:



Antene – neželjena svojstva

- Elektromagnetski inženjeri mogu samo ustvrditi da li je prisutna jakost polja (gustoća snage) manja od maksimalno dozvoljene (\Rightarrow norme).
- Kako su se utvrdile maksimalno dozvoljene razine polja:
 - Ispitni miševi su obasjani elektromagnetskim valovima velike gustoće snage.
 - Zabilježene su razine polja kod kojih je dolazilo do promjena u strukturi tkiva
 - Tako dobivene razine električnog polja su smanjene 10 puta (gustoća snage je smanjena 100 puta) i te vrijednosti su proglašene maksimalno dozvoljenim razinama za pučanstvo.



Antene – neželjena svojstva

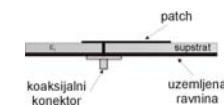
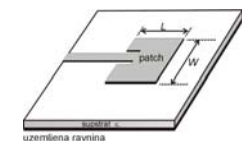
Neovisno o rezultatima znanstvenih istraživanja možemo napraviti dvije stvari:

- Djeca bi trebala vremenski što kraće telefonirati
- Ako vodimo duži razgovor, svakih cca. 5 minuta premjestimo telefon na drugo uho.



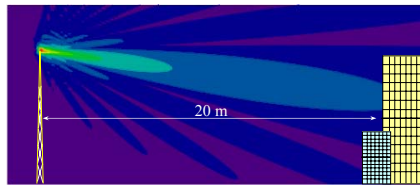
Antene – neželjena svojstva

- Pitanje: da li možemo učiniti da antena zrači u suprotnom smjeru od položaja glave?
- Odgovor: moramo povećati dimenziju antene.
- Kako ne želimo povećati dimenzije mobilnog telefona, potrebno je povećati frekvenciju (smanjiti valnu duljinu).
- GSM sustavi – bolja svojstva pokazuju mobilni uređaji na 1800 MHz nego na 900 MHz.
- Primjer ugrađene antene:



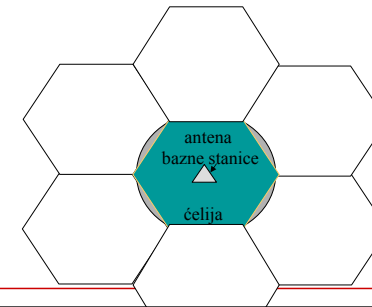
Antene – neželjena svojstva

- Bazne stanice – zrače puno većom snagom nego mobilni telefoni.
- *Pitanje*: da li je bolje da se bazna stanica nalazi na mojoj ili susjedovoj zgradi?
- *Odgovor*: na mojoj zgradi!
- Idealno: niti na mojoj niti na susjedovoj zgradi (ali tada nema mogućnosti telefoniranja mobilnim telefonom)!



Antene – neželjena svojstva

- *Pitanje*: da li su “opasnije” bazne stanice u gradovima ili izvan naseljenih područja?
- *Odgovor*: iako je u gradskim područjima puno veća gustoća basnih stanica, bazne stanice zrače veće snage izvan naseljenih područja (problem interferencije).



Sažetak

- Osnovna svojstva antena
- **Konformne antene**
- Mala pričica iz povjesti
 - usporedba znanstvenika i inženjera



Konformne antene

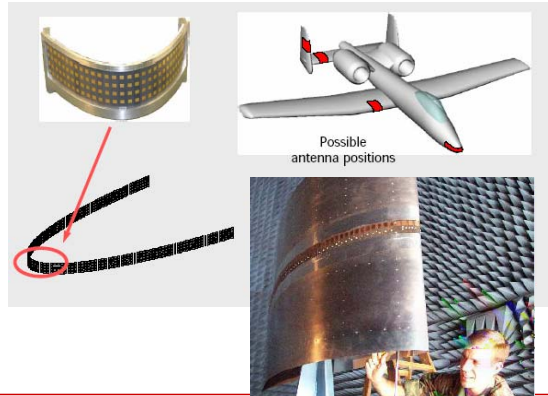
Konformne antene – potencijalne prednosti nad uobičajnim (standardnim) rješenjima:

- Mogućnost postizanja aerodinamičkog profila
- Mogućnost usmjeravanja glavne latice u proizvoljnom smjeru
- Mogućnost izgradnje puno ljepših antena
- Dimenzije planarnih i konformnih antena su slične.



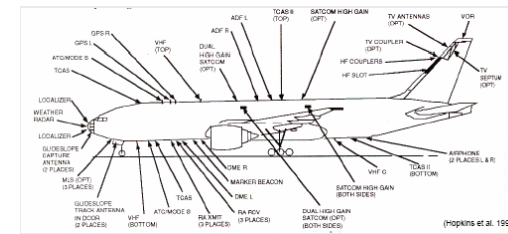
Konformne antene

- Aerodinamički razlozi



Konformne antene

- Tipičan civilni avion (npr. Airbus 319/320)

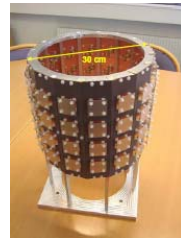


Na avionu se nalazi oko 40 antena.



Konformne antene

- Pametne bazne stanice

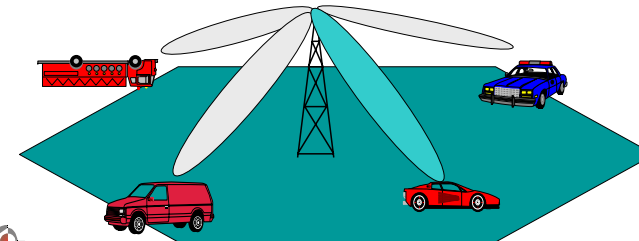


Ispitni modeli
Ericsson AB, Göteborg, Švedska



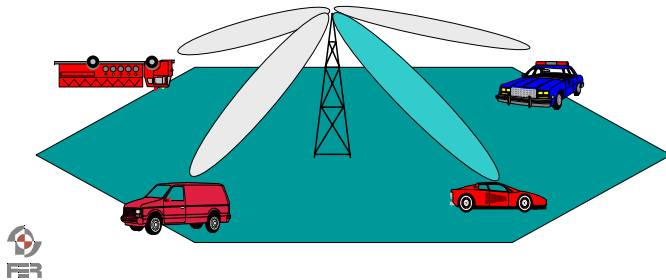
Pametne bazne stanice –veći kapacitet

- Češće ponavljanje frekvencije
- Višestruki pristup prostorne podjele (SDMA)



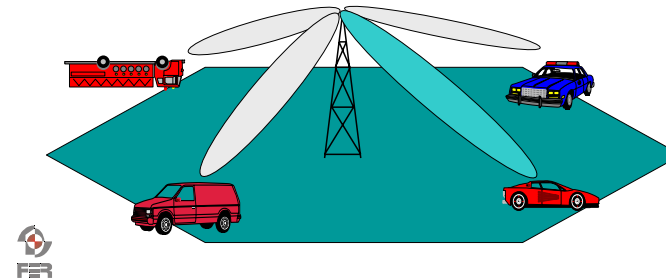
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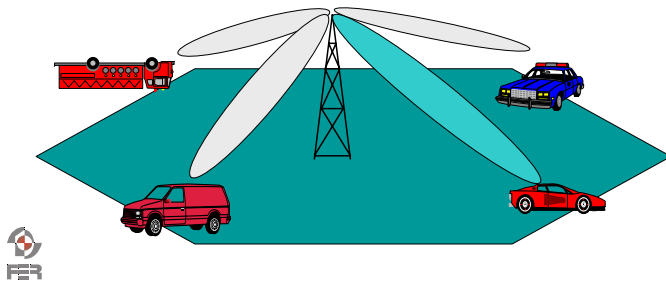
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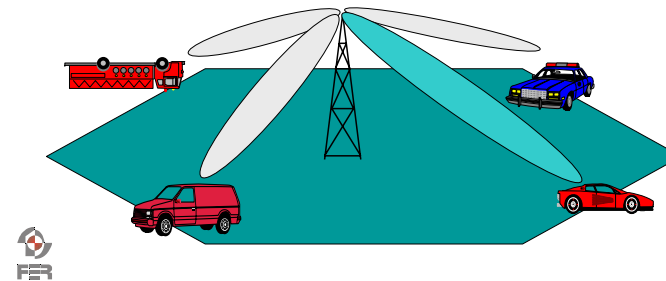
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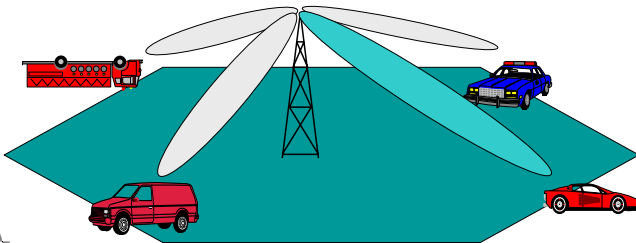
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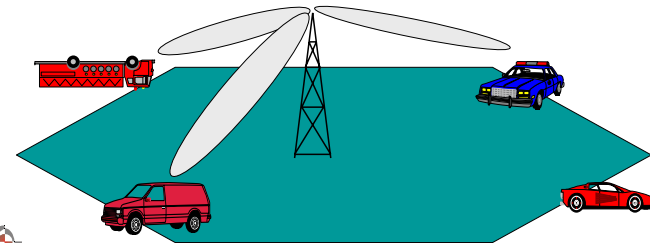
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Pametne bazne stanice –veći kapacitet

- Češće ponavljanje frekvencije
- Višestruki pristup prostorne podjele (SDMA)



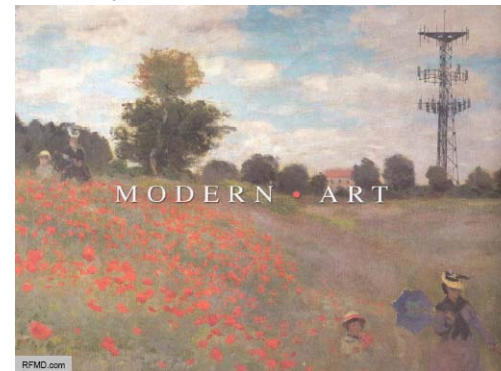
Konformne antene

- Claude Monet (1840 – 1926)



Konformne antene

- Moderna umjetnost !?!



Konformne antene posvuda ?!?

- Na drvetu



- Na uličnim stupovima

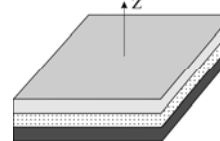


- U crkvenom križu

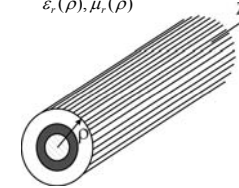


One-dimensional (1D) structures

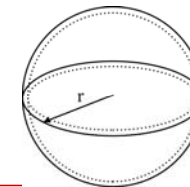
Multilayer planar structure
 $\epsilon_r(z), \mu_r(z)$



Multilayer cylindrical structure
 $\epsilon_r(\rho), \mu_r(\rho)$



Multilayer spherical structure
 $\epsilon_r(r), \mu_r(r)$



One-dimensional (1D) structures

- The structures are homogeneous in two dimensions and vary in one dimension.
- Planar structure:
 - homogeneous in x and y directions
 - varies in z direction
- Cylindrical structure:
 - homogeneous in ϕ and z directions
 - varies in ρ direction
- Spherical structure:
 - homogeneous in θ and ϕ directions
 - varies in r direction



Plane wave expansion



- In a homogeneous media, all finite sources may be represented by a set of plane waves with various propagation directions, amplitudes and phases.



Plane wave expansion

- Mathematical description of uniform plane wave:

$$\mathbf{E}(x, y, z, t) = \hat{u} E_0 e^{-jk_x x} e^{-jk_y y} e^{-jk_z z} e^{j\omega t}$$

k_x -propagation constant in x -direction

k_y -propagation constant in y -direction

k_z -propagation constant in z -direction

$$k_x^2 + k_y^2 + k_z^2 = k^2 = \frac{2\pi}{\lambda}$$

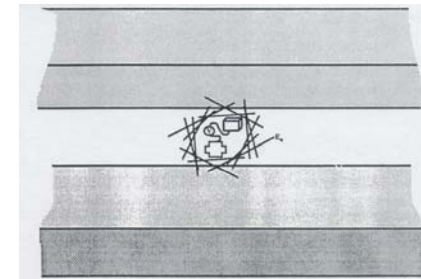
- If the plane wave is propagating in (θ, ϕ) direction

$$k_x = k \sin \theta \cos \phi, \quad k_y = k \sin \theta \sin \phi, \quad k_z = k \cos \theta$$

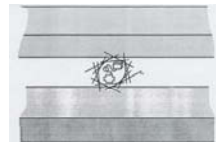


General multilayer problem

- Example of a source located inside planar structure:



Plane wave representation – general multilayer problem

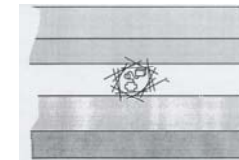


- At each boundary the tangential components of the E- and H-field are continuous.
- Consequently, variation of the total field in x - and y -directions (in directions where the structure is homogeneous):

$$e^{-jk_x x} e^{-jk_y y}$$



Plane wave representation – general multilayer problem



- The variation of the EM field in x - and y -directions is known:

$$e^{-jk_x x} e^{-jk_y y}$$

- Only the field variation in z -direction is unknown.
- Therefore, for each plane wave excited by the source we need to solve **one-dimensional (1D)** problem.



Plane wave expansion - spectral domain approach

- Definition of inverse Fourier transformation

$$\mathbf{E}(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\mathbf{E}}(k_x, k_y, z) e^{-jk_x x} e^{-jk_y y} dk_x dk_y$$

$$\cong \sum_{-\infty}^{\infty} \sum_{-\infty}^{\infty} \frac{1}{4\pi^2} \tilde{\mathbf{E}}(k_x, k_y, z) \Delta k_x \Delta k_y e^{-jk_x x} e^{-jk_y y}$$

- The inverse Fourier transformation has a form of a sum of plane waves (in x- and y-directions).
- Therefore, the plane wave expansion is mathematically obtained by the Fourier transformation.



Summary of spectral domain method

- Cylindrical structures:

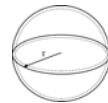
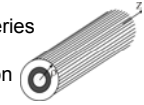
- The Fourier transformation in z-direction and Fourier series in ϕ -direction is applied to fields and currents.
- For each cylindrical wave excited by the source variation of the total field in z- and ϕ -direction is:

$$e^{-jk_z z} e^{-jm\phi}$$

- Only the field variation in ρ -direction is unknown.

- Spherical structures

- The vector-Legendre transformation is applied to fields and currents.
- The field variation in r -direction is unknown.



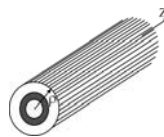
Mathematical background of cylindrical wave representation

Cylindrical structures:

- Definition of Fourier transformation in the ρ - direction and Fourier series in the ϕ - direction:

$$\tilde{\mathbf{E}}(\rho, m, k_z) = \int_{-\infty}^{\infty} \int_0^{2\pi} \mathbf{E}(\rho, \phi, z) e^{jm\phi} e^{jk_z z} d\phi dz$$

$$\mathbf{E}(\rho, \phi, z) = \frac{1}{4\pi^2} \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\mathbf{E}}(\rho, m, k_z) e^{-jm\phi} e^{-jk_z z} dk_z$$



Summary of spectral domain method

- Two-dimensional Fourier transformation is applied in directions where the structure is homogeneous.
- In these two directions each spectral component of EM field has the same variation as the source.
- Therefore, three-dimensional problem is transformed in spectrum of one-dimensional problems.



Method of Moments (MoM)

- Let L denotes a linear operator (differential, integral, ..).
- We need to solve the following integral equation:

$$Lu = w$$

← Linear operator ← Known function
← Unknown function

- In electromagnetic problems
 - $u = \mathbf{J}$
 - $L(u) = \mathbf{E}(\mathbf{J})$
 - $w = \mathbf{E}^{\text{inc}}$ - incident (known) field



Method of Moments (MoM)

- 1st step: approximation of unknown function u

$$u = \sum_{i=1}^M \alpha_i u_i$$

← Basis functions ← Unknown coefficients

$$Lu = \sum_{i=1}^M \alpha_i L(u_i) = w$$

- Now we have 1 equation with M unknowns ($\alpha_i, i = 1, \dots, M$)



Method of Moments (MoM)

- 2nd step: testing the equation with M testing functions g_j (testing means multiplying and integration over test function domain)

$$\sum_{i=1}^M \alpha_i L(u_i) = w \quad | \cdot g_j \quad \leftarrow \text{Test functions}$$

$$\sum_{i=1}^M \alpha_i \int_{\text{domain of } g_j} g_j \cdot L(u_i) dS = \int_{\text{domain of } g_j} g_j \cdot w dS$$

$$\sum_{i=1}^M \alpha_i \langle g_j, L(u_i) \rangle = \langle g_j, w \rangle$$



The result is the system of M equations with M unknowns.

Method of Moments (MoM)

- The result is the system of M equations with M unknowns.

$$\sum_{i=1}^M \alpha_i \langle g_j, L(u_i) \rangle = \langle g_j, w \rangle, \quad j = 1, \dots, M$$

$$\begin{bmatrix} \langle g_1, L(u_1) \rangle & \langle g_1, L(u_2) \rangle & \cdots & \langle g_1, L(u_M) \rangle \\ \langle g_2, L(u_1) \rangle & \langle g_2, L(u_2) \rangle & \cdots & \langle g_2, L(u_M) \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle g_M, L(u_1) \rangle & \langle g_M, L(u_2) \rangle & \cdots & \langle g_M, L(u_M) \rangle \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_M \end{bmatrix} = \begin{bmatrix} \langle g_1, w \rangle \\ \langle g_2, w \rangle \\ \vdots \\ \langle g_M, w \rangle \end{bmatrix}$$



Method of Moments (MoM)

- The elements of the MoM matrix have a form:

$$Z_{ij} = \langle \mathbf{J}_i, \mathbf{E}(\mathbf{J}_j) \rangle$$

- Calculation of the elements of the MoM matrix in the spectral domain (e.g. cylindrical case):

$$\begin{aligned} Z_{ij} &= \langle \mathbf{J}_i, \mathbf{E}(\mathbf{J}_j) \rangle = \int_{\text{test function}} \int_{\text{basis function}} \mathbf{J}_i(\phi, z) \cdot \mathbf{E}(\mathbf{J}_j(\phi', z')) dS' dS \\ &= \int_{\text{test function}} \mathbf{J}_i(\phi, z) \cdot \left[\frac{1}{4\pi^2} \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\mathbf{G}}(m, k_z, \rho | \rho') \tilde{\mathbf{J}}_j(m, k_z) e^{-jm\phi} e^{-jk_z z} dk_z \right] dS \\ &= \frac{1}{4\pi^2} \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{\mathbf{J}}_i(-m, -k_z) \tilde{\mathbf{G}}(m, k_z, \rho | \rho') \tilde{\mathbf{J}}_j(m, k_z) \end{aligned}$$



Calculation of Green's functions

Analytic methods:

- need less computer time
- if the topology of the problem is changed, the new Green's functions must be derived
- convenient for problems where the topology of the structure is fixed.

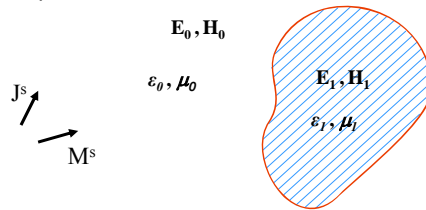
Numerical methods:

- more general
- need more computer time
- convenient for problems where the topology of the structure is changeable.



The equivalence principle

- Example:



- We need to determine $\mathbf{E}_0, \mathbf{H}_0$ and $\mathbf{E}_1, \mathbf{H}_1$:

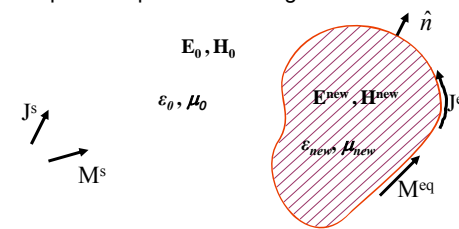
$$\mathbf{E}_0 = \mathbf{E}_0(\mathbf{J}^s) + \mathbf{E}_0(\mathbf{M}^s) = \int \overline{\mathbf{G}}_{EJ} \cdot \mathbf{J}^s dV' + \int \overline{\mathbf{G}}_{EM} \cdot \mathbf{M}^s dV'$$



Problem: we do not know the Greens functions.

The equivalence principle

- The equivalent problem for Region 0:



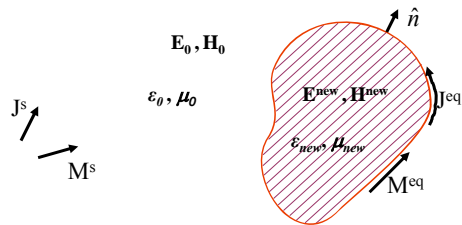
- $\mathbf{E}^{\text{new}}, \mathbf{H}^{\text{new}}$ – some arbitrary EM fields which fulfill the Maxwell equations.
- In order to fulfill the boundary conditions at the boundary between two regions we have to introduce the equivalent sources:



$$\mathbf{J}^{\text{eq}} = \hat{n} \times (\mathbf{H}_0 - \mathbf{H}_{\text{new}}), \quad \mathbf{M}^{\text{eq}} = -\hat{n} \times (\mathbf{E}_0 - \mathbf{E}_{\text{new}})$$

The equivalence principle

- The equivalent problem for Region 0:



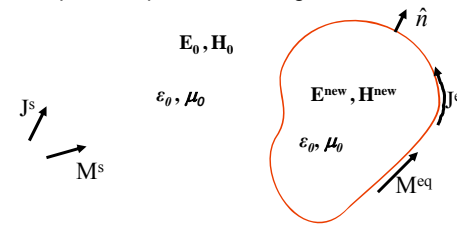
- How to select \mathbf{E}^{new} and \mathbf{H}^{new} ?

- ⇒ The simplest choice is $\mathbf{E}^{\text{new}} = 0$ and $\mathbf{H}^{\text{new}} = 0$.
- ⇒ In that case we can put any material inside the Region 1.
- ⇒ Love's equivalence principle: $\epsilon_{\text{new}} = \epsilon_0$ and $\mu_{\text{new}} = \mu_0$.



The equivalence principle

- The equivalent problem for Region 0:



- The Green's functions for the equivalent problem are known (Green's functions for the homogeneous space).
- However, we need to determine the equivalent currents \mathbf{M}^{eq} and \mathbf{J}^{eq} .
(there is no free lunch).



G1DMULT algorithm

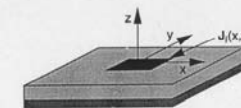
G1DMULT algorithm - example of algorithms that can treat general structures:

- algorithm calculates Green's functions in spectral domain
- planar, circular-cylindrical and spherical structures
- multilayer structures

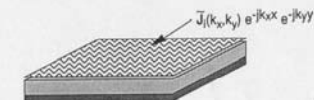


Structure of G1DMULT algorithm planar case

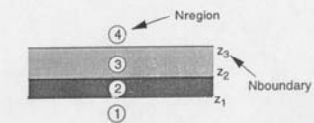
(a) 3-D problem



(b) Harmonic 1-D problem



(c) Definition of material boundaries and regions
Regions 1 and 4 (Nregion) extend to $-\infty$, respectively



Structure of G1DMULT algorithm planar case (cont'd)

(d) Equivalent problem of region j
Boundary fields: E_j^b and H_j^b

$\vec{M}_j = \vec{E}_j^b \times \vec{n}_u$ $\vec{J}_j = \vec{n}_u \times \vec{H}_j^b$

$\vec{M}_{j-1} = \vec{E}_{j-1}^b \times \vec{n}_l$ $\vec{J}_{j-1} = \vec{n}_l \times \vec{H}_{j-1}^b$

(e) The basic homogeneous harmonic 1-D field problem

$\vec{J} e^{-jk_x x} e^{-jk_y y}$
 $z = 0$

Structure of G1DMULT algorithm

- EM field inside each layer (e.g. electric field):

$$\vec{E}_j = \vec{G}_{EJ}^{\text{homo}} \vec{J}_{j-1}^{\text{eq}} + \vec{G}_{EJ}^{\text{homo}} \vec{J}_j^{\text{eq}} + \vec{G}_{EM}^{\text{homo}} \vec{M}_{j-1}^{\text{eq}} + \vec{G}_{EM}^{\text{homo}} \vec{M}_j^{\text{eq}}$$

$$+ \vec{G}_{EJ}^{\text{homo}} \vec{J}_j^{\text{exci}} + \vec{G}_{EM}^{\text{homo}} \vec{M}_j^{\text{exci}}$$

↑ region
↑ boundary
- Boundary conditions for each boundary:

$$\vec{E}_{x,j+1} - \vec{E}_{x,j} = 0, \quad \vec{E}_{y,j+1} - \vec{E}_{y,j} = 0,$$

$$\vec{H}_{x,j+1} - \vec{H}_{x,j} = 0, \quad \vec{H}_{y,j+1} - \vec{H}_{y,j} = 0.$$

↑ region

Structure of G1DMULT algorithm

- Matrix inside G1DMULT:

EM field components at 1st boundary

EM field components at 2nd boundary

EM field components at Nth boundary

12 terms $\neq 0$

sub-diagonal matrix

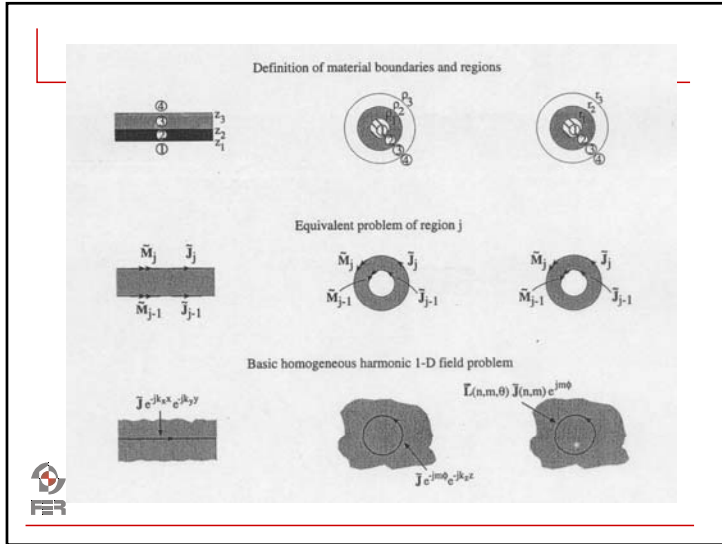
excitations

amplitudes of equivalent currents (4 unknowns per boundary)

Structure of G1DMULT algorithm

3-D problem

Harmonic 1-D problem



Development of MoM programs

We have developed several programs for analyzing different types of conformal arrays:

Benchmarking process - spherical patch array

- Comparison of calculated and measured magnitude of S_{21} parameter in E-plane (patch separation is 30.9°)

$R_{GND} = 18.5 \text{ cm}$
 $\epsilon_r = 1.0$
 $h = 0.52 \text{ cm}$
 $W_\theta = 5.1 \text{ cm}$
 $W_\phi = 5.1 \text{ cm}$
 $\theta_{probe} = 1.95 \text{ cm}$
 $\phi_{probe} = 0$
 $\Delta\theta = 10.25 \text{ cm}$
 $\Delta\phi = 0$

Benchmarking process

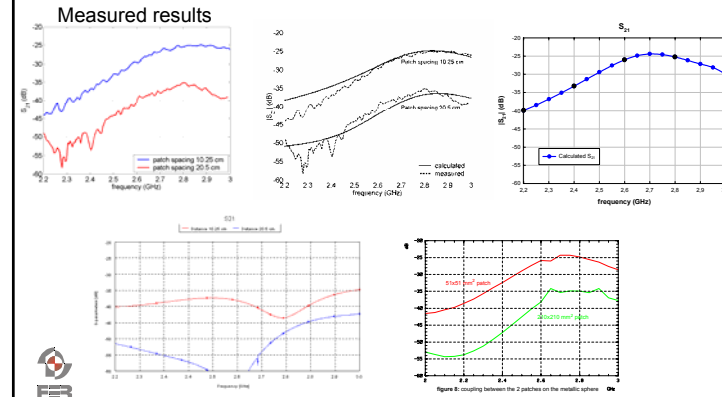
- Question – why is so important to analyze mutual coupling between antennas in antenna array?

Benchmarking process

Software description	S_{21max} frequency	S_{21max}	CPU time per frequency point
Measured	2.87 GHz	-24.8 dB	
MoM Spectral – domain	2.83 GHz	-24.9 dB	4.4 sec
MoM 3D solver	2.7 GHz	-24.5 dB	47 hours
MoM 3D solver	2.5 GHz	-37.5 dB	2 hours
FEM	2.7 GHz	-24.0 dB	8 min



Benchmarking process



Sažetak

- Osnovna svojstva antena
- Konformne antene
- Mala priča iz povjesti
- usporedba znanstvenika i inženjera



Glavni likovi u priči

- H.H. – znanstvenik
- N.T. – inženjer i znanstvenik
- G.M. – inženjer i poslovni čovjek



James Clerk Maxwell

- Elektromagnetski valovi prvo su teoretski predviđeni!
- James Clerk Maxwell je 1873. g. teoretski opisao širenje elektromagnetskih valova:

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{d\mathbf{B}}{dt}$$
$$\nabla \times \mathbf{B} = \frac{\mu}{c} \left(4\pi \mathbf{i} + \frac{d\mathbf{D}}{dt} \right)$$
$$\nabla \cdot \mathbf{D} = 4\pi \rho$$
$$\nabla \cdot \mathbf{B} = 0$$

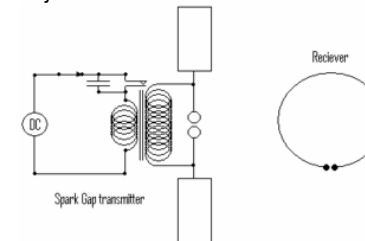


James Clerk Maxwell.



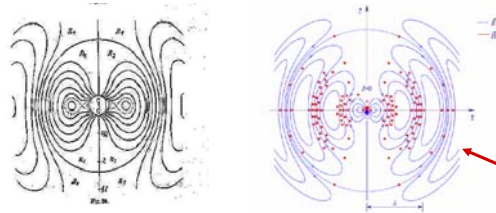
Heinrich Rudolf Hertz

- Heinrich Rudolf Hertz (1857 –1894) pokušao je eksperimentalno dokazati postojanje elektromagnetskih valova.
- U eksperimentu je koristio kratki dipol na predajnoj strani te prstenastu antenu na prijamnoj strani:



Heinrich Rudolf Hertz

- Osim što je eksperimentalno dokazao postojanje elektromagnetskih valova, otkrio je kako takvi valovi opadaju s udaljenosti, kakva im je prostorna ovisnost te kako su polarizirani.
- Dokazao je također da se elektromagnetski valovi šire brzinom svjetlosti.



Vježba
za studente



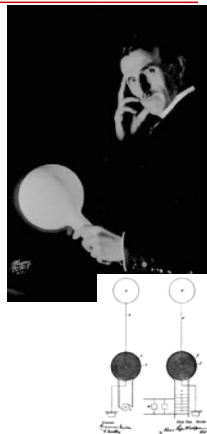
Heinrich Rudolf Hertz

- Između ostaloga, Heinrich Hertz je ustvrdio:
Ne vjerujem da će bežični valovi koje sam otkrio imati ikakvu praktičnu primjenu!
- Nažalost, Heinrich Hertz je umro veoma mlad (1894. godine).



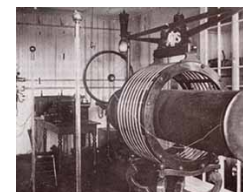
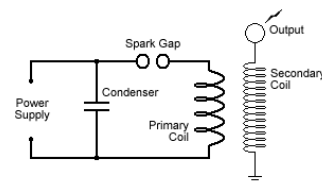
Nikola Tesla – demonstracija radiokomunijskog sustava

- **1893. godine** u St. Louis-u (SAD) Nikola Tesla je javno demonstrirao bežičnu komunikaciju.
- Iste godine je u detalje opisao principe radiokomunikacije.
- Dva glavna patenta:
 - U.S. patent 645576, "System of Transmission of Electrical Energy" (filed Sept. 1897)
 - U.S. patent 649621, "Apparatus for Transmission of Electrical Energy" (filed Feb. 19, 1900).



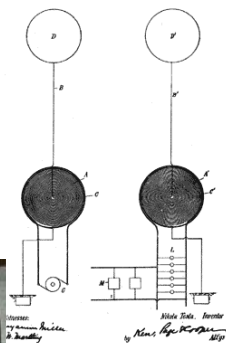
Nikola Tesla – radiokomunijski sustav Izvor visokofrekvencijskog signala

- Teslin transformator – izvor visokonaponskih odnosno visokofrekvencijskih signala.
- Zanimljivost – jedini uređaj koji nosi Teslino ime.



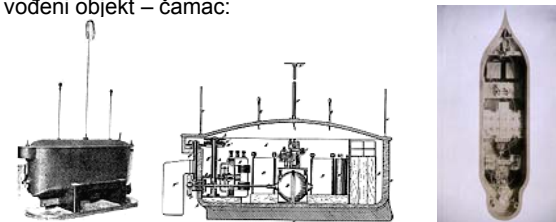
Nikola Tesla – radiokomunijski sustav Prilagođenje

- Tesla je shvatio da u kvalitetnom predajniku i prijamniku moramo misliti na prilagođenje:
 - Antena mora biti prilagođena na izlaz predajnika i na okolinu u koju emitira (zato su Tesline antene bile uzemljene)
 - Prijamnik mora biti osjetljiv na uski frekvencijski pojas (zato je Tesla stavio rezonantni titrajni krug u prijamnik).
- Današnji primopredajnici upravo rade na tom principu.



Nikola Tesla – radiokomunijski sustav Daljinski vođeni uređaji - teleautomati

- **1898. godine** u New Yorku Tesla predstavlja prvi daljinski vođeni objekt – čamac:

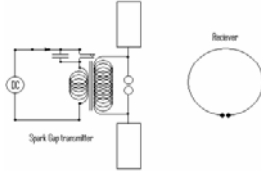


- Na demonstraciji sustava posjetioci su grčevito tražili žice s kojim je brod spojen.
- Uređaj predstavlja rođenje telemetrijskih sustava (danas se koriste od dječijih igračka do svemirskih brodova).

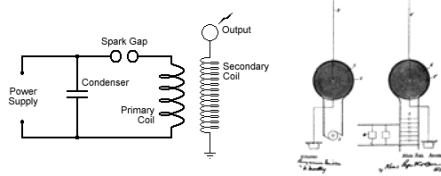


Usporedba Hertzovog i Teslinog sustava

■ Sustav Heinricha Hertza



■ Sustav Nikole Tesle



Tko je izumitelj radija?

- Za izumitelja radija često se smatra Guglielmo Marconi.



Tko je izumitelj radija?

- Za izumitelja radija često se smatra Guglielmo Marconi:
 - 1896. godine dobio je patent u Velikoj Britaniji (inicijalni patent za radio). Patent je sakupio ideje raznih Teslinih eksperimenata i principe rada instrumenata koje su drugi izumili (npr. Popov). Za usporedbu, Teslini glavni patenti iz radiotehnike bili su objavljeni 1897. i 1900. godine.
 - 1898. godine Marconi je otvorio prvu tvornicu radija u Velikoj Britaniji (50 zaposlenih radnika). Tvrtka je poslije razvila radijski sustav komunikacije s brodovima.
 - 1901. godine Marconi je uspio prenjeti telegrafski signal preko Atlantika.



Tko je izumitelj radija?

- Za izumitelja radija često se smatra Guglielmo Marconi (nastavak):
 - 1909. godine Marconi dobiva Nobelovu nagradu (Tesla to smatra velikom nepravdom).
 - 1943. godine (u doba kada su i Tesla i Marconi bili već mrtvi) Vrhovni sud SAD-a je poništio Marconijev patent na osnovu kojeg je ostvario prijenos signala preko Atlantika. Sud je naime donio odluku po kojoj nema ništa novog u Marconijevom patentu, već je sve opisano u patentima čiji su autori Tesla, Lodge i Stone.



Nikola Tesla

Svjetski komunikacijski i energetska sustav

Pitanje: Zašto je Tesla osato nepoznat u području radiokomunikacija?

Tesla je od 1899. do 1902. godine razvijao **Svjetski sustav** koji je trebao omogućavati:

- bežični prijenos energije
- bežični prijenos korisničkih informacija
- bežični prijenos telemetrijskih informacija



Svjetski komunikacijski i energetska sustav

- Izgradnja započela 1899. godine u Colorado Springs, a nastavljena 1901. godine na Long Island.
- U tom razdoblju izvršen niz pokusa s visokofrekvencijskim i visokonaponskim signalima.
- Postignuti naponi od 10 do 12 miliona volta (*današnji dalekovodi – do 400 kV*).
- Postignute munje duže od 30 metara.
- Cilj: prijenos informacija i energije na daljinu.



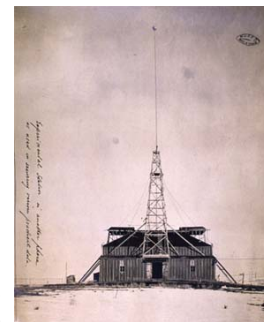
Svjetski komunikacijski i energetska sustav

- Bežični prijenos **energije** je moguć!
- Tesla je demonstrirao bežični prijenos energije na 40 km udaljenost (pri tome je za demonstraciju upogonio 200 žarulja i jedan elektromotor).
- Postoji "mal" problem kod takvog sustava:
 - Na takav bežični sustav svatko bi se mogao spojiti, kao što svatko može gledati televizijski program.
 - Stoga ostaje nejasno kako bi se naplaćivala potrošnja električne energije.
 - Tesla je bio veliki humanista te je smatrao da svatko ima pravo besplatno dobiti energije koliko mu treba.
- Dodatni problem – elektromagnetska kompatibilnost.



Svjetski komunikacijski i energetska sustav

- Izgled tornja u Colorado Springs (1900. godina)
- Izgled tornja na Long Island (1901. godina)



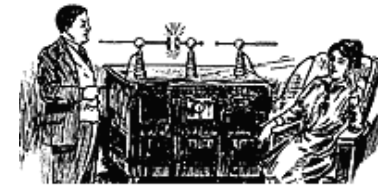
Propast ideje svjetskog komunikacijskog i energetskog sustava

- Obustava izgradnje tornja na Long Islandu obustavljena je 1902. godine, a toranj je srušen 1917. godine.
- Glavni razlog je prestanak financiranja, posebice od glavnog investitora – Morgana.
- Tri glavna razloga prestanka financiranja:
 - recesija na svjetskim burzama (+ devalvacija dolara)
 - 12. prosinca 1901. Marconi je ostvario telegrafsku vezu Europa – SAD, zasnovanu na Teslinim patentima i na razmjerno *jednostavnim i jeftinim* uređajima.
 - ideja da SAD bežičnim prijenosom “darivaju” energiju svima na Zemlji kome je ona potrebna nije naišla na odobravanje političara.



Teslini izumi u polju elektromagnetizma

- Završno pitanje: koji izum u polju elektromagnetizma je Tesli donio najviše novaca?
- Odgovor: uređaj za elektroterapiju!



'Electric' treatment with a Tesla transformer (Electrical Experimenter, 1917)



Hvala na
pažnji