Modeling the communication process at the deep physical layer level

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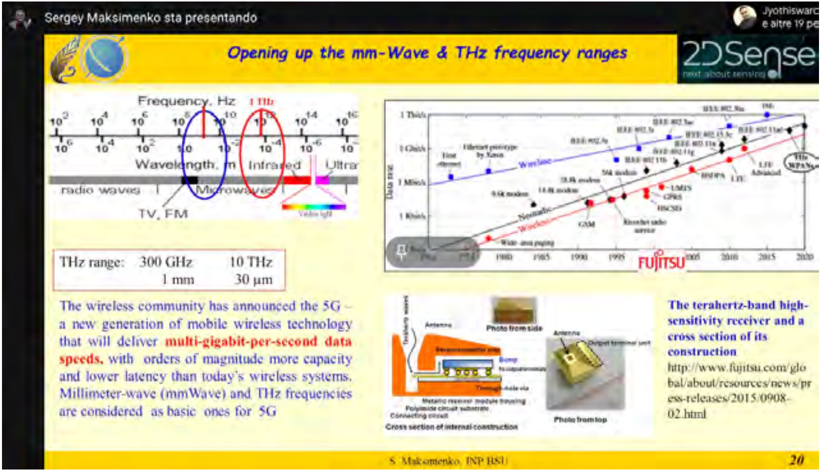
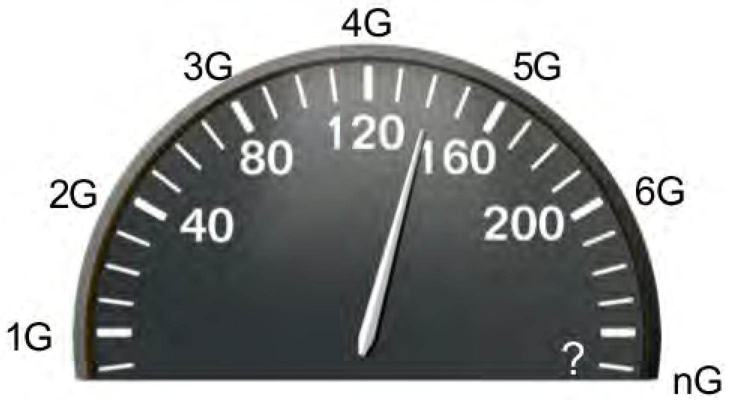
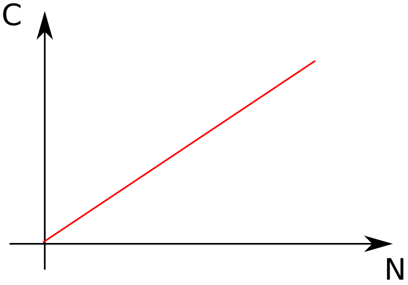
From the lecture of Sergey Maksimenko, 31 May 2021

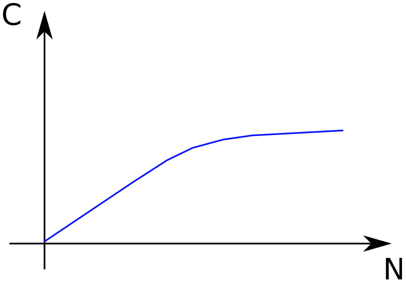



4G
3G
5G
120
80
160
2G
6G
40
200
1G
?
nG

Something missed?

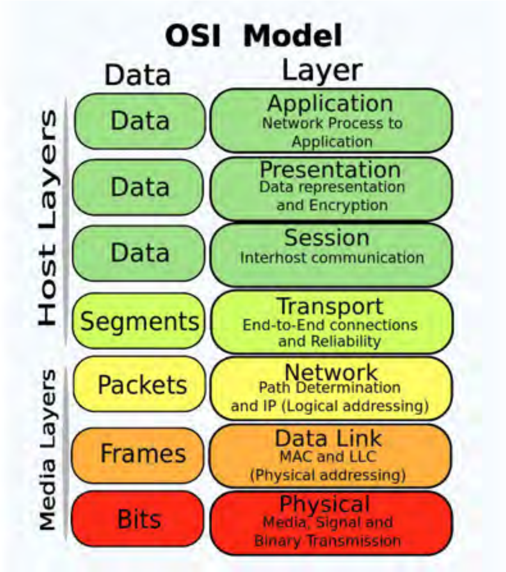


Expectation



Real word

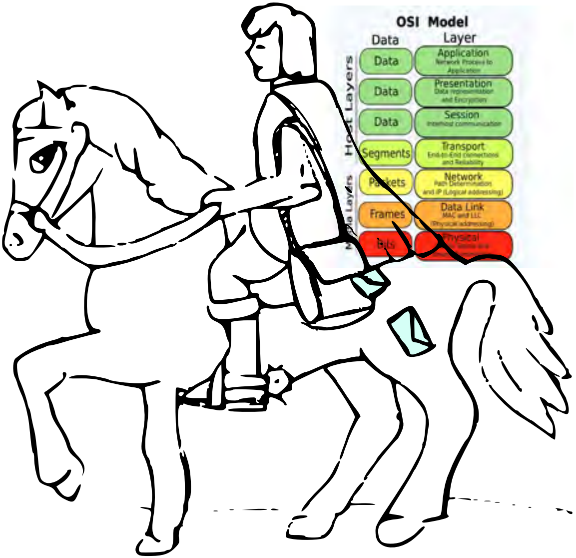
OSI model



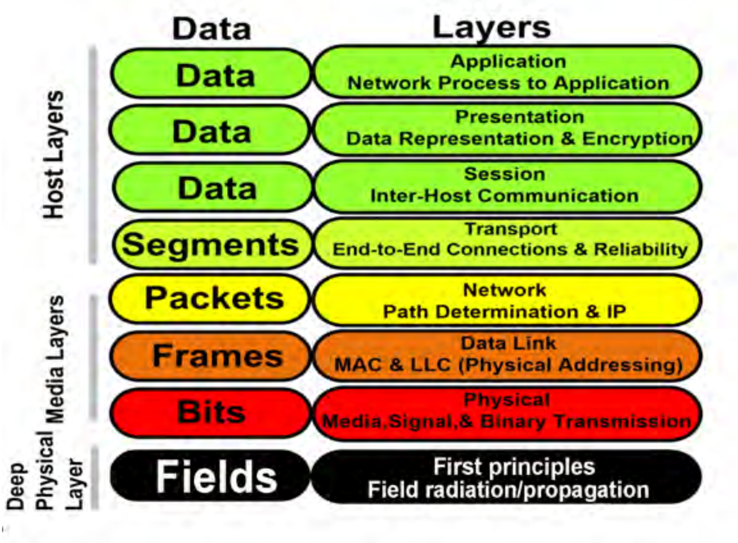
OSI Model
Data
Layer
Host Layers
Media Layers
Data
Application
Network Process to Application
Data
Presentation
Data representation and Encryption
Data
Session
Interhost communication
Segments
Transport
End-to-End connections and Reliability
Packets
Network
Path Determination and IP (Logical addressing)
Frames
Data Link
MAC and LLC (Physical addressing)
Bits
Physical
Media, Signal and Binary Transmission

Horse and horseman

Horse and horseman



The deep physical layer



Some cornerstones in the history of communication

1873
A treatise on electricity and magnetism

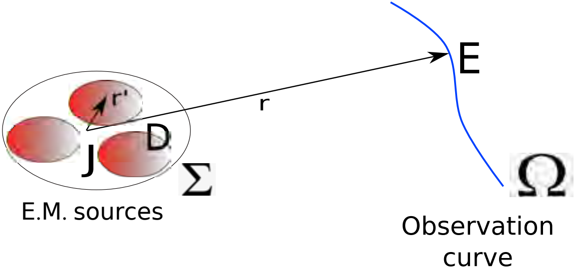
1948
A mathematical theory of communication

Some cornerstones in the history of communication

1873
A treatise on electricity and magnetism

1959 ε-entropy and
ε -capacity sets in functional
spaces

1948
A mathematical theory of
communication



$$E(r) = \int_D G(r, r') \cdot J(r') dr' \qquad r' \in \Omega$$

J: current distributions in *D* , *E*: field distribution on Ω
The radiation integral is a linear operator that maps current distributions into field distributions

The functional approach

Let us introduce a complete orthonormal basis for the current distribution on D and a complete orthonormal basis for the field distribution on Ω

$$J(r') = \sum_{1}^{\infty} x_k f_k(r')$$
$$E(r) = \sum_{1}^{\infty} y_k g_k(r)$$

Geometrically, x_k can be seen as the $k-th$ coordinate of a point x belonging to the infinite-dimensional Hilbert space having $f_1(\mathrm{r}), f_2(\mathrm{r}), ..., f_k(\mathrm{r}), ...$ as basis functions. The same for y_k

An important property of the radiation operator

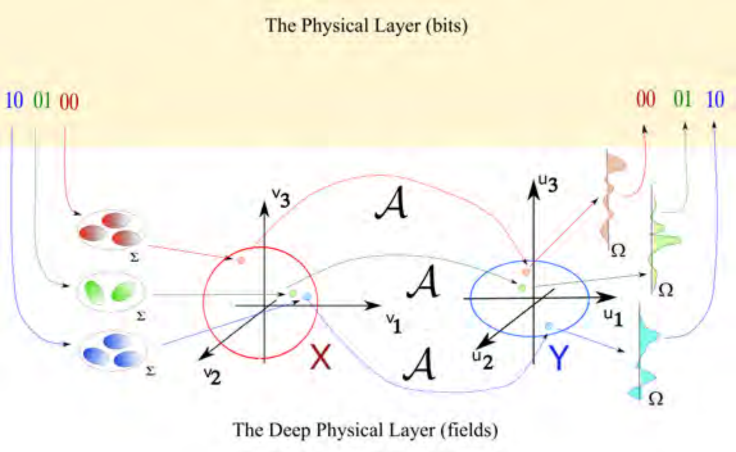
$\mathcal{A}$ is a compact operator. The Hilbert-Schmidt decomposition of $\mathcal{A}$ gives a basis v_k for the currents and a basis u_k for the field that allows the diagonalization of the infinite matrix A

$$
\begin{aligned}
y_1 &= \sigma_1 x_1 \\
y_2 &= \sigma_2 x_2 \\
&\ldots. \\
y_k &= \sigma_k x_k \\
&\ldots.
\end{aligned}
$$

σ_k are the singular values of $\mathcal{A}$

$\lim_{k\to\infty} \sigma_k = 0$
The matrix A has an almost finite rank !
$\mathcal{A}$ maps a hypersphere in a hyperhellipsoid having almost finite dimensions

Geometrical interpretation in functional spaces

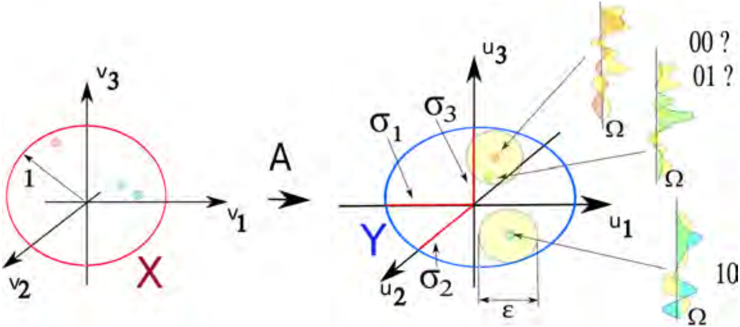


X: set of all the current distributions on D

Y: set of all the field distributions on Ω

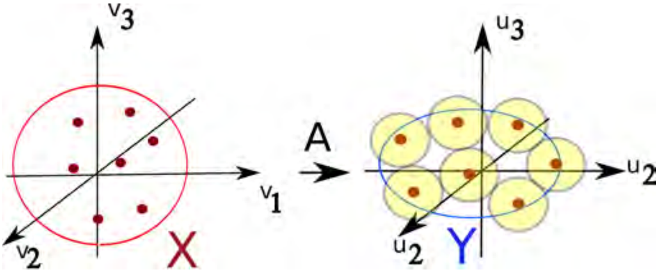
The radiation operator $\mathcal{A}$ maps elements of X into elements of Y

The presence of noise



Due to the presence of noise two field configurations whose distance is smaller than ϵ are indistinguishable.
The number of distinguishable configurations in presence od ϵ uncertainty is equal to maximum number of ϵ-balls that we can pack in Y

Kolmogorov ϵ-capacity



The $\log_2$ of the maximum number of distinguishable configurations in presence of ϵ uncertainty is caller the Kolmogorov ϵ-capacity

The Kolmogorv ϵ capacity is the maximum amount of information expressed in bits that can be reliably transmitted along the spatial channel

The effective dimension of the Y set is called the Number of Degrees of Freedom of the field (NDF)

How much information can we transmit?

$$E(r) = \sum_k y_k u_k(r)$$

$$y_1 = \sigma_1 x_1$$

$$y_2 = \sigma_2 x_2$$

$$....$$

$$y_{NDF} = \sigma_{NDF} x_{NDF}$$

The number of bits is equal to the Kolmogorov ϵ-capacity

$$C_\epsilon(Y) \simeq \sum_{k=1}^{NDF} \log_2 \left(\frac{\sigma_k}{\epsilon} \right)$$

The amount of information that can be reliably transmitted is limited by the *NDF* of the field.

How many NDF do we have?

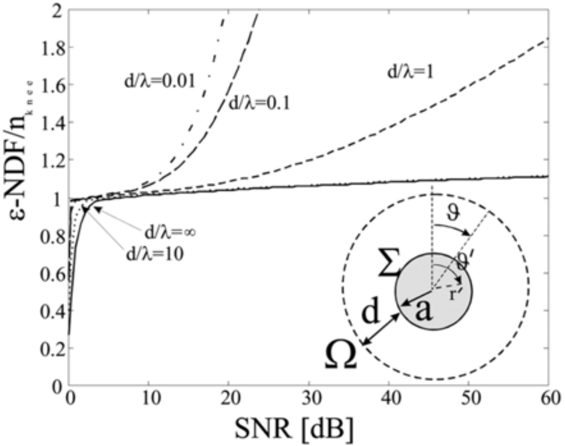
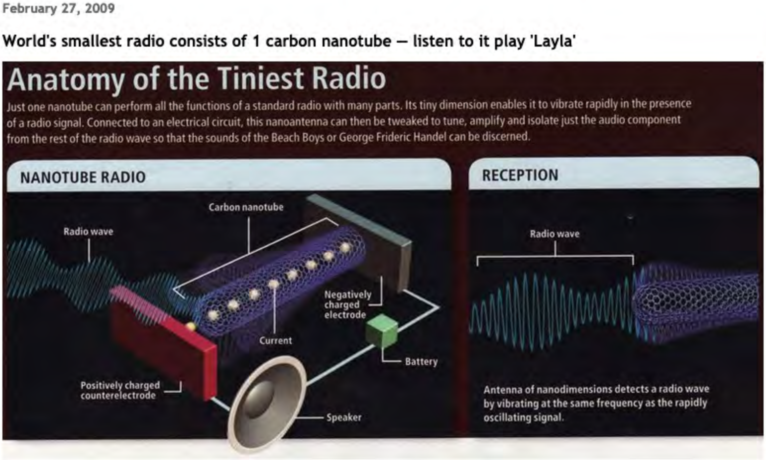


Fig. 5. $\epsilon - NDF$ as a function of the Signal/Noise Ratio (SNR) normalized to n_{knee} for different values of the distance d/λ of the observation circle from the circle including the sources; inset: geometry of the problem;.

The Deep Physical Layer describes the physical mechanisms at the basis of the communication process using standard tools of functional analysis.

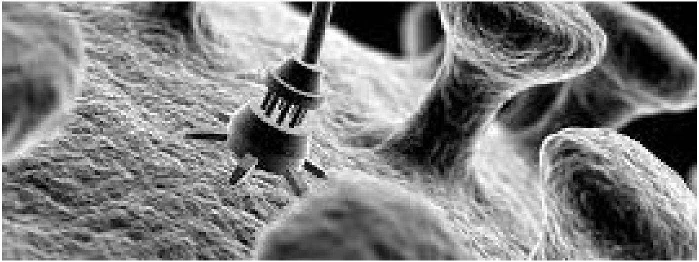
The Deep Physical Layer gives a framework to describe the physical process of communication at different details, up to quantum level.

... is this something interesting?



Nanoradio - Alex Zettl's group, University of California, Berkeley
(image from https://www.bookofjoe.com/2009/02/nanotube-radio.html)

Nanonetworking



A nanonetwork or nanoscale network is a set of interconnected nanomachines which are able to perform only very simple tasks such as computing, data storing, sensing and actuation.

Nanonetworking is one of the newest research trends in communication networks!

IEEE P1906.1 - Recommended Practice for Nanoscale and Molecular Communication Framework

IEEE Communications Magazine May 2021

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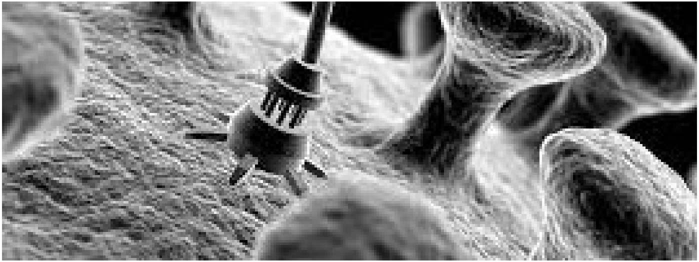
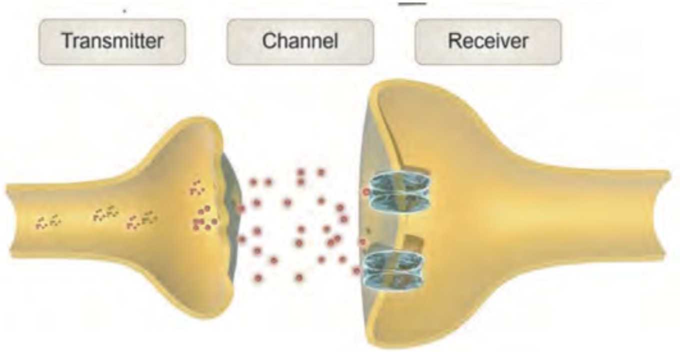
Nanonetworking



In electromagnetic nanonetworks, artificial nanomachines communicate using electromagnetic radiation emitted by nanoantennas.

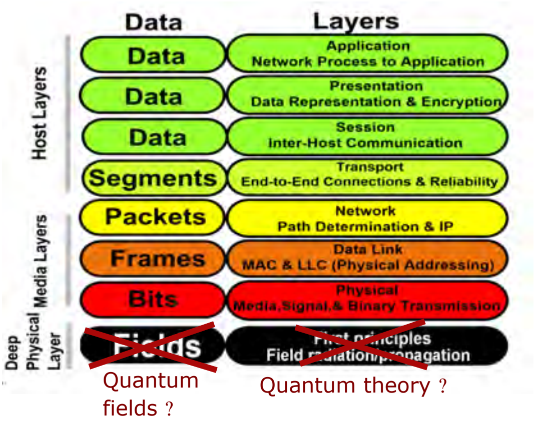
The Deep Physical Layer gives a natural framework for EM-based nanonetworks.

Nanonetworking



The Deep Physical Layer approach can be extended to include molecular nanonetworks (wave equation → diffusione equation)
Is it enough?

Beyond classic electrodinamics communication systems



What does happen in the nano-world communications? I have no idea, but surely...

there's plenty of room at the bottom!

https://youtu.be/8qp7GzIIKHI.