EuCap 2013 8 April 2013

Compact Multiport Antennas for High Spectral Efficiency

Motivation from Energy Considerations

Lessons from Early Wireless History

Design Aspects

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EuCAP 2013

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Recent projects

- Mammalian implanted antennas
- Capacity maximization for digital systems
- Multi-user MIMO: How many antennas?
- Antenna evaluation using physics-based simulation
- Antenna elements: basics of dipole
- Multi-element antenna theory and metrics
- Multi-faceted arrays
- Multipath propagation and signal processing in sonar
- Wireless location algorithms
- Channel phase for estimating the Rice factor
- Spatial interference suppression (automatic noise control) in acoustics – same as wireless

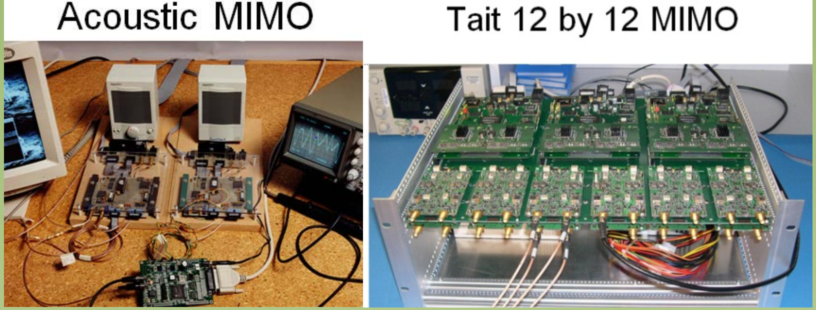
Synchronization

- Preliminaries (2 minutes)
- Part I Motivation of MEAs from energy considerations (~10 min) {Warning: dry!}
- Part II How did we get here? A glimpse of early wireless and lessons (~15 min)
- Part III Design aspects for MEAs for MIMO communications (~10 min)
- Total packet size: ~40 min
- Tutorial style

Early practical projects - signal processing & antennas

Earthquake analyzer

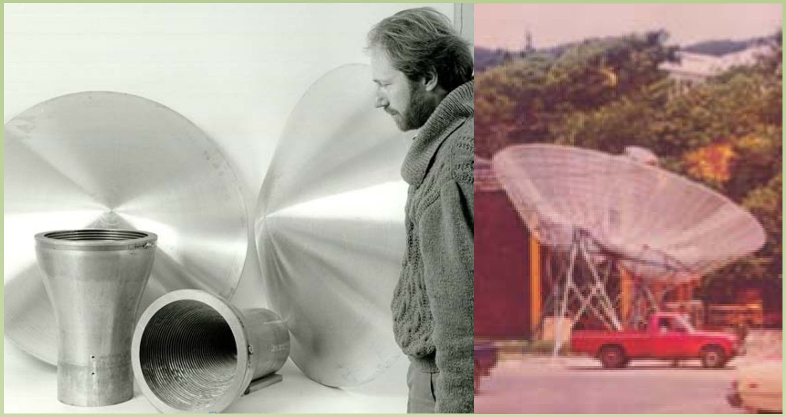
Real-time audio Signal clean


Acoustic MIMO

Tait 12 by 12 MIMO

MIMO DSP hardware

Compact handset MIMO antenna Design & testing



Shaped reflector design

Outdoor propagation tests: in-line monopoles

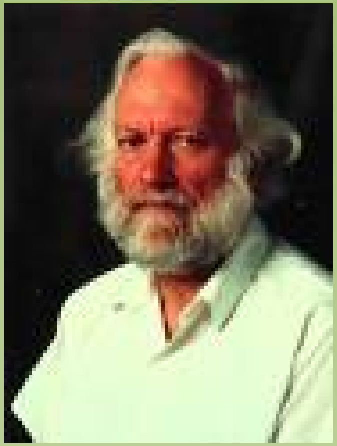
MIMO uses multiple element antennas (MEAs) to improve communication performance.

Single user N=3 MIMO at 450MHz. (PEL, New Zealand, 1987)

Observations:

- **Worked well in “ideal” environments, but unconvincing in most environments**
- **Capacity efficiency pretty lousy compared to limits.**
- **Ad-hoc antenna design**

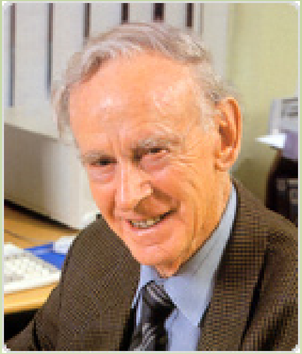
Mentors



(The real JBA)

R.H.T. Bates

J. Bach Andersen



Sir Angus Tait
(Tait Electronics Ltd)

Why MIMO is a household word

Spectral efficiency

- The history of telecommunications has been to add complexity to the terminals to get better spectral efficiency from multipath media.
- But commercial MIMO systems do not perform close to their theoretical potential

- The drive for spectral efficiency has been a triumph of electrical engineering research

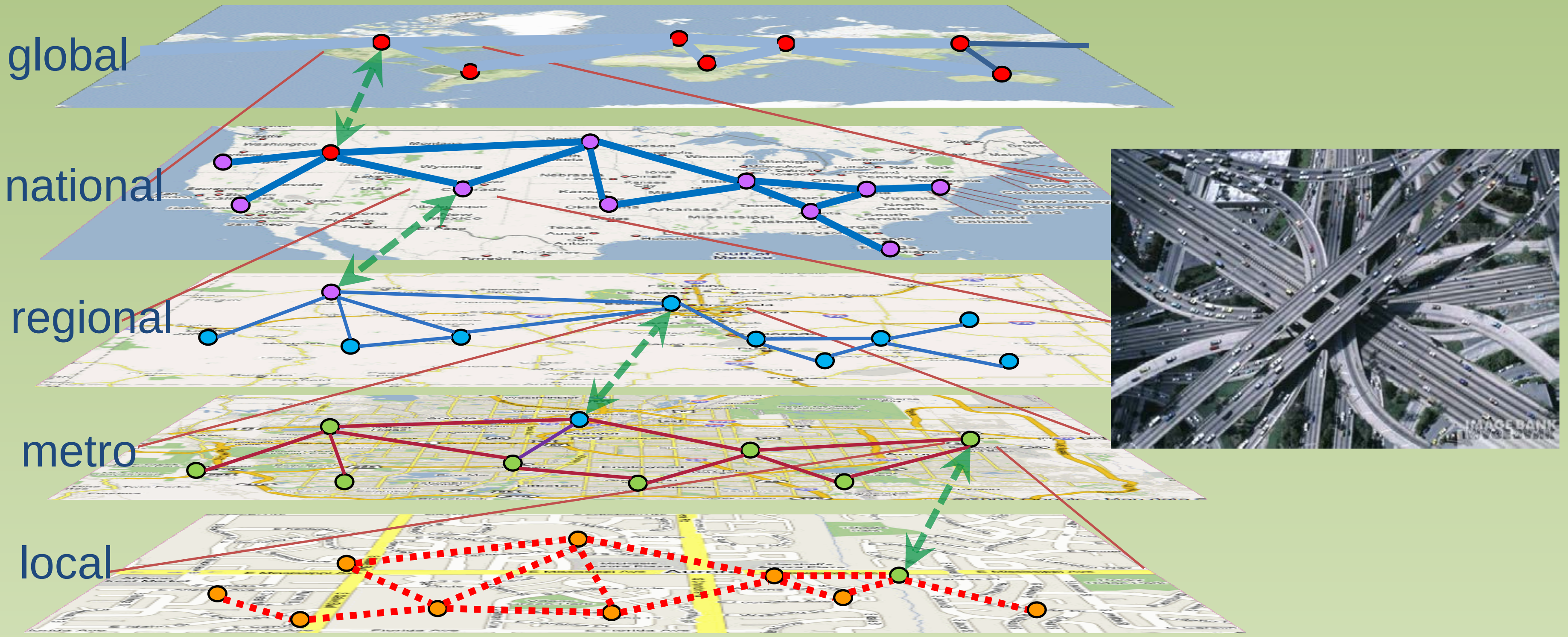
Motivation for MEAs: a power argument

M2M – Machine-to-machine **(aka Internet of Things)**

- **This is the main marketing jingle for the future expansion of wireless systems**
- **According to several market survey companies, some 50 billion M2M devices by 2025**
- **Such unprecedented numbers magnify issues such as Network Access and Spectrum Sharing.**
- **We don't have the complete solutions for these**

Network Access Grand Challenge: We need to connect billions of M2M devices, currently there is no solution to this

Shape of the Industry & Underlying Infrastructure: Network Layers



Graphic from Dr. Adam Drobot

There are many fun grand challenges

- Understanding the information-theoretic spectral efficiency limits
- Developing new communications-theoretic limits
- Understanding spatial channels
- More signal theory for better practical understanding of interference control
- New communications techniques including for networking
- New methods and standards for MEA evaluation

For MEA design, these research areas come together

MIMO antennas for M2M

- New systems will be governed by pragmatic engineering, i.e., economically viable networks systems and economically viable terminals and antennas.
- Research systems tend to put aside many practical limitations and explore the theoretical potential.
- Eg., many MIMO systems articles assume that perfect CSI is always available at all antennas.
- But the spectral overhead required for this overwhelms the spectral efficiency gains, even in slow-changing channels, and especially in multi-user systems

Part I Network power consumption

- Demand for wireless services associated with more compact antennas, which tend to be less efficient.
- This in turn magnifies the network losses:
  - A lossy MS antenna results in higher BS transmit power, causing reduced SINR for other users, which in turn calls for more transmit power, etc.
- For every dB of power lost in the antenna, network costs rise quickly.
- Handset: η= -12dB, BS: η =-13dB.

A communications example

- **Transmission of small, low quality, JPEG encoded image of size 10kbits through a mobile link**
- **Channel bandwidth 10kbits/sec**
- **Modulation PSK, requiring 6dB SNR for error rate that will not degrade coded image**

- **Error in proceedings: (P1, C2, 2nd last paragraph):**

the Nyquist signaling rate is 20kS/sec and so the data rate can be up to 40kbits/sec. A low rate (1/4) code ensures a quasi-error-free 10kbits payload. So 40kbits need to be detected in 1 second. (See edits at end of presentation file)

- **Remove this. The example just deals with 10kbit JPEG coded image, there is no FEC.**

- Need to detect 10^4 bits in 1 sec.
- Noise level:

  kTB = -174dBm/Hz + 40dBHz = -164dBW
- Signal level required is 6dB above this, -158dBW
- Signal energy required at detector:

  $10^{-158/10}$ x 1 sec = 10^{-16} Joules
- This is very low, stemming from physical thermodynamics.
- Much, much smaller power than other circuitry.

- So wireless looks “green”, but..

- Radio transmission is extremely lossy!
- Take antenna gains $G_{Tx} = G_{Rx} = 0$ dBi.
- Gain from Noise Factor at receiver $G_{NF} = -10$dB
- BS (cables, combiners, amps) $G_{BS} = -13$ dB
- Take 12GHz carrier, distance = 20m ($<10^3\ \lambda$)
- Path gain in free space = $(4\pi d/\lambda)^{-2} = -80$dB
- <u>Multipath mean</u>: take exponent as n=4, and reference distance to be $d_r = \lambda$,
- $G_{MPM} = (4\pi d_r/\lambda)^{-2} \times (d/d_r)^{-n} = (4\pi)^{-2} \times (d/d_r)^{-n}$
- So for n=4, $G_{MP} = -140$dB

- Multipath margin: for Rayleigh fading, a fade is 30dB below the mean for a probability of 10^{-3}.
- So for all locations except 1 in 10^3, a fade margin gain of G_{FM} = -30dB is required.
- The sum of the above gain cascade is the link gain, G_{Link} = -170dB (i.e., 10^{-17}).
- The power required at the transmitter to send the image is therefore $10^{-16} \times 10^{17} = 10$ Joules.
- Now take a mere 1 billion M2M links, and the energy for the images is $10^9 \times 10 = 10^{10}$ Joules.

- This corresponds to the output of several power stations (say ten 1GJ nuclear stations) for the 1 second duration of the transmission.
- (and ignores power distribution efficiency and several factors in the link budget, and even interference)
- The total signal power that is required by all the receivers is fractions of a mW but to get this delivered needs more than 10GJ of transmit power.
- The example demonstrates the impact of the lossy nature of wireless transmission through large scale (just 1 billion) deployments.
- More efficient electronics can offer relatively modest improvement, and there is much R&D in this area.
- The propagation loss will remain dominant

- The only technology that can directly tackle the propagation loss is multiport antennas
- The potential of “large-*N* “ MIMO arrays remains largely untapped
- The capacity of *N*–element MEAs is proportional to N^2
- So for just 100 element antennas, the power savings in the example are up to 10GWatt/10^4 = 1 MegaWatt per second.
- In the example, interference was ignored, but in most links it is interference, not thermal noise, that limits.
- Systems such as cellular have their electrical and geographical layout governed by interference.
- Deployment of MEAs can disrupt this limitation.

- With large-aperture, pencil-beam antennas, a point-to-point LOS link uses this idea.
- Here, the transmit beam directs the energy to the receive antenna, which in turn strives to capture all the transmit power.
- In a limiting case, the antenna gains compensate the propagation loss.
- Most interference is spatially filtered out.

- The multipath case is more difficult, but the idea of high gain carries across, through a large gain from an large number of elements working together in the multipath.
- In a MS-BS arrangement, large aperture is required at the BS

Summary of Part I

- Adaptive antennas are some 50 years old
- New theory is being developed, with interesting design breakthroughs in the last few years
- Design of “MIMO antennas” tends to be *ad-hoc*
- Standards are required for MEA evaluation, and limits of compactness
- The need to interchange CSI compromises the very goal of MIMO, that of spectral efficiency gain.
- Nevertheless the potential returns from tackling the propagation loss encourages more research
- A glimpse of history may encourage us as to how progress will come about..

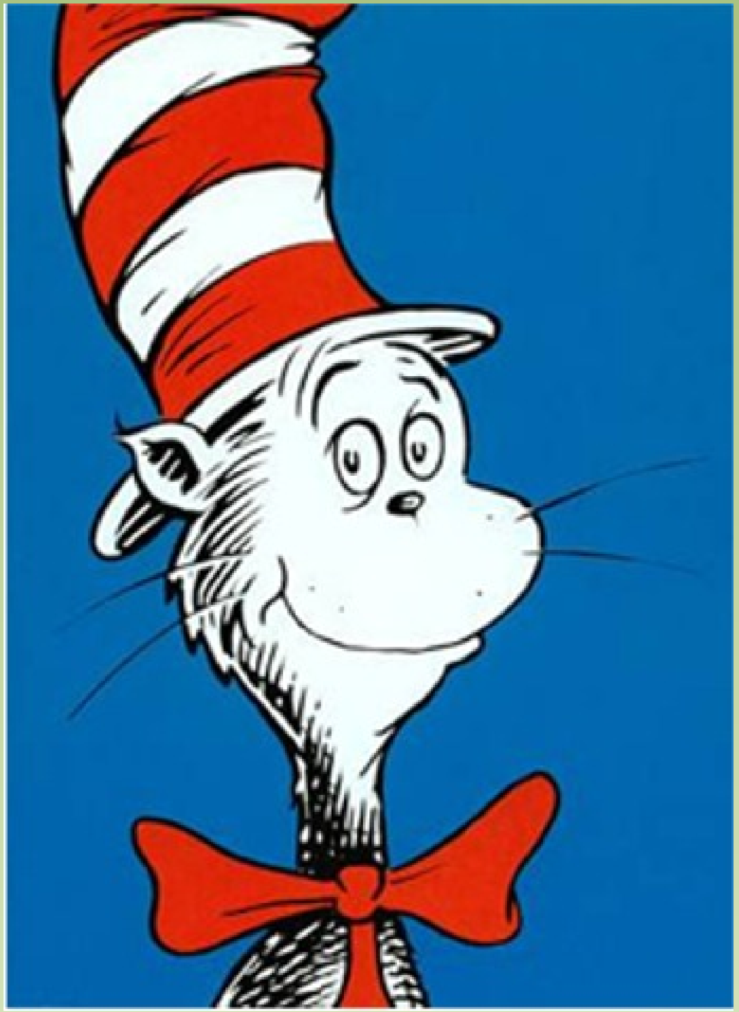
Wireless Communications Technology is BIG and GROWING

- Its development has had a profound impact on our lives
- It governs how we do business
- It governs how we socialize
- Its demand drives much research in science and engineering
- The technology development is mostly on wireless
- In communications we study the Unnatural Sciences!

This stuff is important because it has a profound impact and is great fun!

How big is it?

How fun is it?



- **We have the knowledge of propagation, antennas, signal processing and electronics, to foresee “large” radio capacities.**

- **How did we get to this point?**

Three 50-year breakthroughs in communications

- **Radio waves, propagation, electronics, and antennas**
- **Cellular deployment for spectrum sharing**
- **MIMO for spectral sharing, but we are still stuck on the implementation for "large-*N*" systems**

Part II A glimpse of extraordinary history

- **This is start of the second century**
- **A look at the start of wireless' first century may help us see the way forward for MEAs for MIMO.**
- **The history cannot be separated from Marconi, who is often referred to as the "father of wireless"**
- **But there were many others who bracketed Marconi's scientific role.**
- **The following is a personal choice.**

Communications

- Exchange of:
  - thoughts
  - messages
  - ***information***
- By
  - speech
  - ***signals***
  - writing
  - behaviour

Wireless communications (in 17,000 BC)

- **Bullroarers!**
- **Paleolithic inverse square law: path gain maximized by using low (acoustic) frequency**

Remote Communications

- **Telecommunications** is the ***main motivation*** for wireless.
- French cross of **Latin** and **Greek**
- ***Tele*** (Greek) remote
- ***Communications*** (Latin) common/shared
- ***"The act cannot take off, it is a cross bred ass by name"*** *- F. Scott Fitzgerald?*

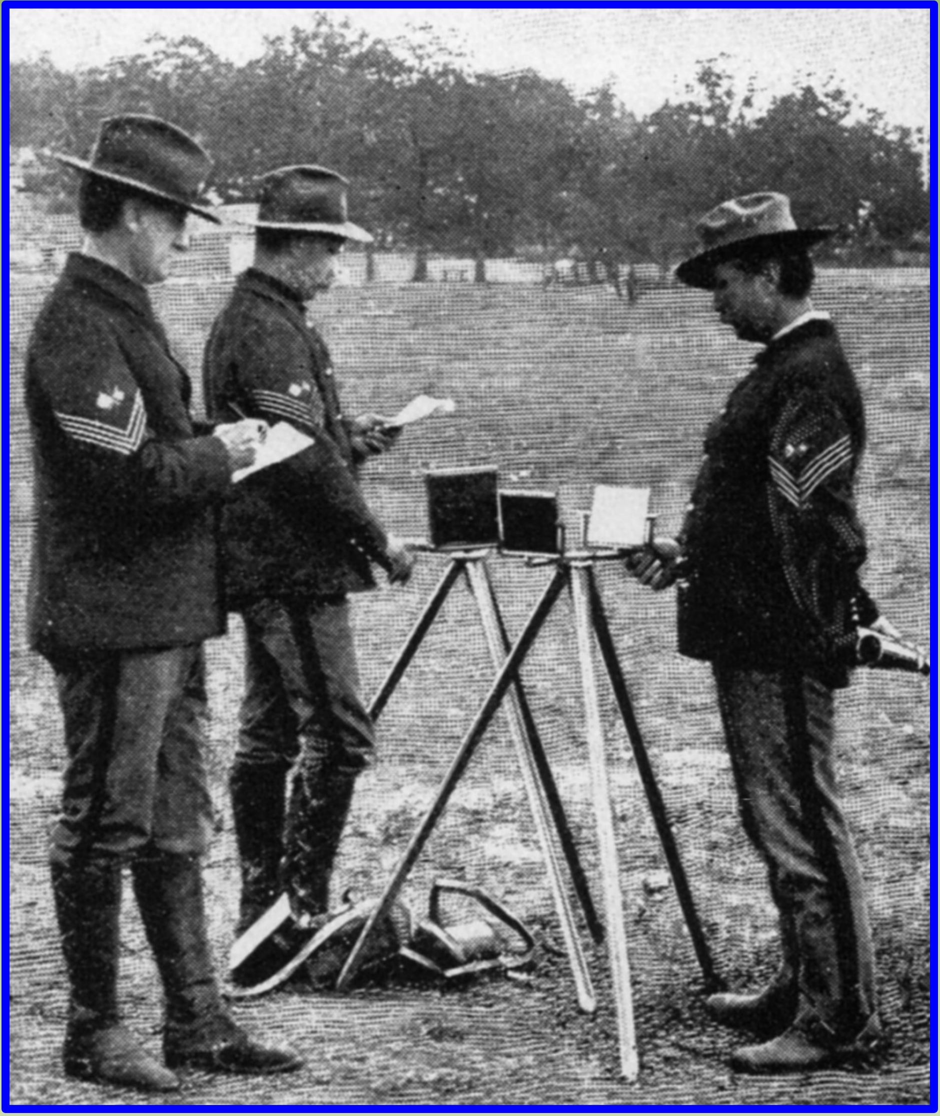
How to telecommunicate

- Gesturing, waving , bullroarer
- Smoke signals, flags, lights, drums, heliograph
- Semaphore, Morse code, telegraph, **wireless (radio)**
- **Quantum teleportation, telepathy?**

distance,

time

Heliograph



1898, US Signal Service

- 1810, *helioptrope* (C.F. Gauss)
- Today: Lasers and digital signal processors
- 405 BC, Ancient Greeks also used light

Some communications landmarks

(Wireless)*

- Telegram, telephone, Marconigram*
- **Broadcast radio and television ***
- Telex
- **Fax**
- Vehicular and personal mobile phones*
- **Internet**
- GPS*
- **Mobile voice data, and *information* ***

Father of Wireless?

- **Guglielmo Marconi**
- Guiseppi Marconi
- Annie Jamieson

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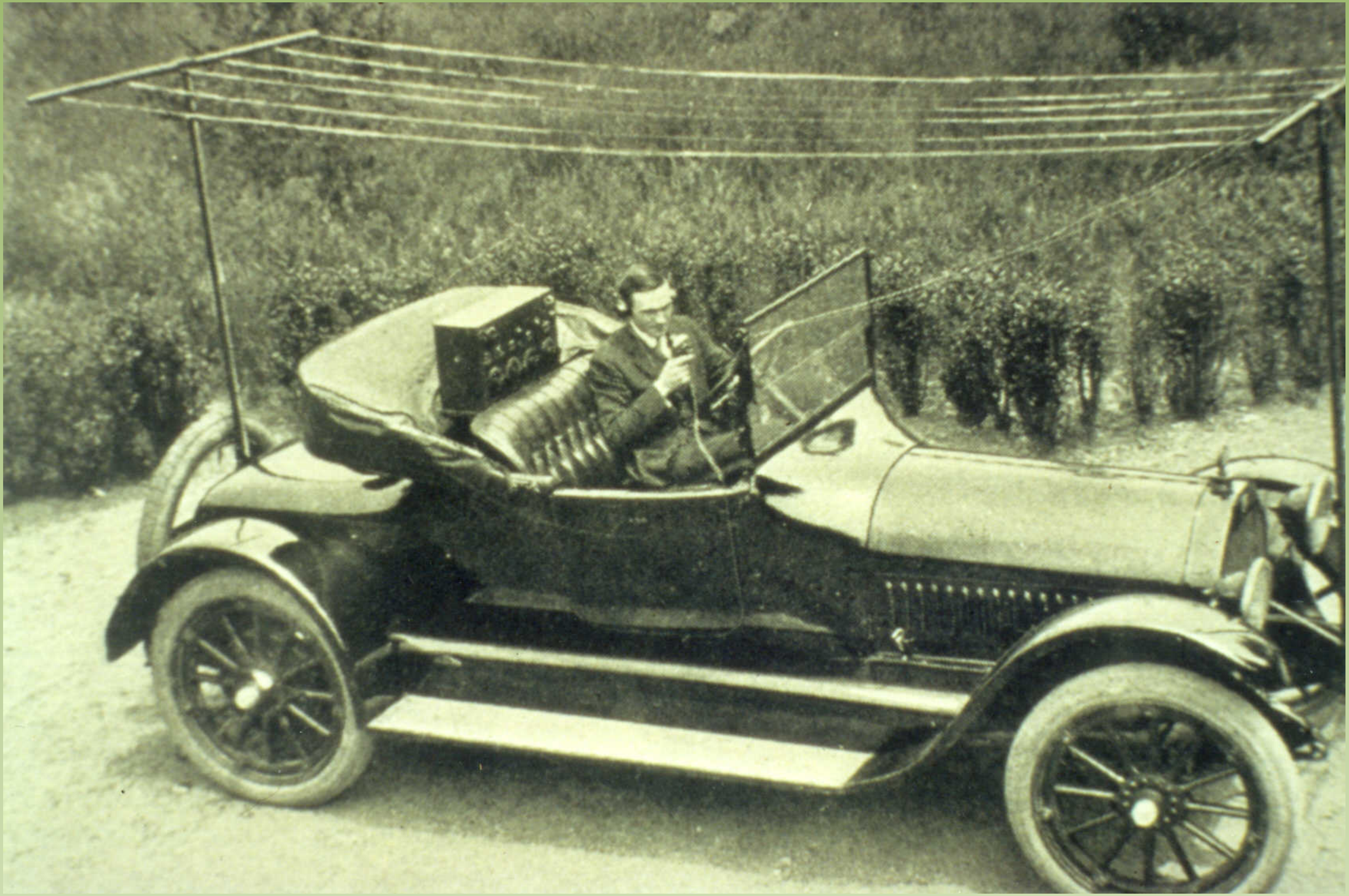

Which came first?

The antenna or the propagation?

Some Foundations of propagation

- **~1820 in Denmark - Hans Christian Ørsted** notices that a wire current deflects a compass needle
- **~1825, in Britain, Michael Faraday's** law of induction
- **~1849, in France -Hippolyte Fizeau and Jean-Bernard Foucault** measure the speed of light to be about 315,000 km/s (cf 299,702 km/s)
- **Also ~ 1676, Rømer in Denmark – reported a measurement method, and Huygens made an estimate**

- **~1864, in Scotland — James Clerk Maxwell** building on **Faraday**'s work, publishes dynamical theory of the electromagnetic field

- **~1873** — The Equations , and **light is electromagnetic**, with **c= 317,040 km/s**, travelling through **lumniferous aether**
- Ranked with Einstein by many.

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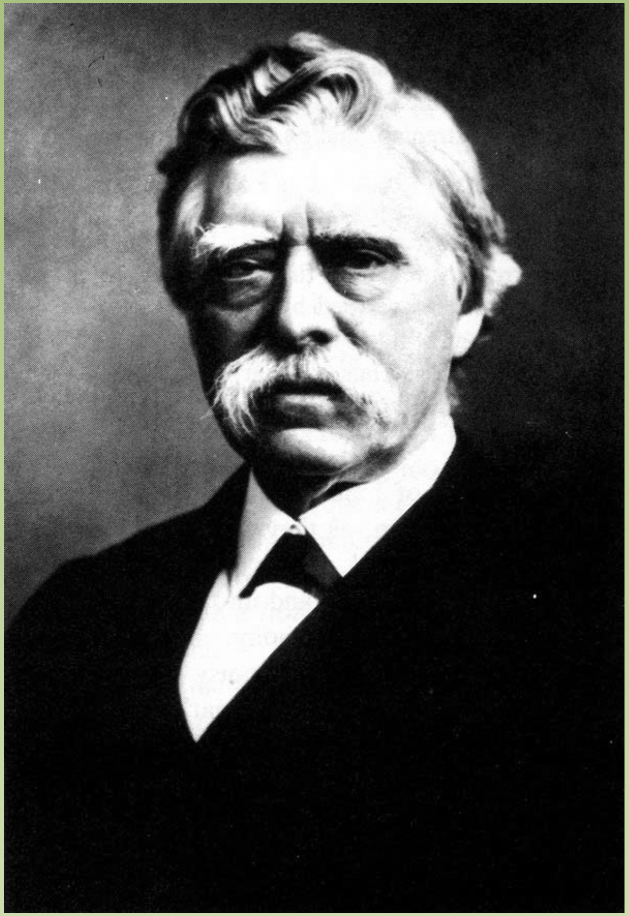
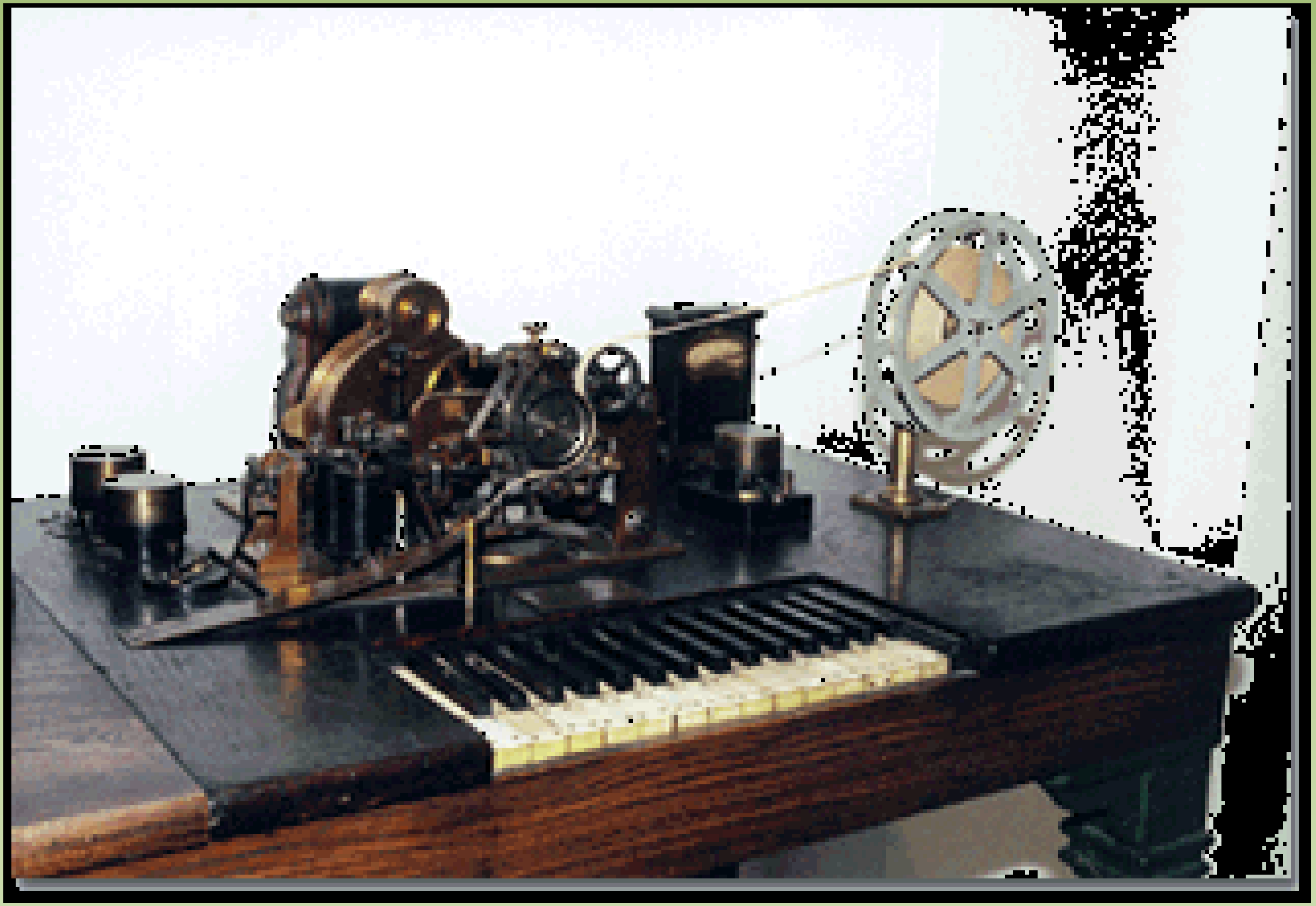
~1878 in America, David Edward Hughes



- 1878: Transmitted and received radiowaves (inadvertently), but recognized what he had done **$\Delta T_{\text{Maxwell}}$= 14 years**
- Knew Preece and Marconi knew of his work through Preece.
- Not recognized for many decades.

Hughes telegraph (1855)



~1886, Germany
Heinrich Hertz

- Helped establish the photoelectric effect
- 1886/7 First to intentionally and systematically transmit and receive electromagnetic (EM) waves

$\Delta T_{Maxwell}$= 22 years

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IEEE Hertz medal

- IEEE Heinrich Hertz Medal, established in 1987, is

- *for outstanding achievements in electromagnetic waves*
- *for achievements which are theoretical or experimental in nature*

Hertzian Waves

- proved that electromagnetic waves can travel over some distance

- Hertz‘s experiments showed all the basic behaviour of EM waves:-

  propagation, reflection, refraction, polarization, interference, velocity.

Hertz on Hertzian waves

- *“It's of no use whatsoever .“*
- *“This is just an experiment that proves Maestro Maxwell was right - we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.”*
- Ramifications of discoveries?

  - “Nothing, I guess.”

~1896, Germany, Arnold J.W. Sommerfeld)

- Omitted from credits!
- 6 of his students got Nobel Prizes.
- Pauling, Rabi;
- Heisenberg, Pauli, Debye, Bethe.
- Also: Hopf, Brillouin, Morse…

~ 1894, in New Zealand
Ernest Rutherford

- Worked in England
- And Canada (Chair of Physics at McGill), where his work led to a Nobel prize in Chemistry (1908).

Rutherford

- **1894 demonstrated radiowave transmission across a laboratory**
- Demonstrated that the waves could propagate through or round, brick walls
- 1895, to Cambridge, made a world record in wireless propagation distance
- Then defected from radio, but did OK anyway, becoming “father of nuclear physics”…

"Rutherford was encouraged in his work by Sir Robert Ball … who wished to solve the difficult problem of a ship's inability to detect a lighthouse in fog. Sensing fame and fortune, Rutherford increased the sensitivity of his apparatus until he could detect electromagnetic waves over a distance of several hundred meters. Thomson ... quickly realized that Rutherford was a researcher of exceptional ability and invited him to join in a study of the electrical conduction of gases. The commercial development of wireless technology was thus left for Guglielmo Marconi."

- John Campbell

~1905, Switzerland, Albert Einstein

- Special theory of relativity showed that neither Maxwell’s equations nor the lumniferous aether are needed to describe radiation
- Unfortunately, Maxwell’s equations are much easier to most..

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Practical Players

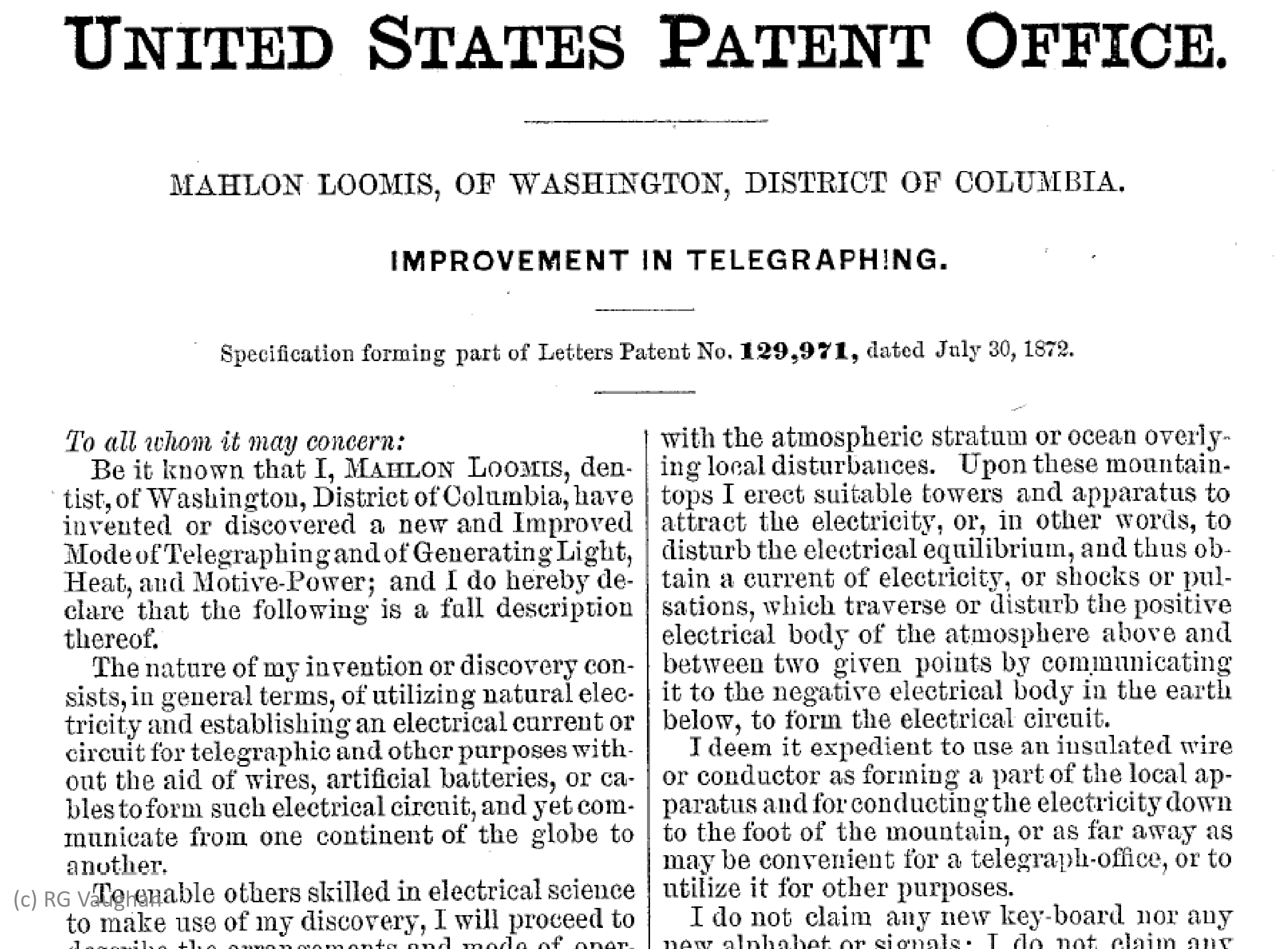
- By this time, a marked separation had developed between the theoretical-based efforts and the practically-oriented efforts

- Some of the practical players were as follows

Practical Players

- **Mahlon Loomis**, Dentist, USA 1826 -1886.
- Claimed to have transmitted signals in October 1866 between two mountain tops14 miles apart in Virginia, using kites as antennas,
- No independent witnesses, no diagrams.

[Thomas Appleby, *Mahlon Loomis, Inventor of Radio*, 1967 reprint]



UNITED STATES PATENT OFFICE.

MAHLON LOOMIS, OF WASHINGTON, DISTRICT OF COLUMBIA.

IMPROVEMENT IN TELEGRAPHING.

Specification forming part of Letters Patent No. **129,971**, dated July 30, 1872.

To all whom it may concern:

Be it known that I, MAHLON LOOMIS, dentist, of Washington, District of Columbia, have invented or discovered a new and Improved Mode of Telegraphing and of Generating Light, Heat, and Motive-Power; and I do hereby declare that the following is a full description thereof.

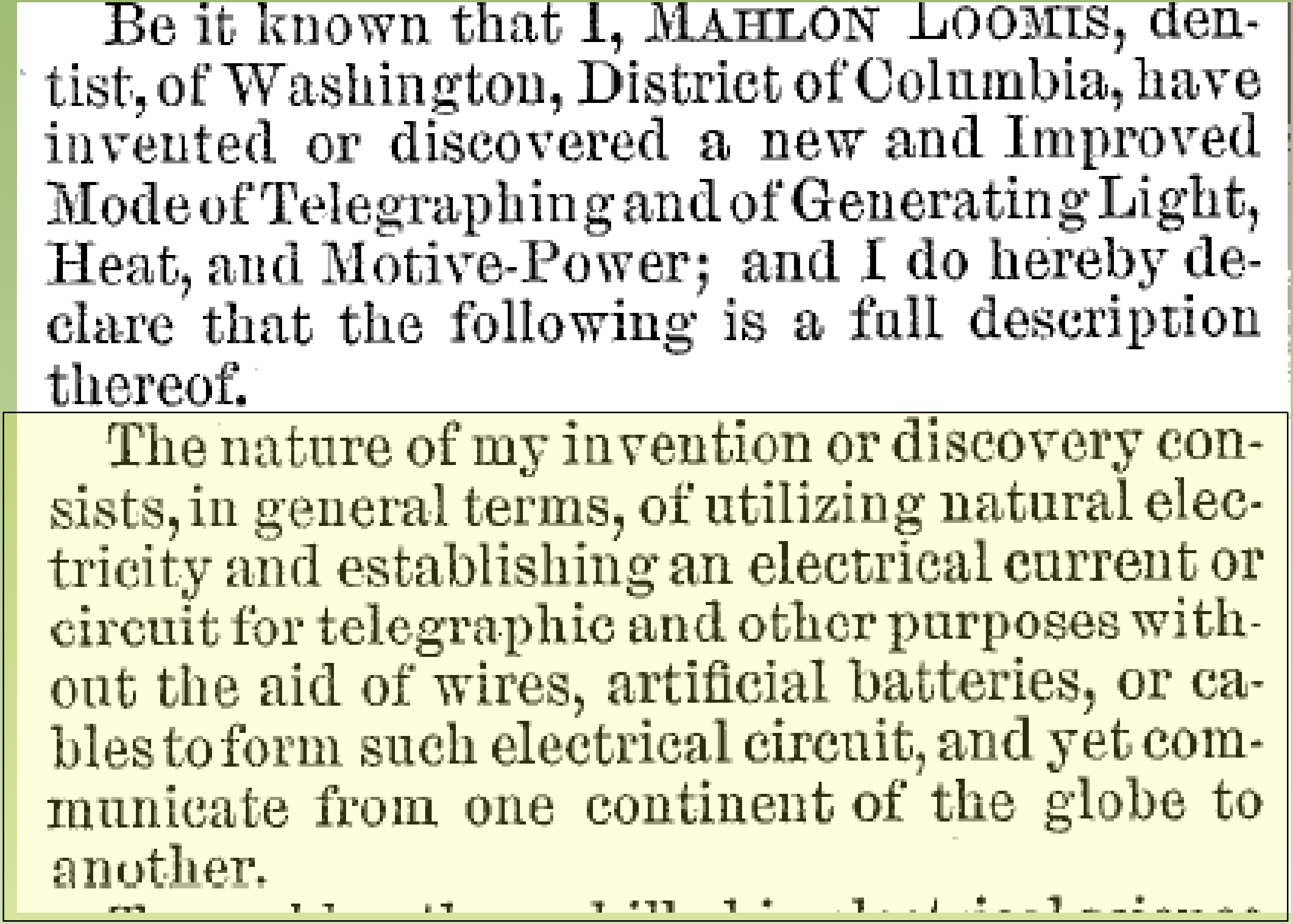
The nature of my invention or discovery consists, in general terms, of utilizing natural electricity and establishing an electrical current or circuit for telegraphic and other purposes without the aid of wires, artificial batteries, or cables to form such electrical circuit, and yet communicate from one continent of the globe to another.

To enable others skilled in electrical science to make use of my discovery, I will proceed to

with the atmospheric stratum or ocean overlying local disturbances. Upon these mountain-tops I erect suitable towers and apparatus to attract the electricity, or, in other words, to disturb the electrical equilibrium, and thus obtain a current of electricity, or shocks or pulsations, which traverse or disturb the positive electrical body of the atmosphere above and between two given points by communicating it to the negative electrical body in the earth below, to form the electrical circuit.

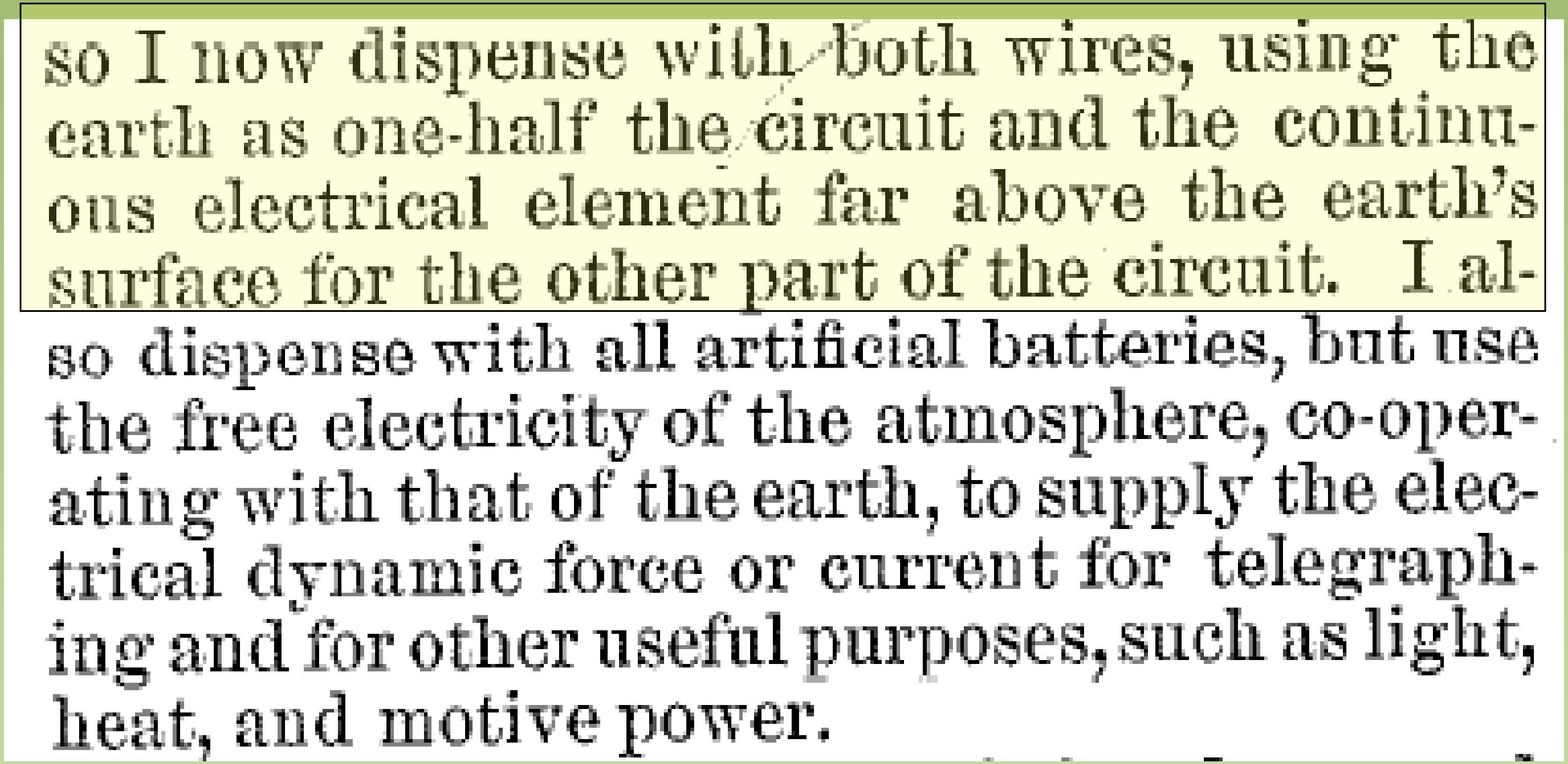
I deem it expedient to use an insulated wire or conductor as forming a part of the local apparatus and for conducting the electricity down to the foot of the mountain, or as far away as may be convenient for a telegraph-office, or to utilize it for other purposes.

I do not claim any new key-board nor any

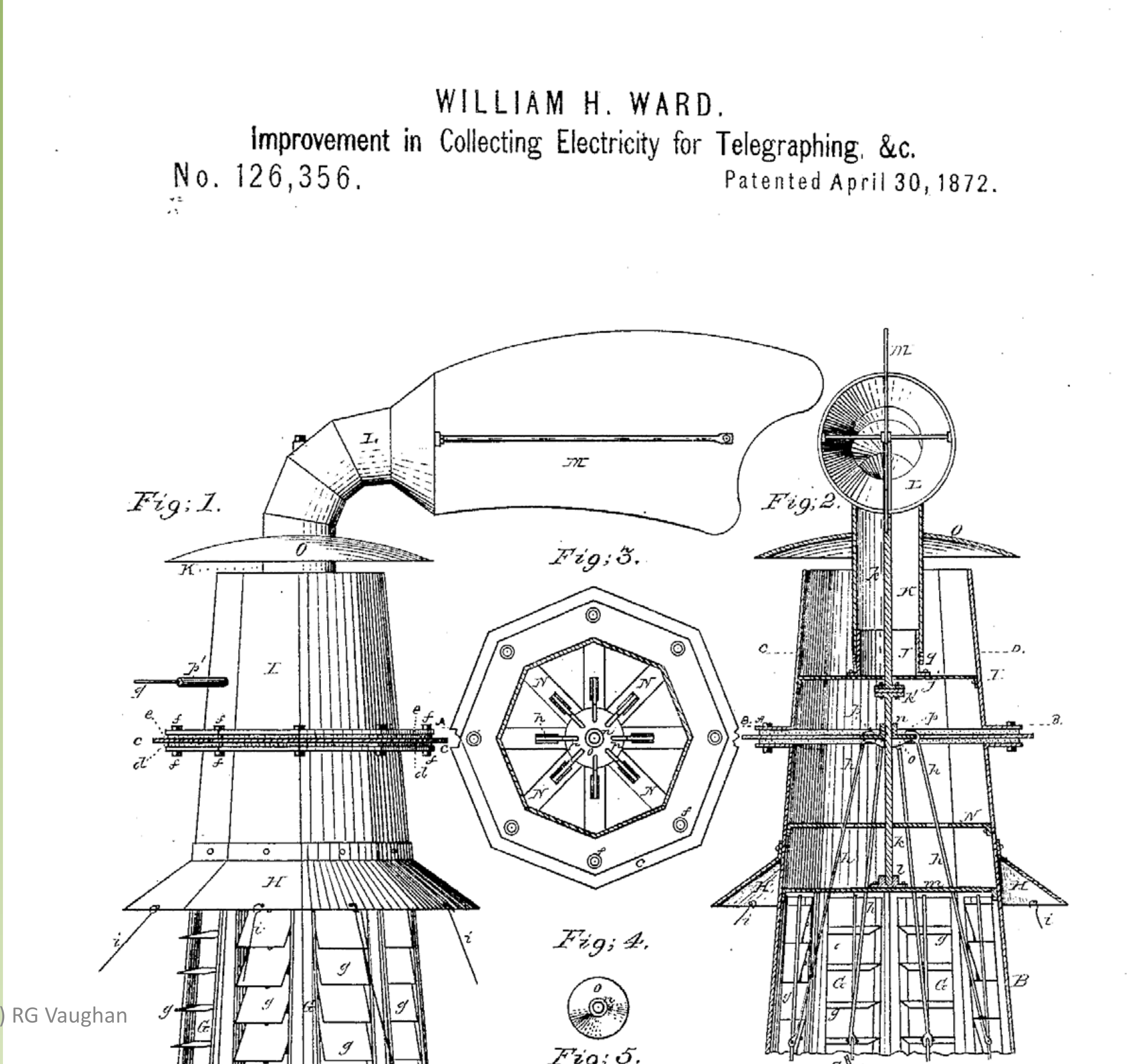


Be it known that I, Mahlon Loomis, dentist, of Washington, District of Columbia, have invented or discovered a new and Improved Mode of Telegraphing and of Generating Light, Heat, and Motive-Power; and I do hereby declare that the following is a full description thereof.

The nature of my invention or discovery consists, in general terms, of utilizing natural electricity and establishing an electrical current or circuit for telegraphic and other purposes without the aid of wires, artificial batteries, or cables to form such electrical circuit, and yet communicate from one continent of the globe to another.



so I now dispense with both wires, using the earth as one-half the circuit and the continuous electrical element far above the earth's surface for the other part of the circuit. I also dispense with all artificial batteries, but use the free electricity of the atmosphere, co-operating with that of the earth, to supply the electrical dynamic force or current for telegraphing and for other useful purposes, such as light, heat, and motive power.



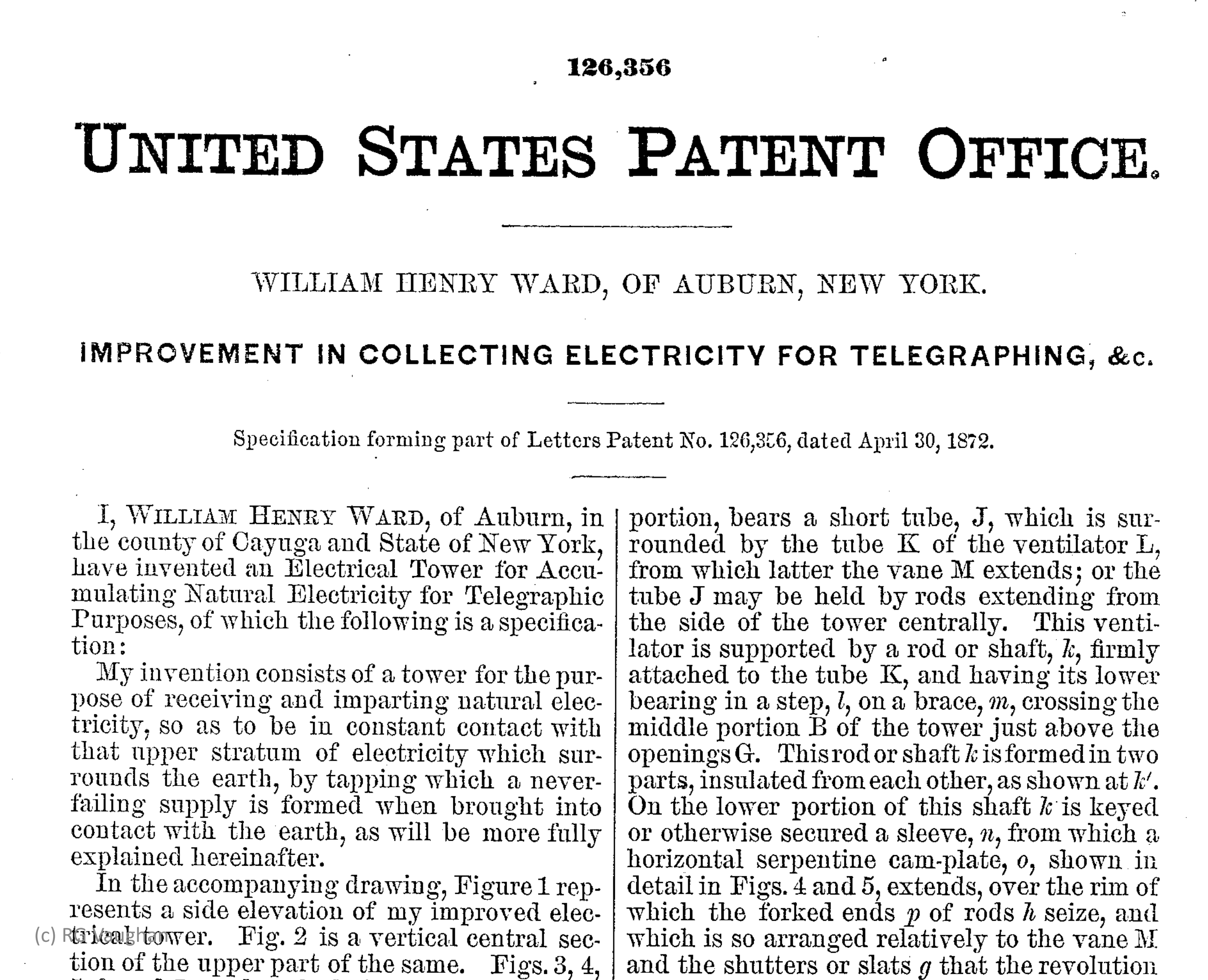
WILLIAM H. WARD.

Improvement in Collecting Electricity for Telegraphing, &c.

No. 126,356.

Patented April 30, 1872.

(c) RG Vaughan



126,356

UNITED STATES PATENT OFFICE.

WILLIAM HENRY WARD, OF AUBURN, NEW YORK.

IMPROVEMENT IN COLLECTING ELECTRICITY FOR TELEGRAPHING, &c.

Specification forming part of Letters Patent No. 126,356, dated April 30, 1872.

I, WILLIAM HENRY WARD, of Auburn, in the county of Cayuga and State of New York, have invented an Electrical Tower for Accumulating Natural Electricity for Telegraphic Purposes, of which the following is a specification:

My invention consists of a tower for the purpose of receiving and imparting natural electricity, so as to be in constant contact with that upper stratum of electricity which surrounds the earth, by tapping which a never-failing supply is formed when brought into contact with the earth, as will be more fully explained hereinafter.

In the accompanying drawing, Figure 1 represents a side elevation of my improved electrical tower. Fig. 2 is a vertical central section of the upper part of the same. Figs. 3, 4,

portion, bears a short tube, J, which is surrounded by the tube K of the ventilator L, from which latter the vane M extends; or the tube J may be held by rods extending from the side of the tower centrally. This ventilator is supported by a rod or shaft, *k*, firmly attached to the tube K, and having its lower bearing in a step, *l*, on a brace, *m*, crossing the middle portion B of the tower just above the openings G. This rod or shaft *k* is formed in two parts, insulated from each other, as shown at *k′*. On the lower portion of this shaft *k* is keyed or otherwise secured a sleeve, *n*, from which a horizontal serpentine cam-plate, *o*, shown in detail in Figs. 4 and 5, extends, over the rim of which the forked ends *p* of rods *h* seize, and which is so arranged relatively to the vane M and the shutters or slats *g* that the revolution

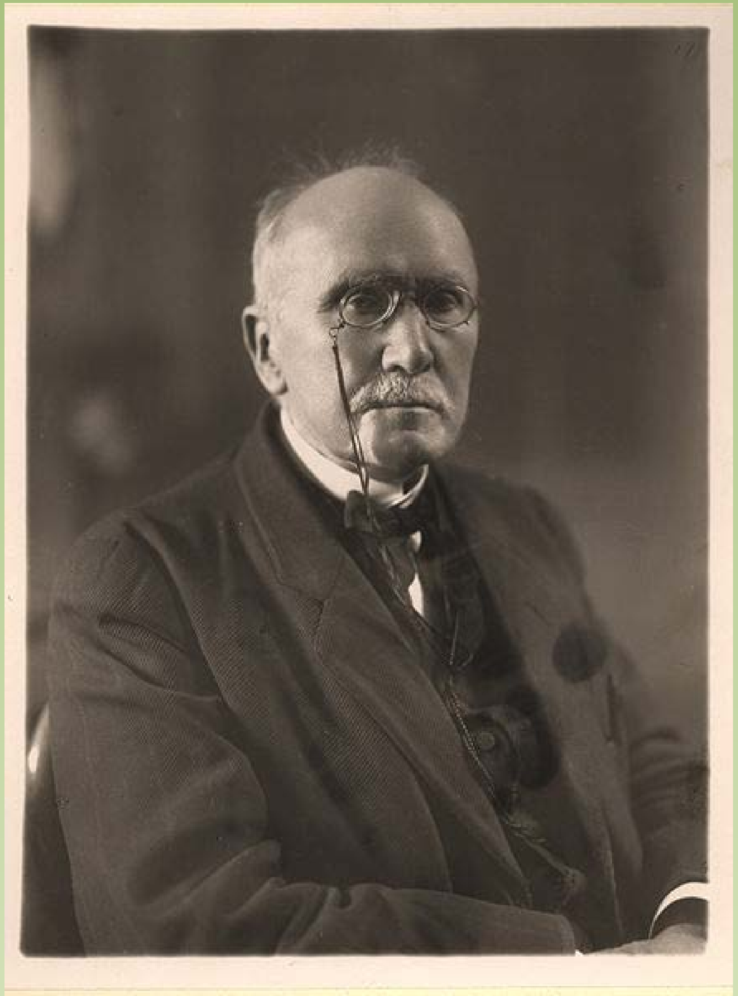
Practical players

- **William Henry Ward**,
- Applied for very similar patent 3 months before Loomis.
- No diagram, just sketches of towers

~ 1884 Italy,
Temistocle Calzecchi-Onesti

- **Temistocle Calzecchi Onesti** 1853 -1922 Italian physicist
- Noted radio frequency current induction in iron filings. This led much later, to the coherer developed **Branly, Lodge and Marconi (Braun), *et al***.

~ 1890 France, Édouard Eugène Désiré Branly



- **Édouard Eugène Désiré Branly** 1844 -1940
- French inventor and physicist.
- 1890: the Branley Coherer
- **Basis for radio reception**, good for 10 years.
- Used by **Marconi**

~1894 in England

Oliver Joseph Lodge

- **Sir Oliver Joseph Lodge** 1851-1940.
- English mathematician, physicist, inventor
- Demonstrated Hertz’s measurements
- Improved Branly's coherer by adding a "trembler" which periodically dislodged clumped filings, restoring the device's sensitivity.

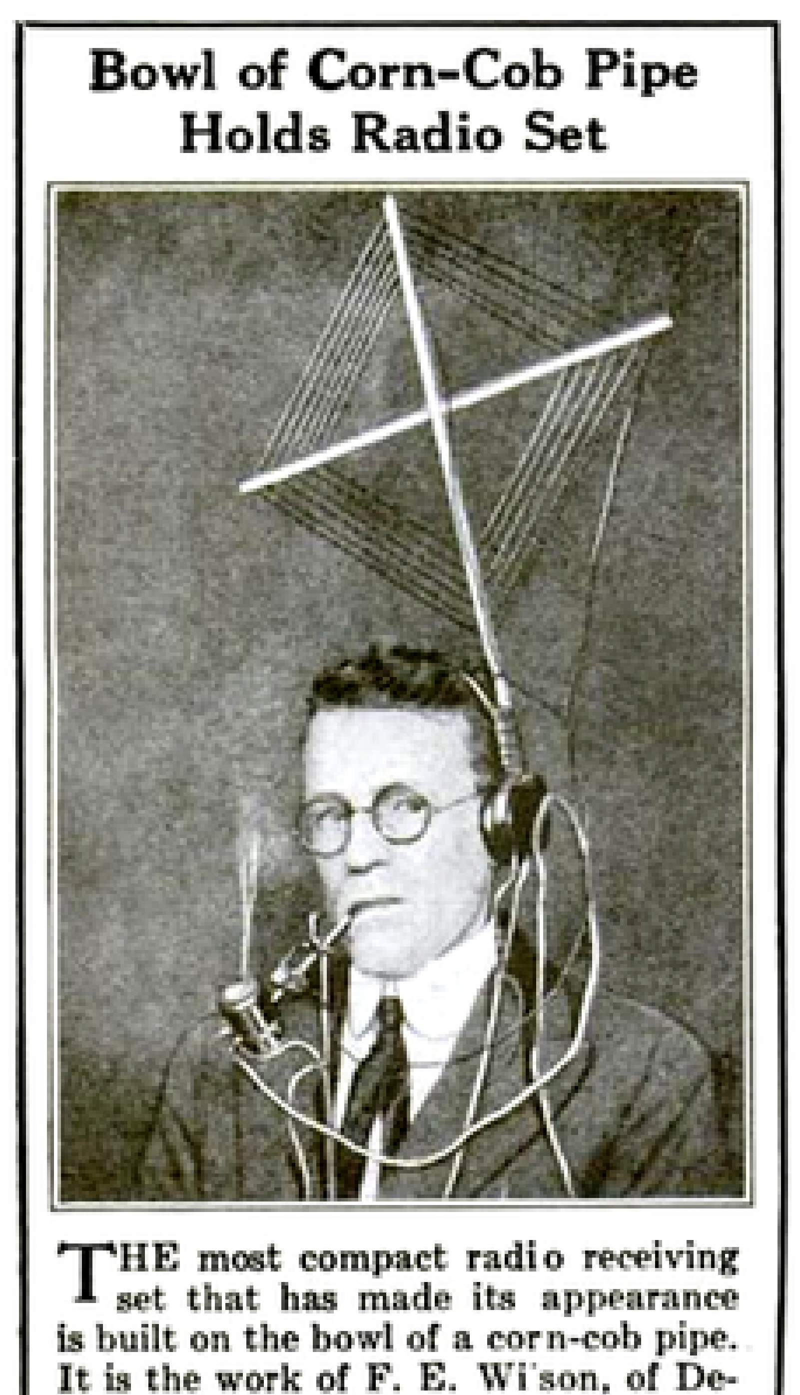
Lodge

- 1897: Wireless system patented, including the coherer. **Marconi purchased the patent in 1911.**

- Also wrote some 40 books
- Many attribute him inventing the moving-coil loudspeaker, the vacuum tube valve, and the variable tuner.
- Invented the spark plug.

Personal wireless receiver

Coherer, and cat's whisker diode for AM reception, enables small radios



Bowl of Corn-Cob Pipe Holds Radio Set

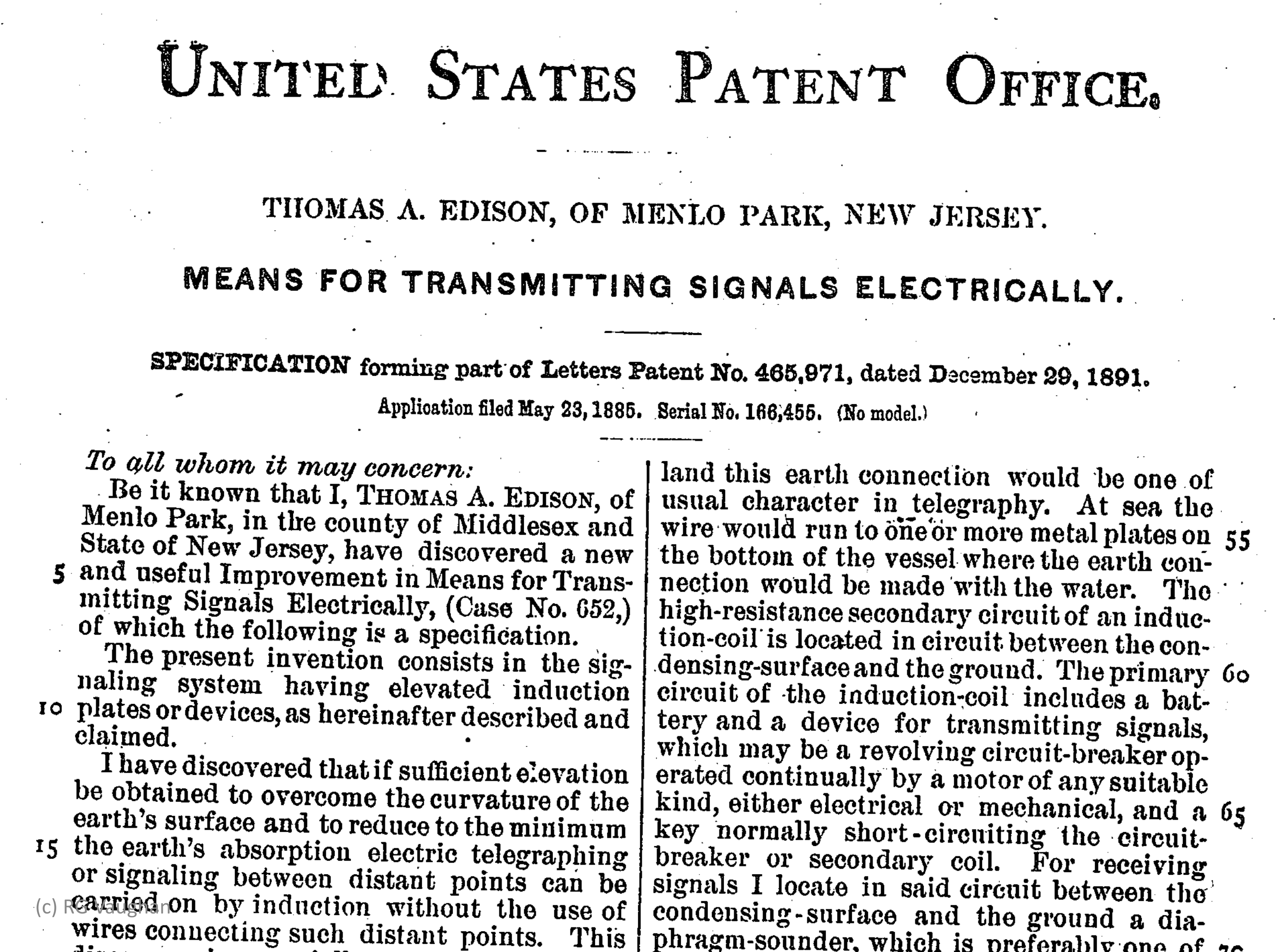
THE most compact radio receiving set that has made its appearance is built on the bowl of a corn-cob pipe. It is the work of F. E. Wilson, of De-

(c) RG Vaughan

Practical players

- **Thomas Alva Edison**, 1847-1931.
- 1875: announced to the press that while experimenting with the telegraph, he had noted a phenomenon that he termed "etheric force". (Later abandoned)

- 1885: Applies for patent for wireless communications using “induction”.



UNITED STATES PATENT OFFICE.

THOMAS A. EDISON, OF MENLO PARK, NEW JERSEY.

MEANS FOR TRANSMITTING SIGNALS ELECTRICALLY.

SPECIFICATION forming part of Letters Patent No. 465,971, dated December 29, 1891.

Application filed May 23, 1885. Serial No. 166,455. (No model.)

To all whom it may concern:

Be it known that I, THOMAS A. EDISON, of Menlo Park, in the county of Middlesex and State of New Jersey, have discovered a new and useful Improvement in Means for Transmitting Signals Electrically, (Case No. 652,) of which the following is a specification.

The present invention consists in the signaling system having elevated induction plates or devices, as hereinafter described and claimed.

I have discovered that if sufficient elevation be obtained to overcome the curvature of the earth's surface and to reduce to the minimum the earth's absorption electric telegraphing or signaling between distant points can be carried on by induction without the use of wires connecting such distant points. This

land this earth connection would be one of usual character in telegraphy. At sea the wire would run to one or more metal plates on the bottom of the vessel where the earth connection would be made with the water. The high-resistance secondary circuit of an induction-coil is located in circuit between the condensing-surface and the ground. The primary circuit of the induction-coil includes a battery and a device for transmitting signals, which may be a revolving circuit-breaker operated continually by a motor of any suitable kind, either electrical or mechanical, and a key normally short-circuiting the circuit-breaker or secondary coil. For receiving signals I locate in said circuit between the condensing-surface and the ground a diaphragm-sounder, which is preferably one of

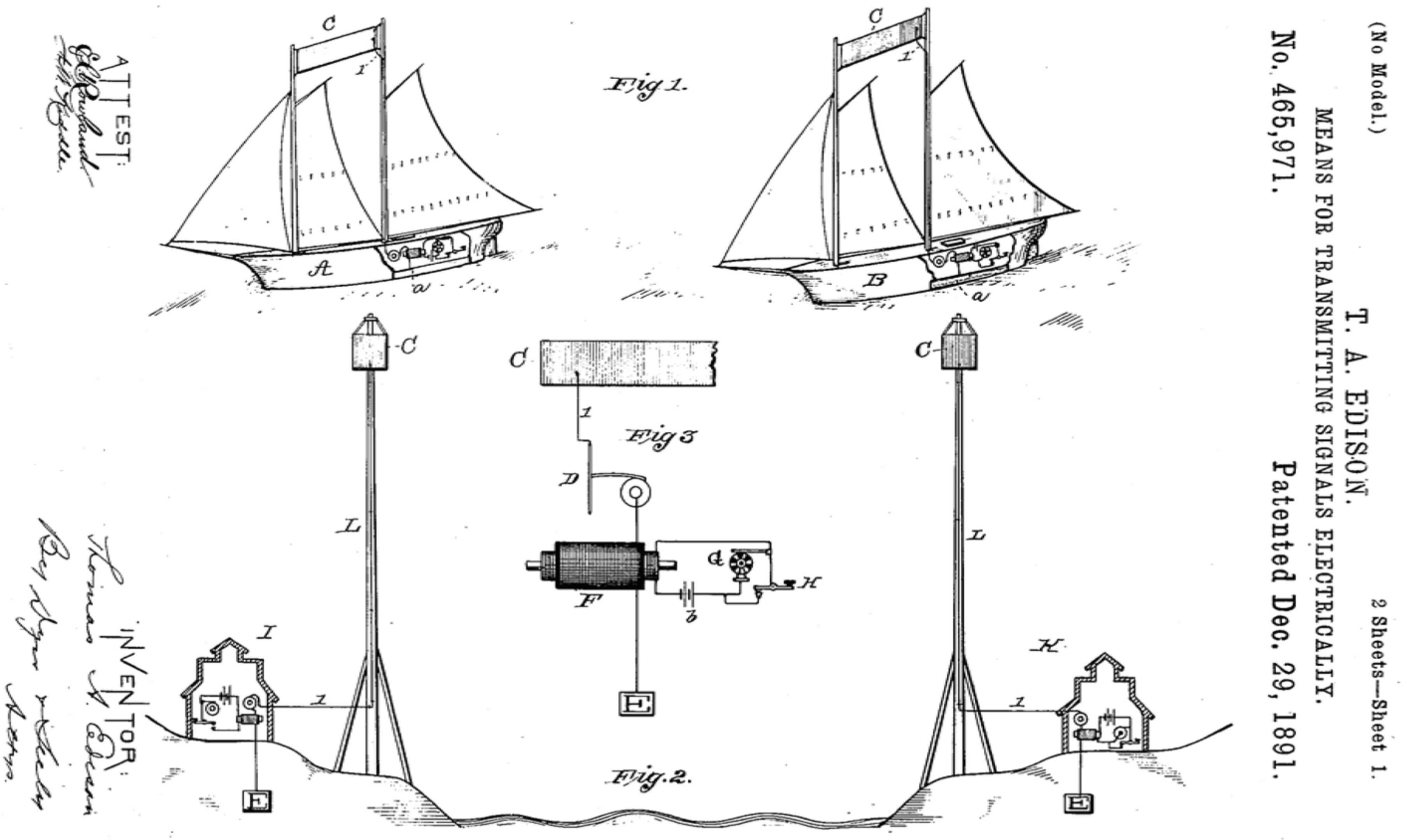

(No Model.)
2 Sheets—Sheet 1.
T. A. EDISON.
MEANS FOR TRANSMITTING SIGNALS ELECTRICALLY.
No. 465,971.
Patented Dec. 29, 1891.
Fig 1.
C
1
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Fig 3
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Fig. 2.
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K
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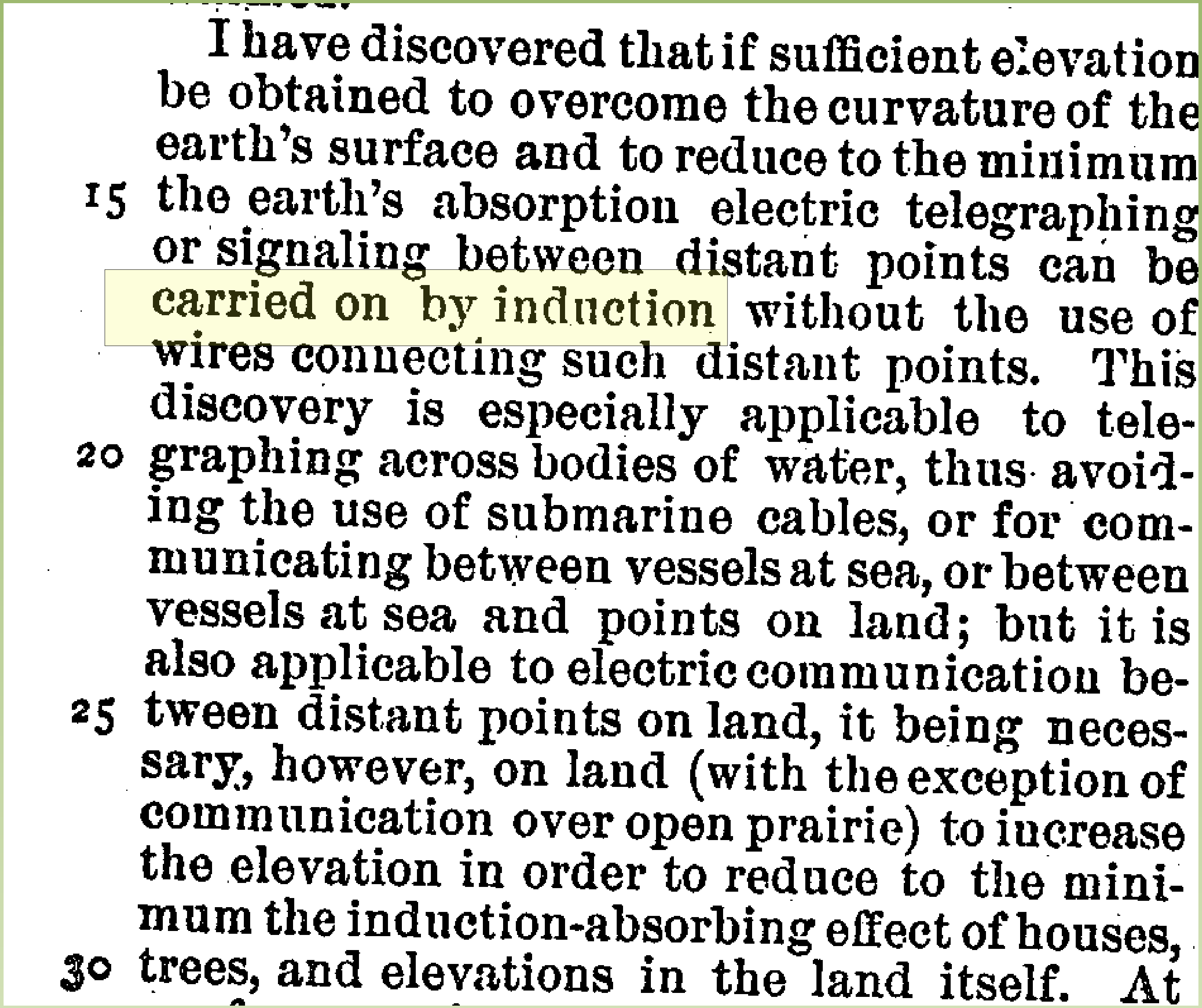
ATTEST
INVENTOR
Thomas A. Edison
By Dyer & Seely
Attys.



I have discovered that if sufficient elevation be obtained to overcome the curvature of the earth's surface and to reduce to the minimum the earth's absorption electric telegraphing or signaling between distant points can be carried on by induction without the use of wires connecting such distant points. This discovery is especially applicable to telegraphing across bodies of water, thus avoiding the use of submarine cables, or for communicating between vessels at sea, or between vessels at sea and points on land; but it is also applicable to electric communication between distant points on land, it being necessary, however, on land (with the exception of communication over open prairie) to increase the elevation in order to reduce to the minimum the induction-absorbing effect of houses, trees, and elevations in the land itself. At

Practical players

- **Nathan B. Stubblefield**, s1860-1928
- American inventor and farmer.
- Used inductive techniques.
- 1892 broadcast voice using induction ground electrodes.
- 1902 Ship-to-shore voice
- 1908 Wireless telephone patent.

~ 1894, Russia, Alexander Stepanovich Popov

- 1859-1906
- 1894 built a working radio
- presented May 7,1895 – *Radio Day*.
- 1896: radio transmission in St. Petersburg.
- 1897, inspired by Marconi, he transmitted ship-to-shore; 30 miles in '98

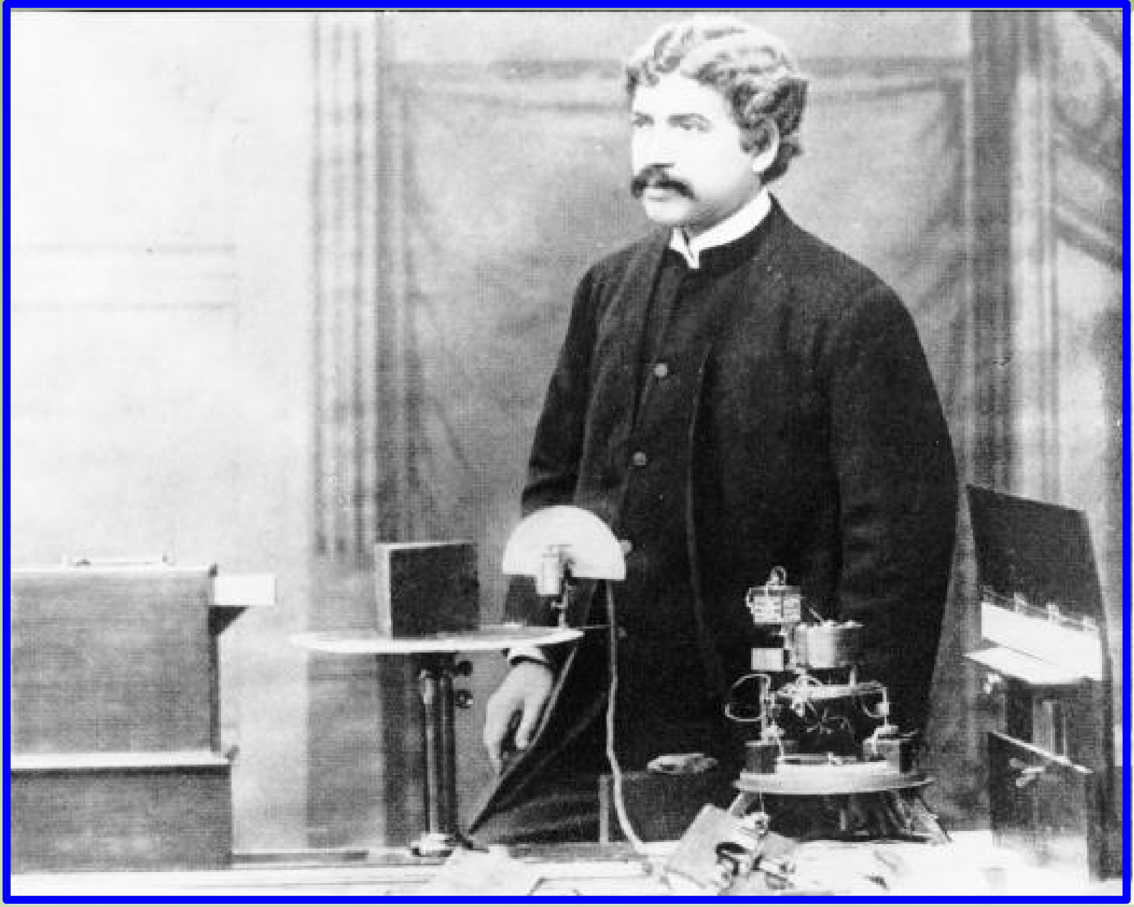
- 1989: USSR stamp:

Alexander Popov, - the inventor of radio

(c) RG Vaughan

~1895 in India, Jagadish Chandra Bose

- **Sir Jagadish Chandra Bose**, 1858 -1937



J. C. Bose

- Bengali polymath, physicist, biologist, botanist, archaeologist, and science fiction writer.
- Pioneering investigation of radio and microwave optics.
- Met Marconi et. al., in 1896.
- Very “unthreatening” with commercialization

J. C. Bose (cont'd)

- Priority over Marconi in his timing
- 60 years ahead of his time in solid state electronics
- Used spark gap for his source

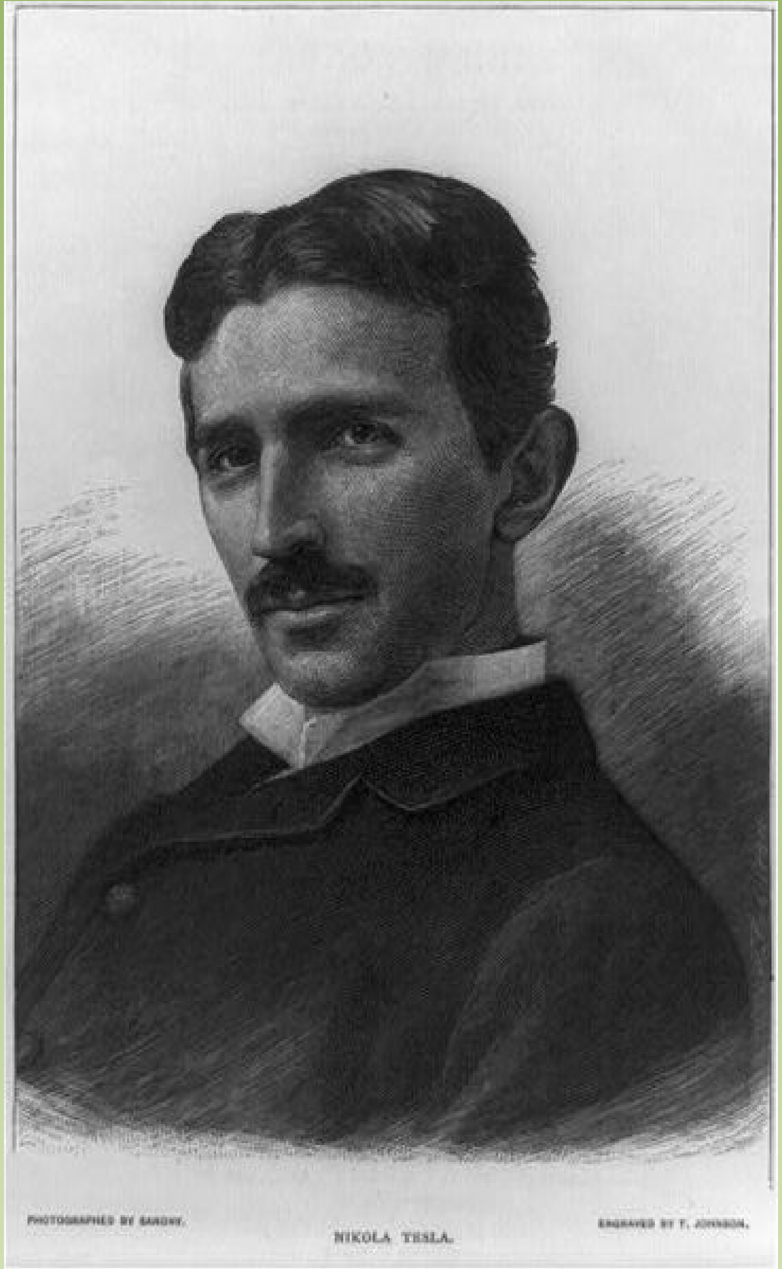
~1900, Brazil, Roberto Landell de Moura

- **Father Roberto Landell de Moura**, 1861–1928.
- 1900: demonstrated **voice** broadcast by wireless (8km); 1901: Brazilian patent; later got 3 US Patents.
- Existing systems: telegraph Morse (1837); telephone Bell (1876) and radio telegraph, Marconi (1895).

~1893 America, Nikola Tesla

- **Nikola Tesla,**1856 –1943
- 1885, **Edison** applies for a patent that looks like Tesla’s work.
- Serbian/American inventor, physicist, mechanical and electrical engineer.
- A bit wacky…
- 1943: The US supreme court turned over Marconi’s patents because of Tesla’s prior art.

Tesla,1856-1943

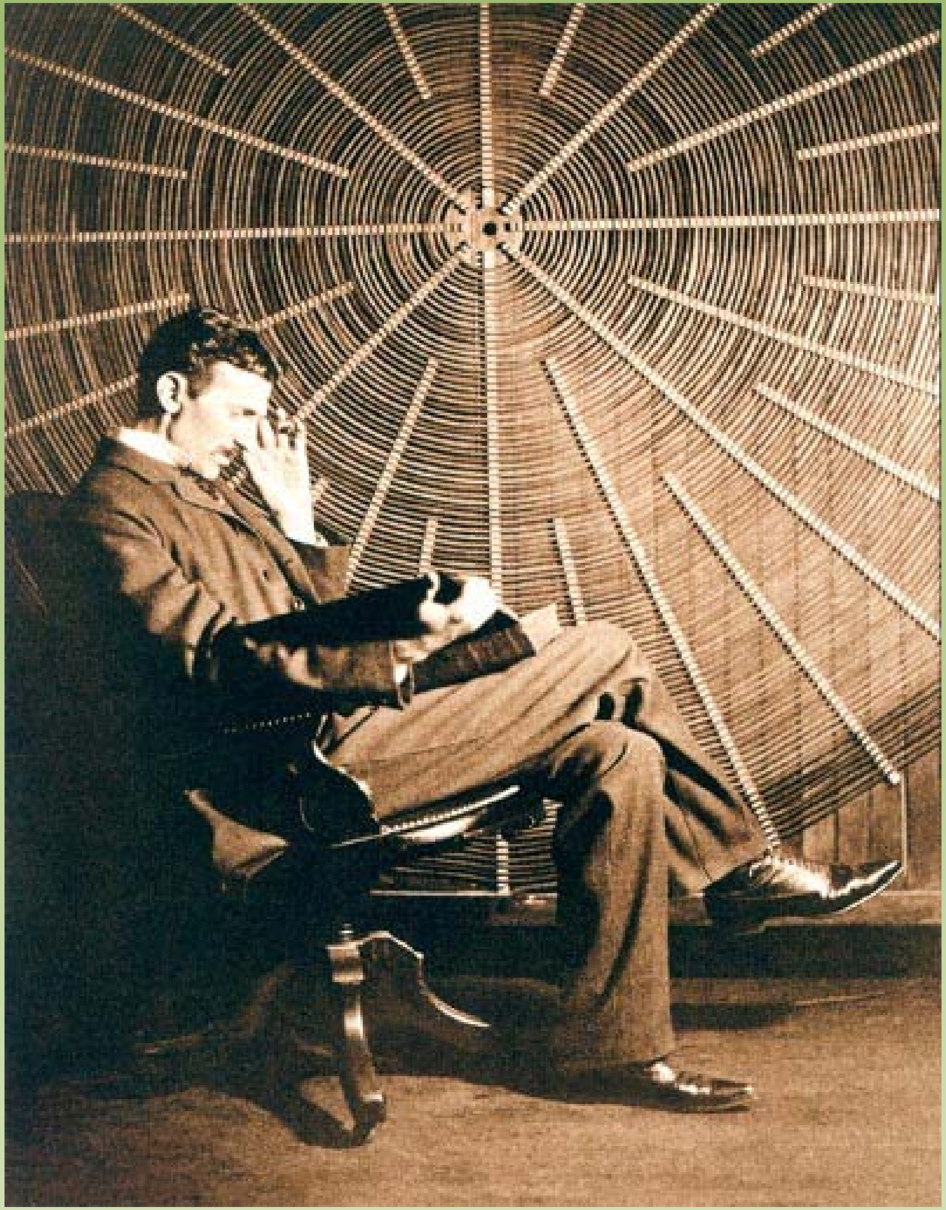


PHOTOGRAPHED BY SARONY.

NIKOLA TESLA.

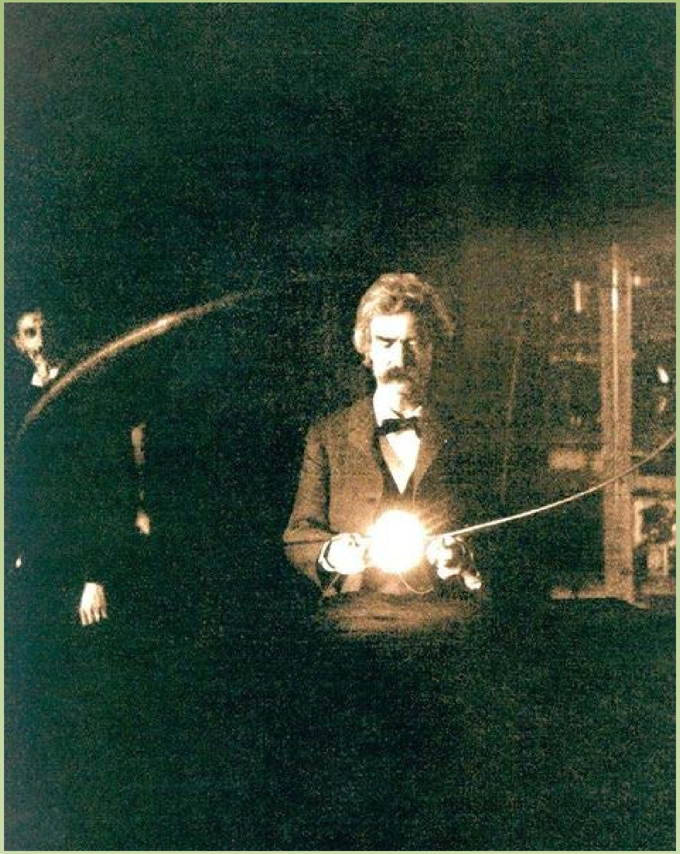
ENGRAVED BY T. JOHNSON.

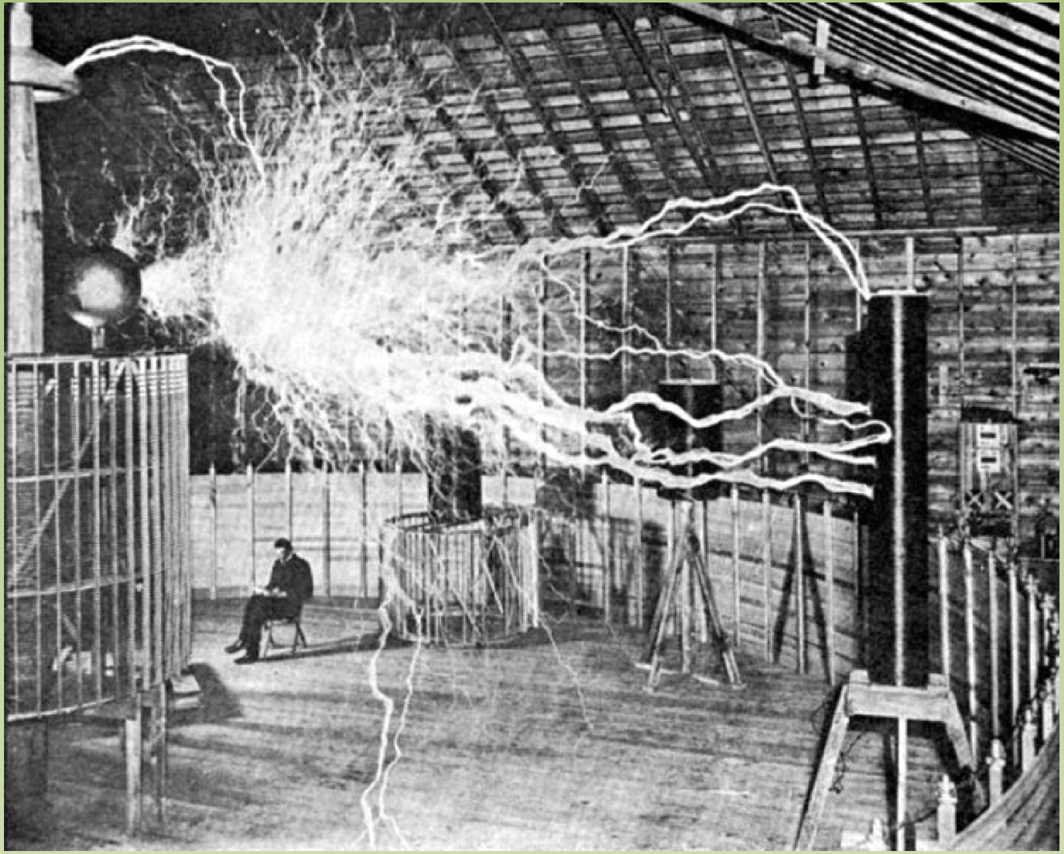
- 1875, B.EE (?) at Graz, Austria?
- 1880, Charles-Ferdinand University, Prague, 1 term
- Photographic memory and 3D imagination
- June 1844, New York.
- Worked for Edison until 1885, on power stuff, +?



- Tesla Reading Rudjer Boscovich's "Theoria Philosophiae Naturalis", in front of the spiral coil of his high-frequency transformer, New York

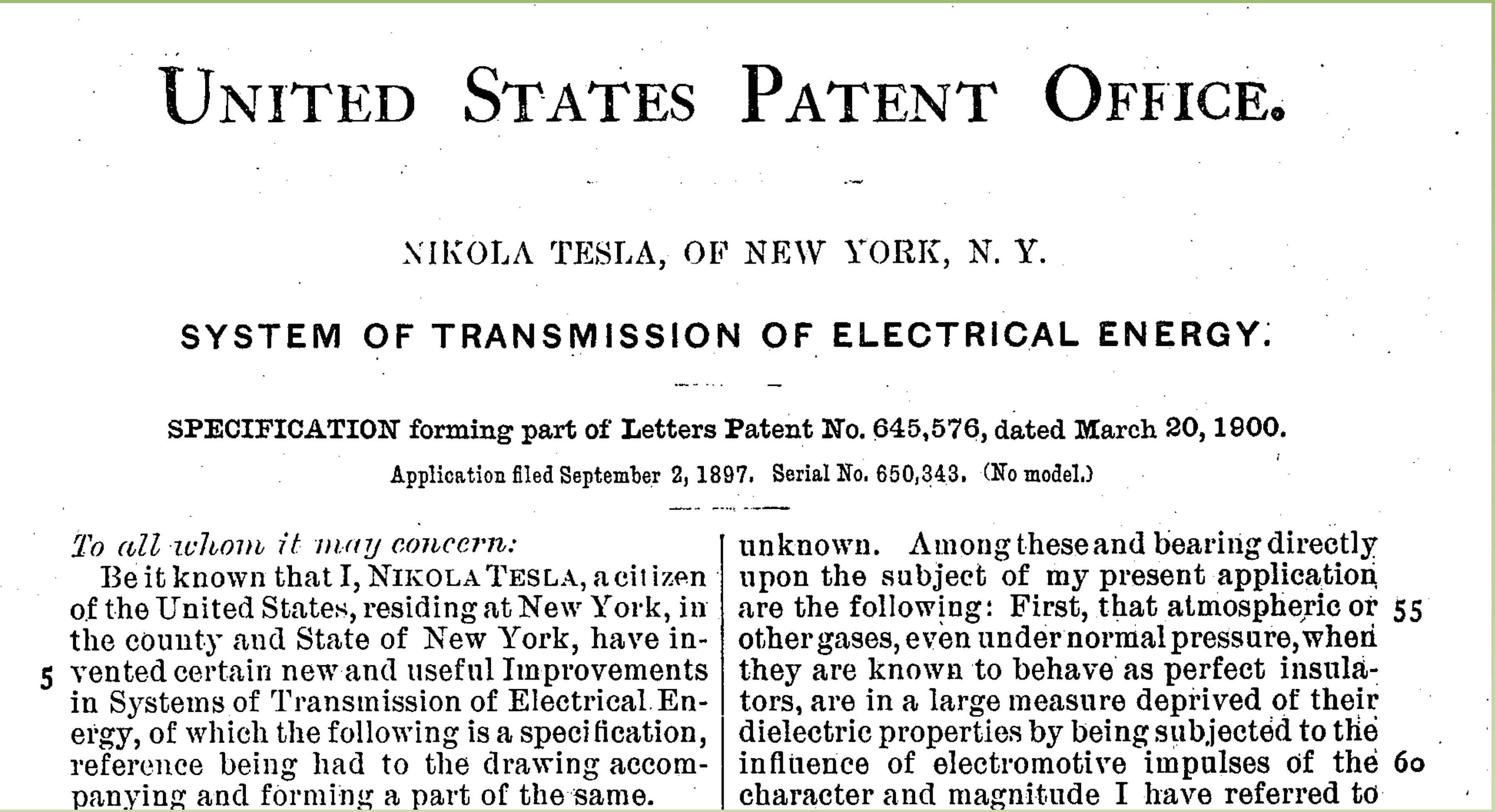
Tesla’s laboratory shots





The Tesla effect (induction)

- *“the transmission of electrical energy without wires”*, aka **Tesla conduction**
- 1893 demonstration in St Louis, Missouri, ***related to*** radio communication in 1893.
- However, he later invented coherers (receivers) and other ***radiative radio*** components.



UNITED STATES PATENT OFFICE.

NIKOLA TESLA, OF NEW YORK, N. Y.

SYSTEM OF TRANSMISSION OF ELECTRICAL ENERGY.

SPECIFICATION forming part of Letters Patent No. 645,576, dated March 20, 1900.

Application filed September 2, 1897. Serial No. 650,343. (No model.)

To all whom it may concern:

Be it known that I, NIKOLA TESLA, a citizen of the United States, residing at New York, in the county and State of New York, have invented certain new and useful Improvements in Systems of Transmission of Electrical Energy, of which the following is a specification, reference being had to the drawing accompanying and forming a part of the same.

unknown. Among these and bearing directly upon the subject of my present application are the following: First, that atmospheric or other gases, even under normal pressure, when they are known to behave as perfect insulators, are in a large measure deprived of their dielectric properties by being subjected to the influence of electromotive impulses of the character and magnitude I have referred to

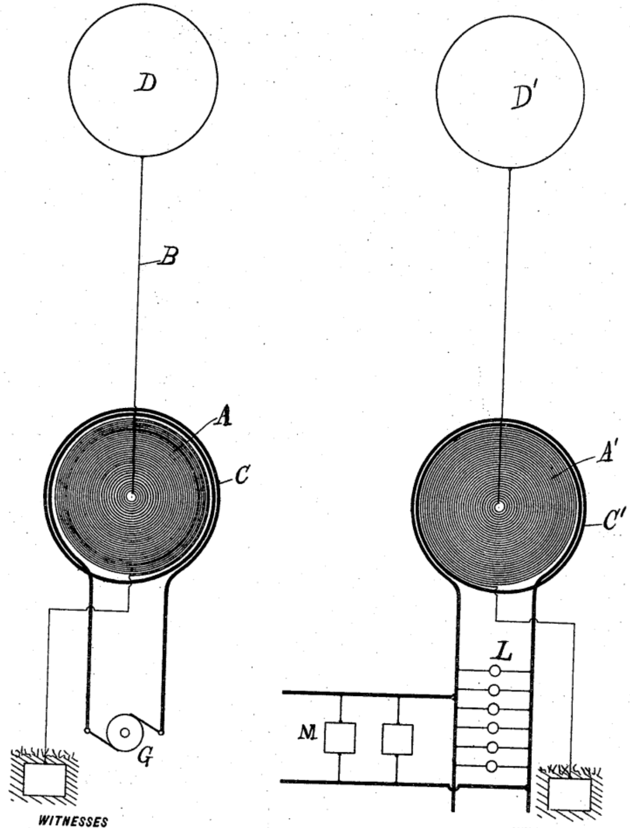
No. 645,576. Patented Mar. 20, 1900.

N. TESLA.

SYSTEM OF TRANSMISSION OF ELECTRICAL ENERGY.

(Application filed Sept. 2, 1897.)

(No Model.)



WITNESSES

Drury W. Cooper

M. Lawson Dyer.

INVENTOR

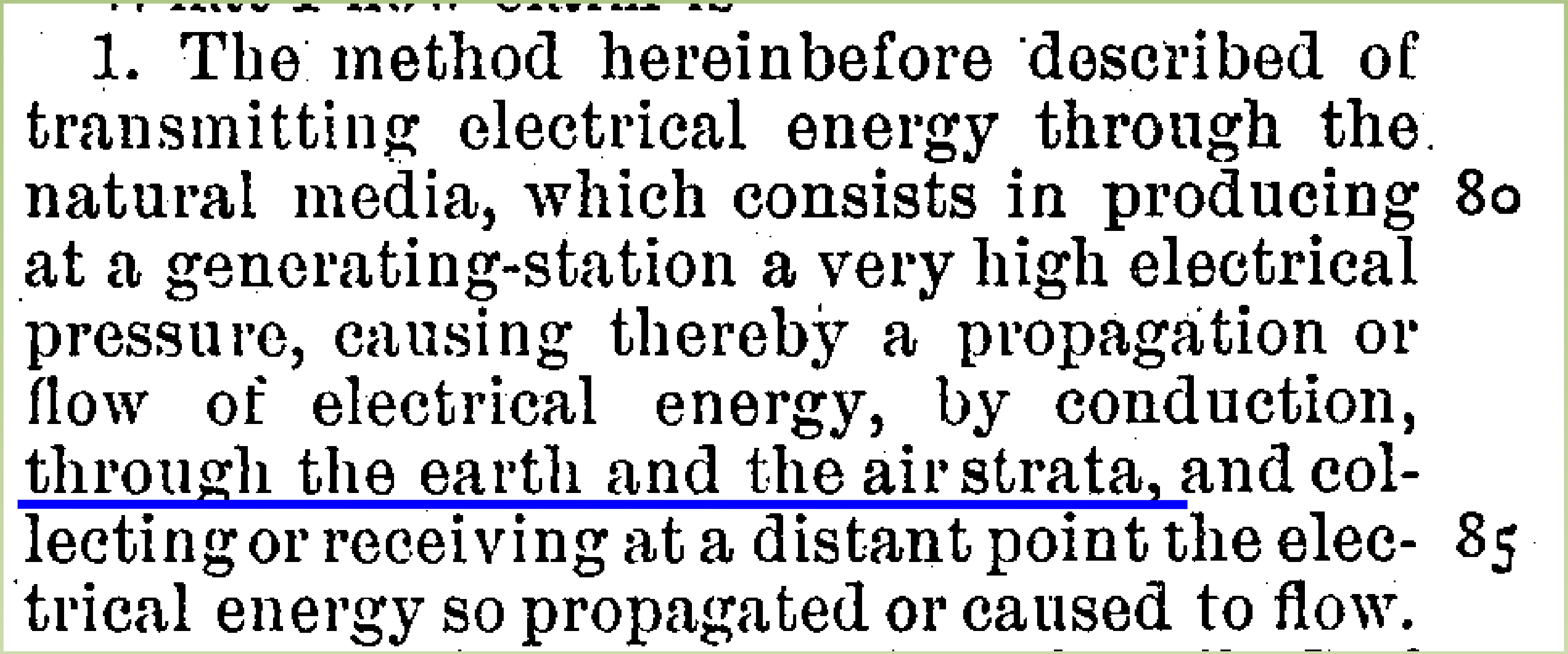
Nikola Tesla

BY

Kerr, Curtis & Page

ATTORNEYS.

A Zenneck wave?



1. The method hereinbefore described of transmitting electrical energy through the natural media, which consists in producing at a generating-station a very high electrical pressure, causing thereby a propagation or flow of electrical energy, by conduction, through the earth and the air strata, and collecting or receiving at a distant point the electrical energy so propagated or caused to flow.

Who invented wireless ?

- J.C Bose in 1894 demonstrated microwave radiation transmission in ***India***, and ***about the same time*** as lower frequencies by **Rutherford** in ***New Zealand***, Tesla in ***America***, **Marconi** and **Lodge** in in ***Britain***, and **de Moura** in ***Brazil***, and **Popov** in ***Russia***.
- All well after **Hertz** and **Hughes**
- ***All a long time after Maxwell***
- **Was Marconi a scientific also-ran?**

The Father of Wireless?

- Understood the experimental facts of propagation much better than anyone else.
- Understood practical antennas effects better than anyone else
- Understood the radio electronics

Marconi understood antennas

I then began to examine the relation between the distance at which the transmittor could affect the receiver and the elevation of the capacity aereas above the earth, and I very soon definitely ascetrained hat **the higher the wires or capacity aereas the greater the distance** over which it was possible to telegraph

Guiseppe Marconi - Annie Jamieson

Luigi, Alfonso, **Guglielmo** - Beatrice O’Brien

Degna (1908), Guilo (1910), Gioia (1918)

- 1927 married Maria Cristina Bezza-Scali

Elektra (1930)

Marconi (1874-1937)

- An engineer! But little formal training.
- Visionary, obsessive, got up rivals' noses
- Father disapproved, but funded early patent
- Cable companies attacked him.
- Some scientists attacked him.
- A combo of Bill Gates and Steve Jobs
- **Propagation, antennas, electronics**.

Marconi (1874-1937)

- 1894 - had read Hertz’s work and appreciated radiowave propagation.
- **INSPIRATION:** To use radiowave propagation to tele-communicate.
- ***Gathers and builds equipment*** for experiments
- **1896** - backyard experiments (>1 km) successful in Italy. - ***After*** Lodge, Rutherford, Tesla, Moura, Bose, Popov.

- 1896 Guiseppi M. funds patent in Italy
- Annie’s connections gets British introductions
- ***William Henry Preece***, Chief Engineer for British Post office, - the most important man in the world in (wired) communications.
- Preece saw potential for the empire.
- *Marconi’s equipment was often called “familiar”, e.g., to Dolbear’s 1882 coherer.*

- March 1897, 6 km Morse transmission across Salisbury plains
- May 1897, 14km across water
- Preece gives public lectures on wireless
- **1899 Across the English Channel**

Conflict!

- Preece **attacks** Marconi (privately)
- British government **withdraws** support
- Sir Oliver Lodge **attacks** publically, in an extraordinary, vicious press release.

Crossing the Atlantic

- 1899: Marconi invited to America's cup
- Hires star engineers, J.A.Fleming, R.N. Vyvyan, *et al.*
- Canadian government support

Seeing the value of Marconi's ship-to-shore wireless to the national economy, not to mention the prestige of being a leader in telecommunications, the Government of Canada agreed to put up $80,000. Canadian broadcaster Warner Troyer noted, sarcastically, that while the Canadian government denied **Reginald A. Fessenden**, a Canadian citizen, financial assistance for his radio experiments, it was "busily funding and supporting an Italian inventor“

[Collins, R. (1990). Culture, communication and national identity: The case of Canadian television. Toronto: University of Toronto Press.]

CANADA MARCONI COMPANY.

Chartered with $5,000,000 Capital, All of Which Is Subscribed.

MONTREAL, Quebec. Jan. 13.—The Marconi Wireless Telegraphy Company of Canada was organized here to-day with a capital of $5,000,000 in a million shares of $5 each. The Directors are Marconi, Andrew A. Allon, Rudolphe Forget, and F. C. Henshaw, local capitalists; W. R. Green of New York, and John D. Oppo of England, who is to be the General Manager of the Canadian company.

It is stated that the capital has all been subscribed. The Canadian company acquires all the property of the Marconi Company in Canada, including the station at Glace Bay, C. B.

The New York Times

Published: January 14, 1903


DOMINION OF CANADA.
THE MARCONI

Transatlantic propagation!(?)

- 12 December 1901, $d=3.5(10)^6$m , daytime

- 150 m kite-supported antenna for reception, from Poldu, Cornwell,

  England

  to Signal Hill, St John's, Newfoundland, **Canada**

- **Massive breakthrough, not repeatable…**

Transatlantic propagation #2

- February, 1902, Marconi sailed from **England**
- Signals strength measured daily
- coherer-tape reception up d=2.5(10)^6 m
- audio reception up to d=3.3(10)^6 m
- Half the distance at daytime.
- Newfoundland claims not confirmed,
- But proved **further than Line-of-Sight**.

Transatlantic propagation #3

- 18 January 1903, a Marconi Station built near Wellfleet, Massachusetts sent a greeting **from Theodore Roosevelt**, the President of the United States, **to King Edward VII** of the United Kingdom
- First transatlantic radio transmission originating in the US.
- Consistency still difficult over extreme *d*.
- Ship-borne deployment of wireless.

More conflict!

- Scientific establishments

  (the straight-liner's) in turmoil
- URSI later formed as a direct result
- Pioneering propagation measurements but conflict over originality of wireless technology and patents
- Cable company unhappy, US unhappy
- Several inventors unhappy.

More controversy!

- Question: Spectrum sharing?
- Answer: 7777 patent on tuned circuits
- But too close to Tesla and Stone, et al.
- P.S. 1943, Marconi's patents overturned.

(Marconi was suing the US govt for their military using his patents for many years with no royalty; c.f., the US had earlier reversed its position on Marconi to avoid Tesla royalties)

The search for propagation mechanisms

- 1909 Marconi gets Nobel Prize in Physics.

- How did Marconi's signals propagate so far?
- Why was the propagation channel unreliable?
- The noise in all this was Marconi's fame and commercial success.

Back to the future with Maxwell

- The hunt was on for solutions to the great propagation problem.

- **The Ionosphere (Heaviside layer) was not known.**

- **Seek solutions to Maxwell's equations**

  and radiating waves with *very* low loss...

Solution 1: The Ionosphere

- 1899 Effect observed by Tesla
- 1902: **Oliver Heaviside** (1850-1925) postulated its existence
- 1902: **Arthur Edwin Kennelly** 1861-1939
- 1902: Kennelly-Heaviside layer
- 1924-27 Experimentally confirmed to exist by **Edward Appleton**. (Nobel prize, 1947)
- 1939 T.S.Eliot’s *Old Possum’s Book of Practical Cats.*

“Ionosphere” coined in 1926

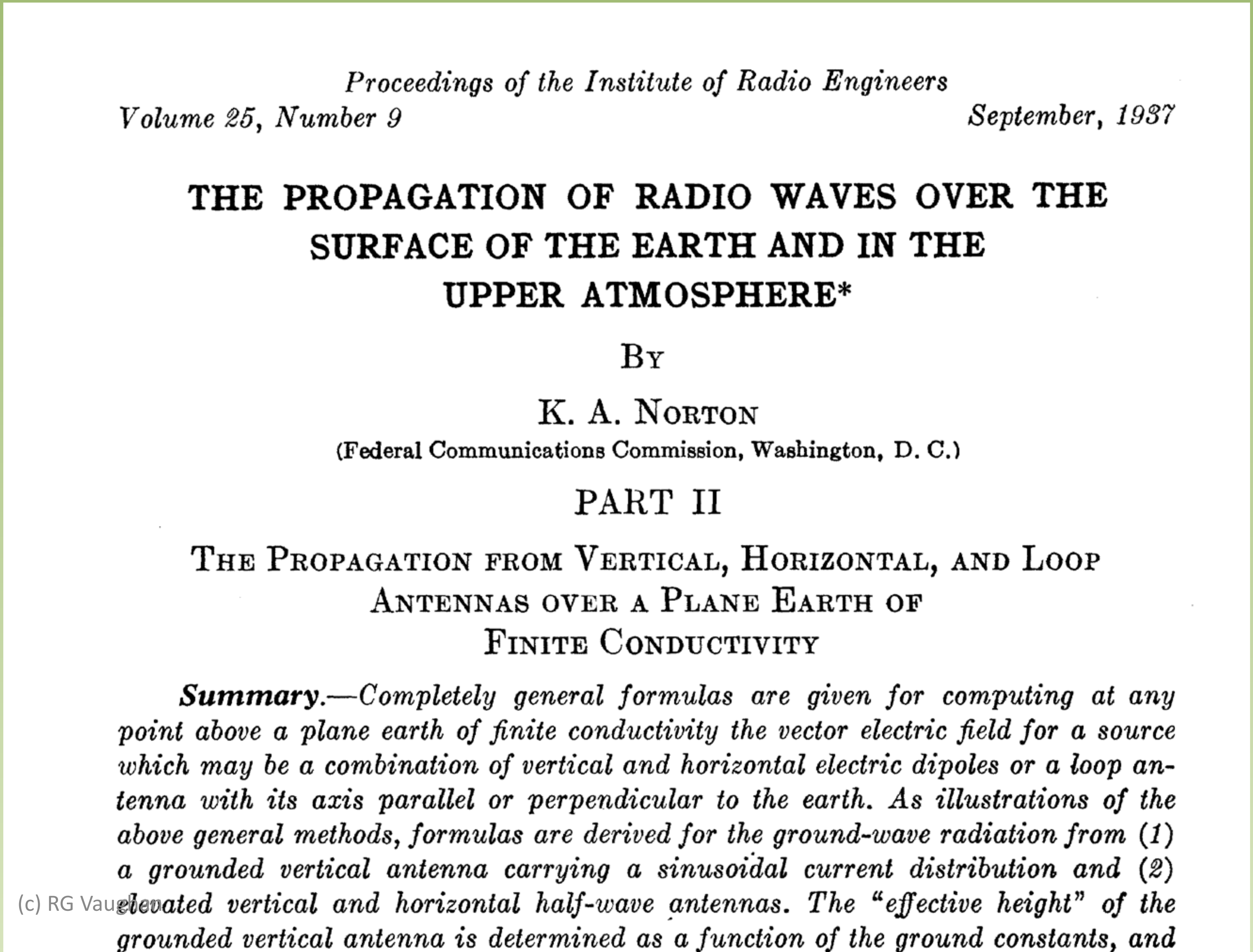
- **Robert Watson-Watt** introduced the term *ionosphere*
- We have in quite recent years seen the universal adoption of the term ‘stratosphere’..and..the companion term ‘troposphere’... **The term ‘ionosphere’,** for the region in which the main characteristic is large scale ionisation … appears appropriate as an addition to this series.
- \- [letter published in 1969 in *Nature*].

2. Surface waves solutions

- **Jonathan Adolf Wilhelm Zenneck** (1871-1959)
- **Arnold Johannes Wilhelm Sommerfeld** (1868 -1951)
- **K. A. Norton** (1907-????)
- **George J.E. Goubau**
- **James R. Wait, A. Banos, Robert E. Collin, Francis J. Zucker**

Surface waves

- (Cell size: planet!)
- 1907, (Zenneck) - mathematically a type of surface wave that could travel along an interface of lossy dielectric and free space.
- 1908 (Sommerfeld) “surface wave”
- 1937 (Norton) “surface wave” = mechanism.



Proceedings of the Institute of Radio Engineers
Volume 25, Number 9 *September, 1937*

THE PROPAGATION OF RADIO WAVES OVER THE SURFACE OF THE EARTH AND IN THE UPPER ATMOSPHERE*

By

K. A. Norton
(Federal Communications Commission, Washington, D. C.)

PART II

The Propagation from Vertical, Horizontal, and Loop Antennas over a Plane Earth of Finite Conductivity

Summary.—*Completely general formulas are given for computing at any point above a plane earth of finite conductivity the vector electric field for a source which may be a combination of vertical and horizontal electric dipoles or a loop antenna with its axis parallel or perpendicular to the earth. As illustrations of the above general methods, formulas are derived for the ground-wave radiation from (1) a grounded vertical antenna carrying a sinusoidal current distribution and (2) elevated vertical and horizontal half-wave antennas. The "effective height" of the grounded vertical antenna is determined as a function of the ground constants, and*

K.A. Norton (1907- ????)

(c) RG Vaughan

Surface wave propagation

- “Trapped” or “guided” wave
- **Does not radiate** into free space
- **Slower** than a free space wave
- Ramifications for antenna mechanisms

- **Structures:**
- Grounded dielectric slab
- Dielectric rod

Antenna: the bit between guided waves (signals) and radiating waves (fields)

What this extraordinary history has told us

- Seldom can one person, group, or country claim to have invented a significant technology
- Commercialism of a disruptive technology gets in the way of accrediting the science correctly
- Plenty of juicy scraps, tiffs, scrapes, controversy and unrepeatable results!

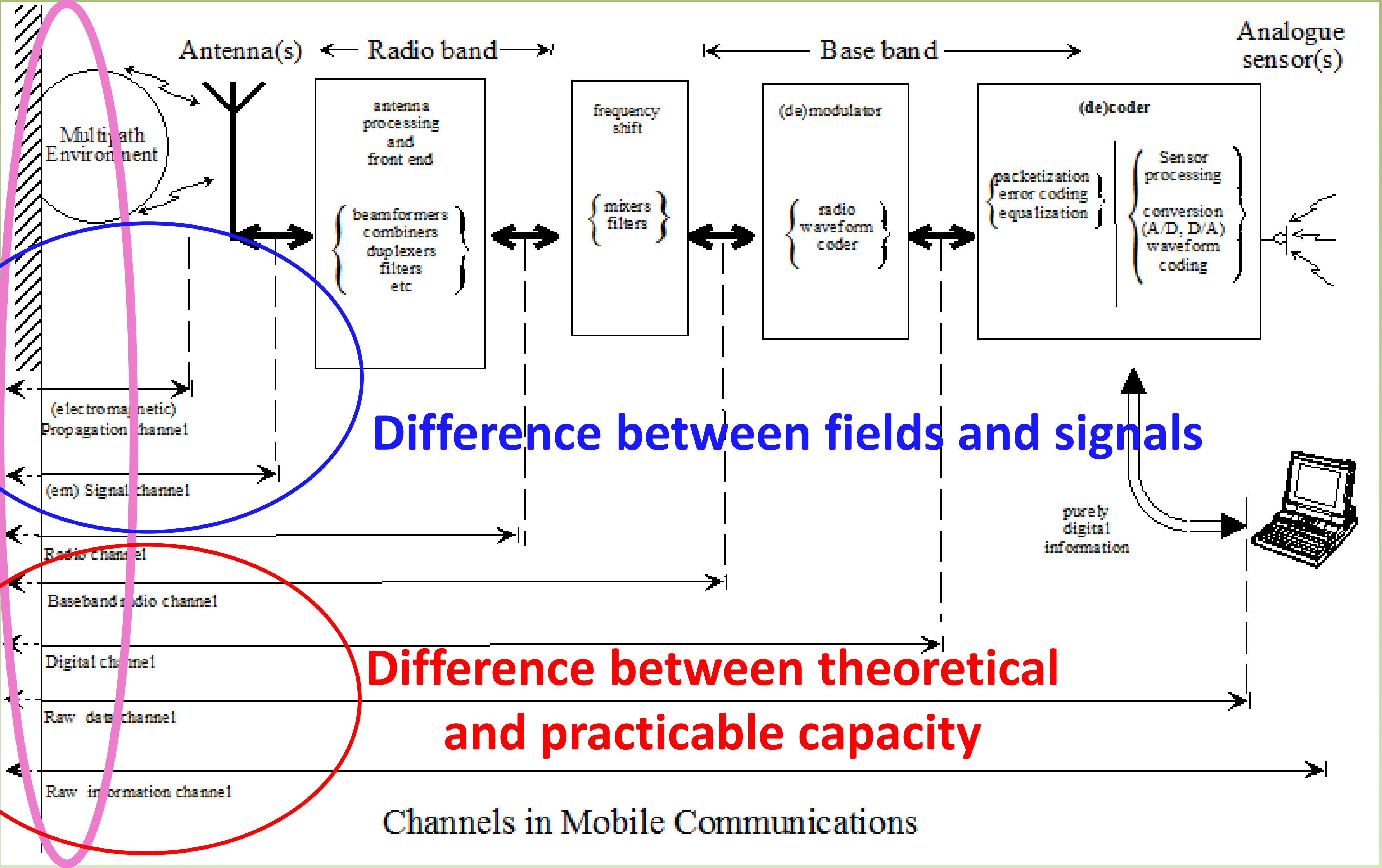
- **The radio spectrum must be shared between all users !**
- **Companies already pay billions for spectrum rights**
- **We need new technologies and business models that share the spectrum.**
- **We need to fix energy efficiency for the growth to continue**
- **Smart antennas are a major part of the answer, and is why they are forefront research**

WHAT HAS HAPPENED SINCE THE EARLY WIRELESS?

- Better understanding of propagation, not just for long distance, but of scattering and how to exploit it
- New and improved communications techniques (multiple access, cellular, MIMO)
- New electronic technology to enable small terminals
- International coordination of spectrum usage
- Antenna technology: arrays, patches, slots
- Information theoretic advances

- **Part III: Design Aspects**
- **Digital Communications and MEAs**
- **It is not really possible to separate optimized antenna design from the communications aspects**

Physical Layer: Many Channels



Difference between fields and signals

Difference between theoretical and practicable capacity

Channels in Mobile Communications

Capacity grand challenge

- Formulation
- Information theoretic channel is <u>transmit oriented</u>

C_{Shannon}

- It is much better to think of the <u>receive limits</u>

$C_{\text{Practicable}}$

- Any optimization gives different answers between these

Capacity gives good economic arguments

- C = income (billable bits)
- B = capital outlay (e.g., $4.3 billion..)
- C/B = profit ratio
- Profits are proportional to energy/bit
- Strong motivation to increase C/B
- => Strong motivation to make better antennas

Basic communications:
it’s all about energy per bit

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

$$\frac{C}{B} = \log_2\left(1+\frac{C}{B}\frac{\varepsilon_b}{N_0}\right).$$

So the Shannon capacity efficiency and the energy per bit are related (transcendentally)

Basic parameter of digital communications:

Energy per bit/Noise

- To the communications engineer:
  - this is about
  detection theory and algorithms
- To the antenna systems engineer:
  - this is about antenna design for
  for high gain
- With diversity/MIMO, these should no longer be separated

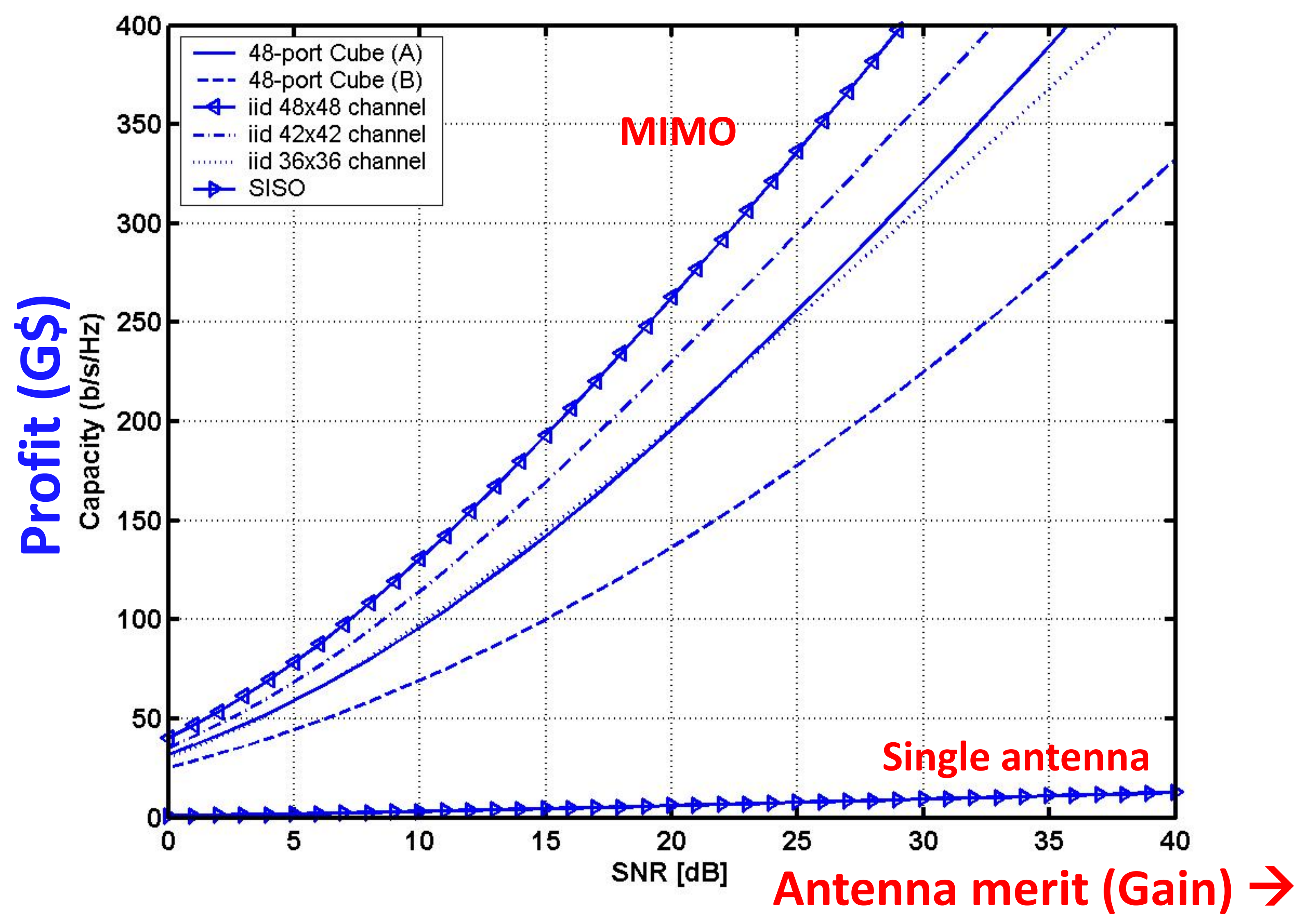
M x M MIMO, single user

$$\frac{C}{B} \approx M \log_2\left(1 + \left(\frac{C}{B}\right) \varepsilon_{Tx_b} G_{Tx} G_{Path} G_{Rx} \frac{1}{\varepsilon_{Rx_b}} \right)$$

- **So the profit is directly proportional to the antennas**

- **An information-theoretic basis for antennas systems.**

Why MIMO is famous: examples like this



MIMO

Profit (G$)

Single antenna

Antenna merit (Gain) →

Limits and limits

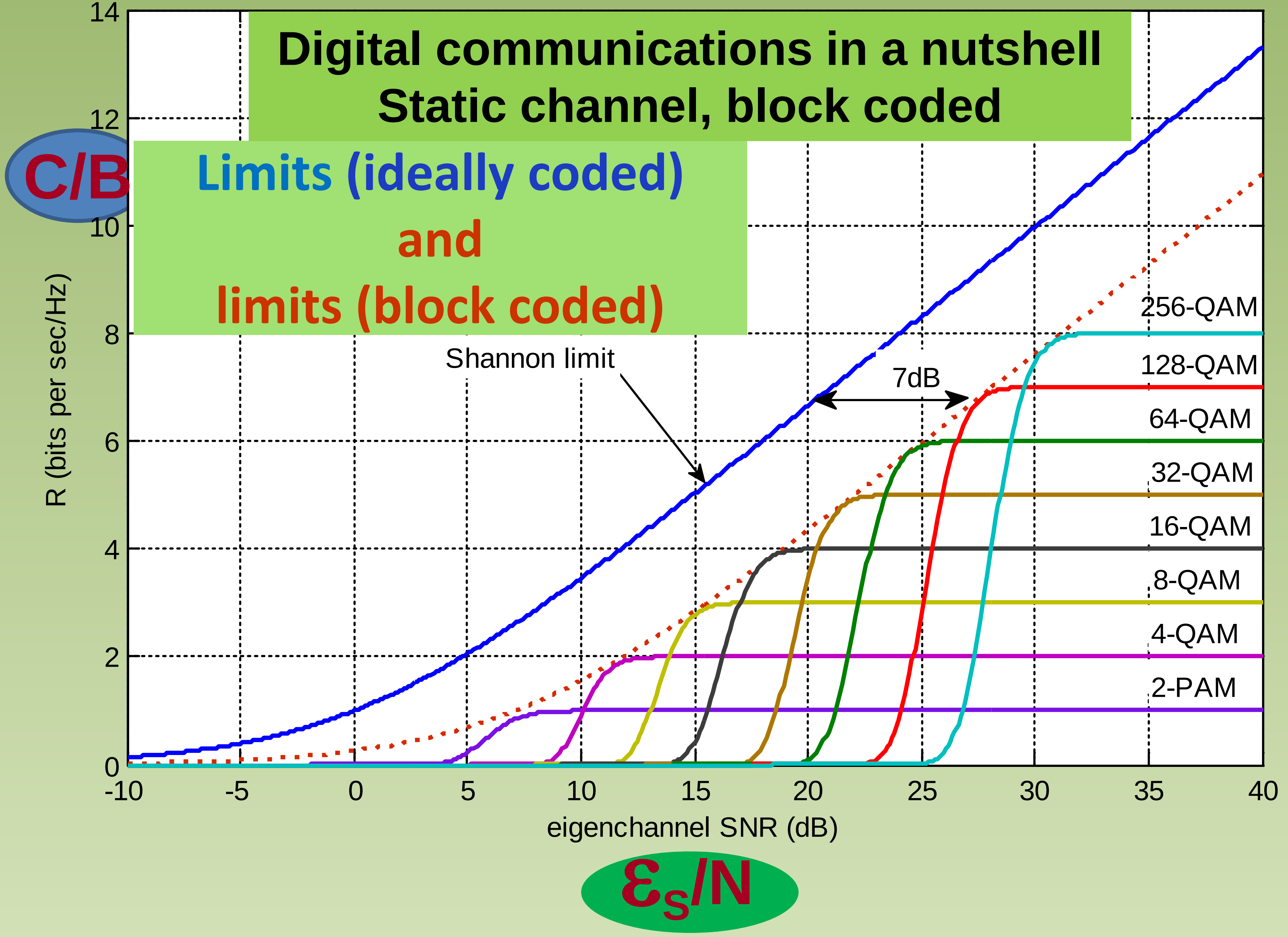
- But the Shannon limit may be reached with infinitely long codes and digital techniques.

- For example, the changing channel compromises the capacity definition

- We need a practicable capacity, this is closed form for modulations, and some block coding; but not data coding in general, except by simulation of specific examples.

- In this sense, we don’t have very good techniques yet..

Digital communications in a nutshell
Static channel, block coded

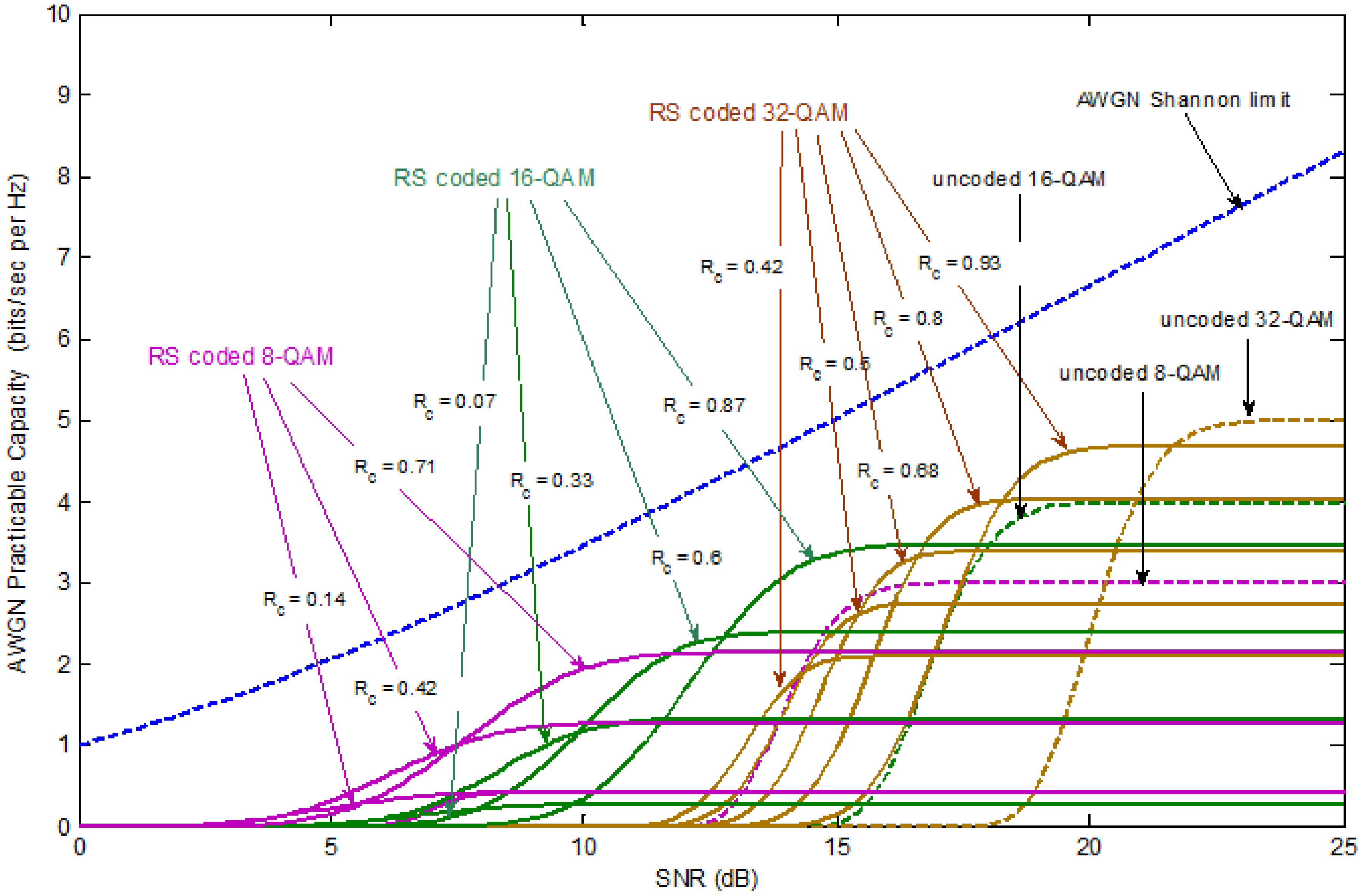


Limits (ideally coded)

and

limits (block coded)

Practicable Capacity (coded)



Moral of the capacity story

- The Shannon capacity is a mathematical form, not a practicable form

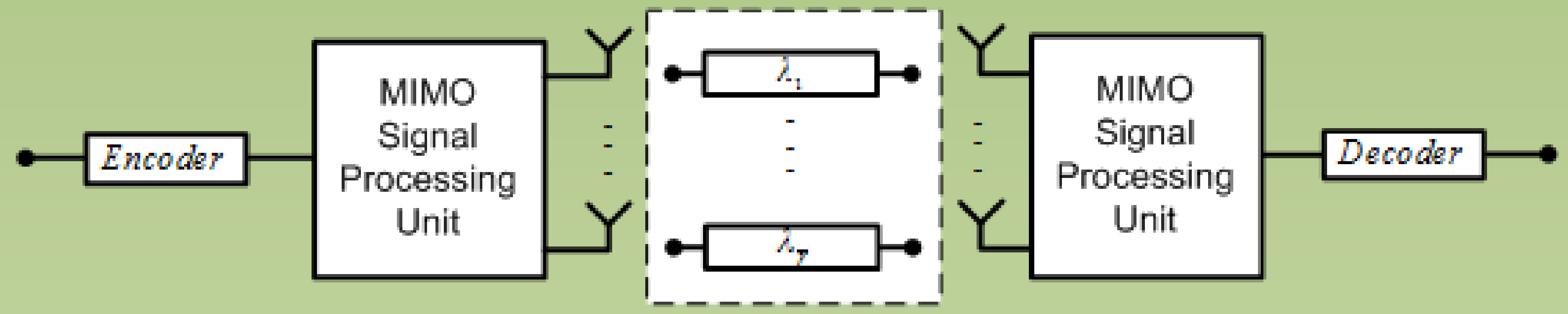
- We cannot get very close to it

- A practicable capacity (throughput of correctly detected bits) is more meaningful, and a better optimization target.

- But we don't have closed forms yet.

Communications techniques

- **Grand challenge for MIMO:**
- **To get the closest possible to the capacity promised by analysis, we need to use eigen-MIMO - the channel needs to be sounded and the CSI sent back to the transmitter. But this uses capacity!**



Equivalent system of eigen-MIMO

Alternative trick 1: throughput improvement in OFDM using a form of diversity

- **with Ali Yazdanpanah and Behrang Nosrat Makouei**
- **Uses data as “ghost pilots” to sound channel**

- “World record” on BER performance for OFDM ….
- Method:
  - use pilots as in standard OFDM
  - Maximum likelihood detection of data
  - Perform expectation maximization on new pilot locations.
  - Use these as pilots for next row, and so on, for whole OFDM frame.
  - Start again in next frame.
- Result: better channel sounding and better data detection.

Alternative trick II: Blind technique for capacity with OFDM

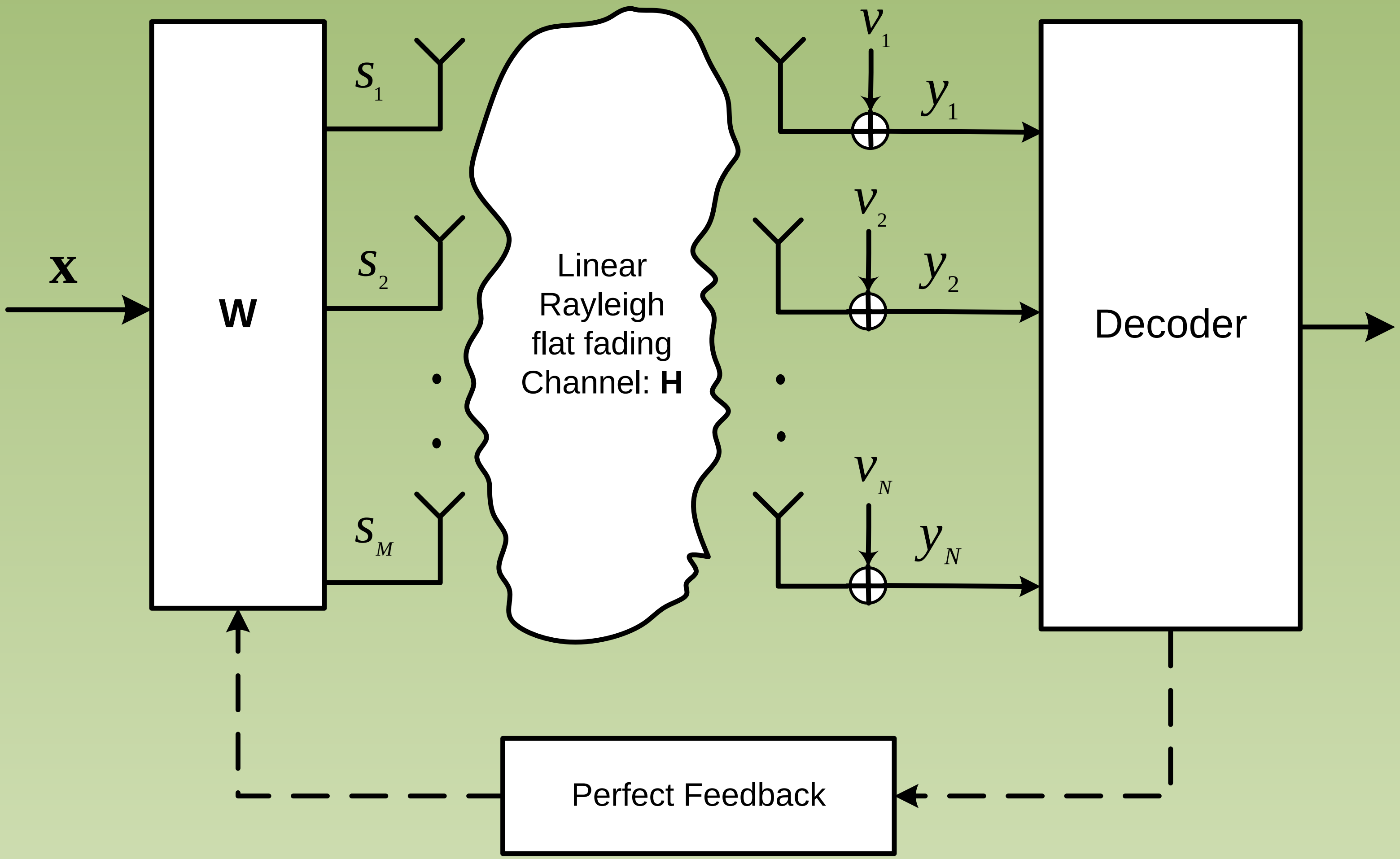
- with Alireza Banani

- Blind channel: - do away with pilots!

- Blind channel sounding has some interesting information-theoretic issues

- There is no ideal blind technique

Capacity maximization for communications



x

W

Linear Rayleigh flat fading Channel: **H**

Decoder

Perfect Feedback

It is often assumed that the channel sounding and CSI feed back is free

Multiuser MIMO: K-user interference channel

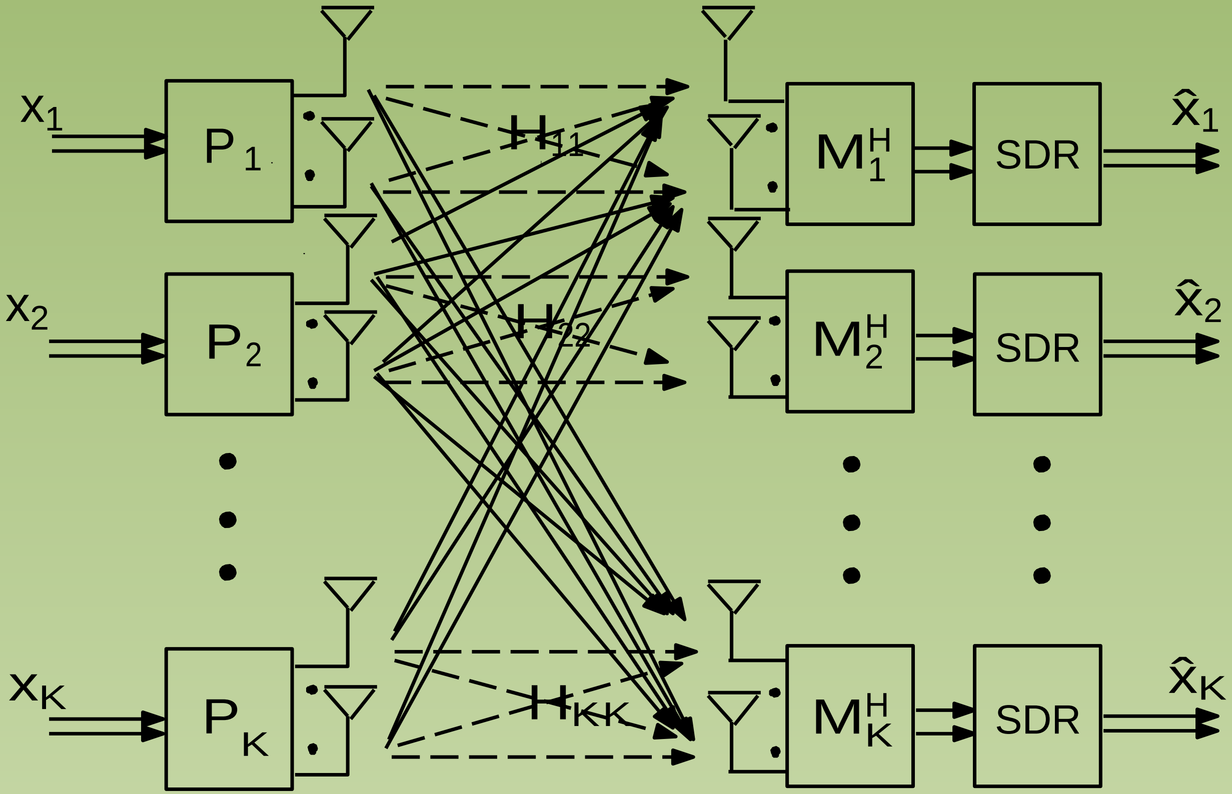


Fig. 1. The system model for multi-stream K user MIMO interference channels.

- **P, M = Tx, Rx beamformers, K independent links**
  - **Maximize overall capacity via SINR**

Beamforming with Multipath Diversity in a Multiuser MIMO-OFDM Interference Channel

- With Milad Toutounchian
- Eliminate interference and then maximize SNR
- Weapon: linear algebra and convex optimization
- Tx beamformers are placed in null space of a function of the channels, and this eliminates one interferer
- Rx beamformer maximizes SNR under constraint of eliminating other intereferers
- Rx beamformer is quasi-convex optimization – simultaneous non-linear equations, can be solved to near-optimality by a simple random search algorithm

Basic formulation

Received signal first user

$$y^{s1}(p) = H_{1,1}(p)v^{s1}(p)x^{s1}(p)$$

$$+ H_{1,2}(p)v^{s2}(p)x^{s2}(p) + \cdots + n_1(p) \qquad (1)$$

First Receive beamformer is

$$v^{si} = \text{Null}\,(H_{Nu+1-i,\,l}) \qquad (3)$$

where

$$\text{Null}\,(A) = \{x|Ax = 0, ||x|| = 1\} \qquad (4)$$

is an orthonormal basis for the null space of A

- **Then maximize: power of received signal subject to: setting all int. to zero, successively for each received signal**

A useful fundamental result drops out of the linear algebra formulation

How many antennas do we need in order to optimize multiuser MIMO?

Lemma 1.

the minimum number of receiver and transmit antennas at each terminal is

$\min(N_r) = N_u$ and $\min(N_t) = N_u + 1$ respectively

- So we have to know the network dimension
- This helps with many questions about the approach

The ergodic capacity for 2, 3 and 4 users

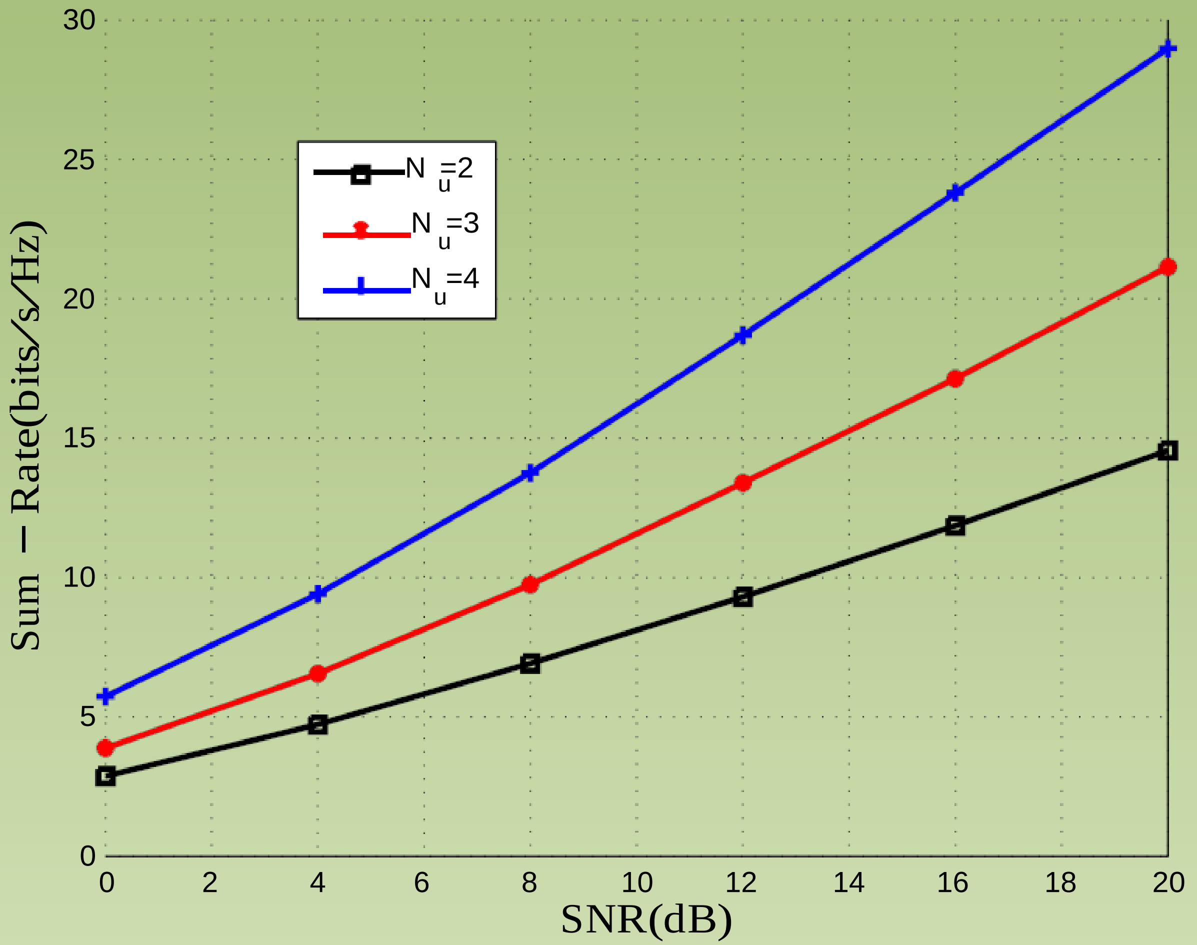


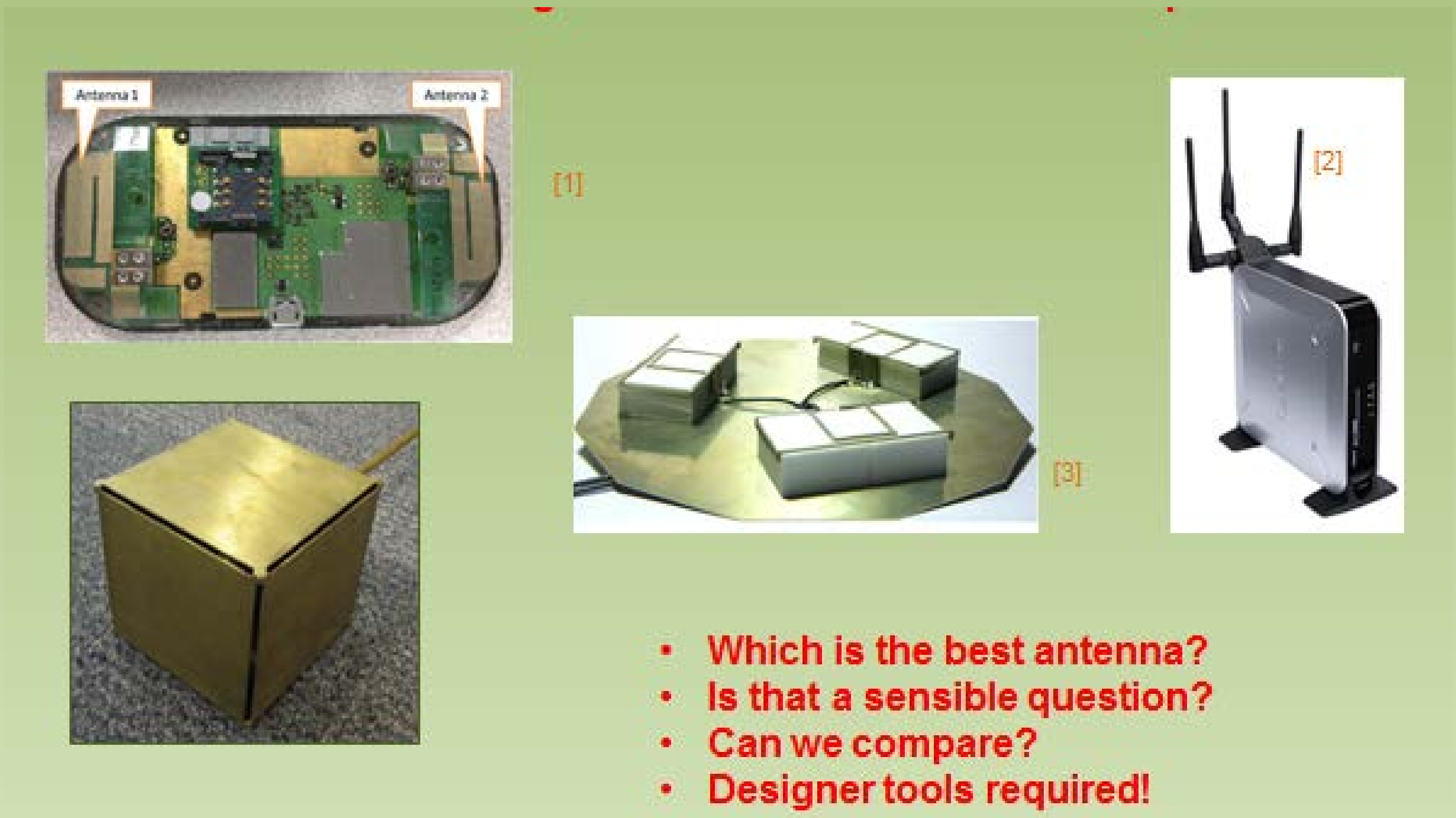
Fig. 6. The ergodic sum-rate for $N_u = 2$, $N_u = 3$, $N_u = 4$ of the proposed system.

The K-user channel

- **With optimized antennas ate all terminals**
- **Is a highly tuned system**
- **If we add another antenna, the performance <u>decreases</u>**
- **Are we taking these formulations too far?**

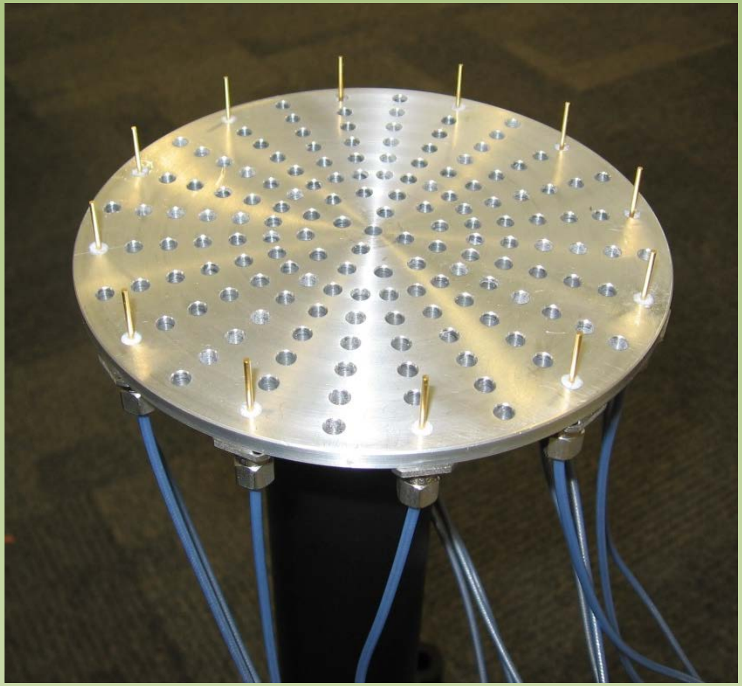
How to make the antennas?

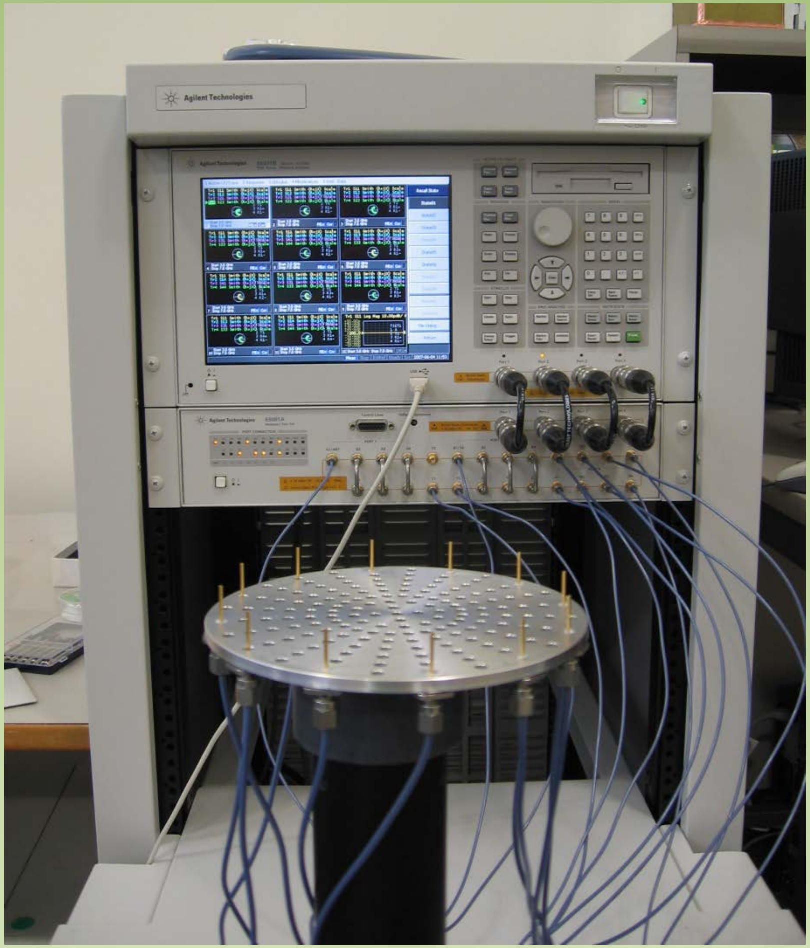
- **Ad- hoc design?**



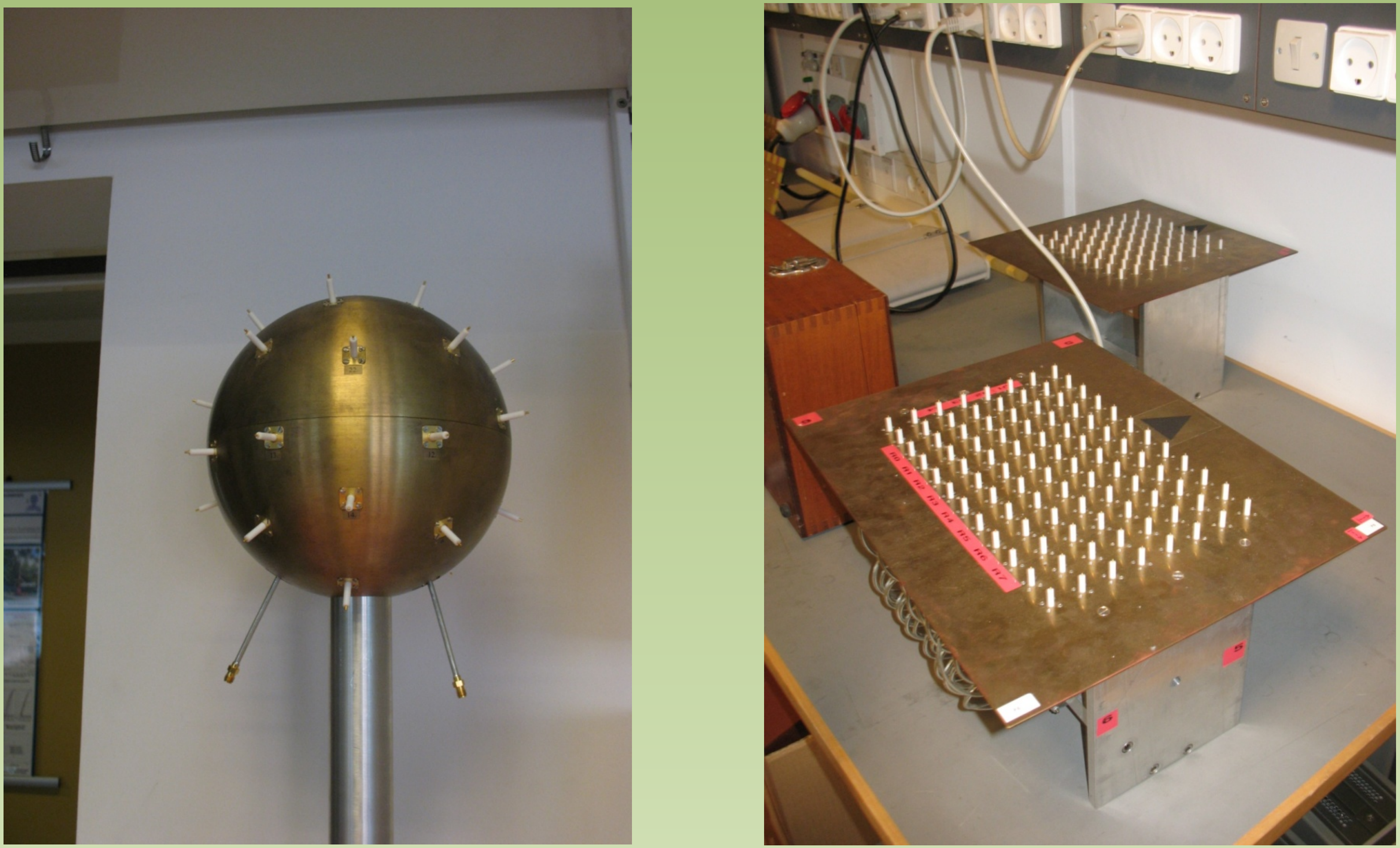
- Which is the best antenna?
- Is that a sensible question?
- Can we compare?
- Designer tools required!

Evaluation: multiport measurement e.g., 12-port monopole circular array



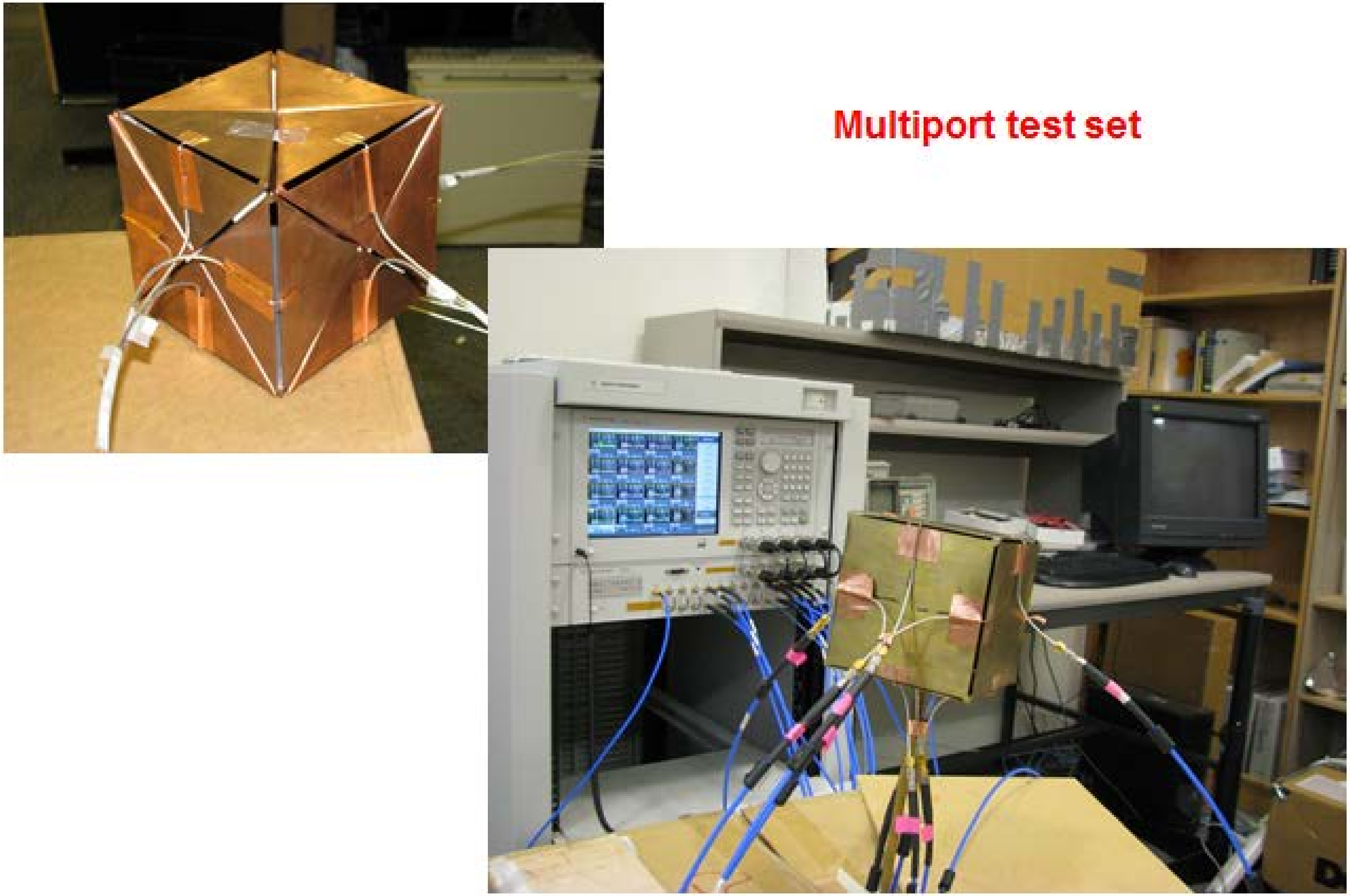


Great antennas of the world



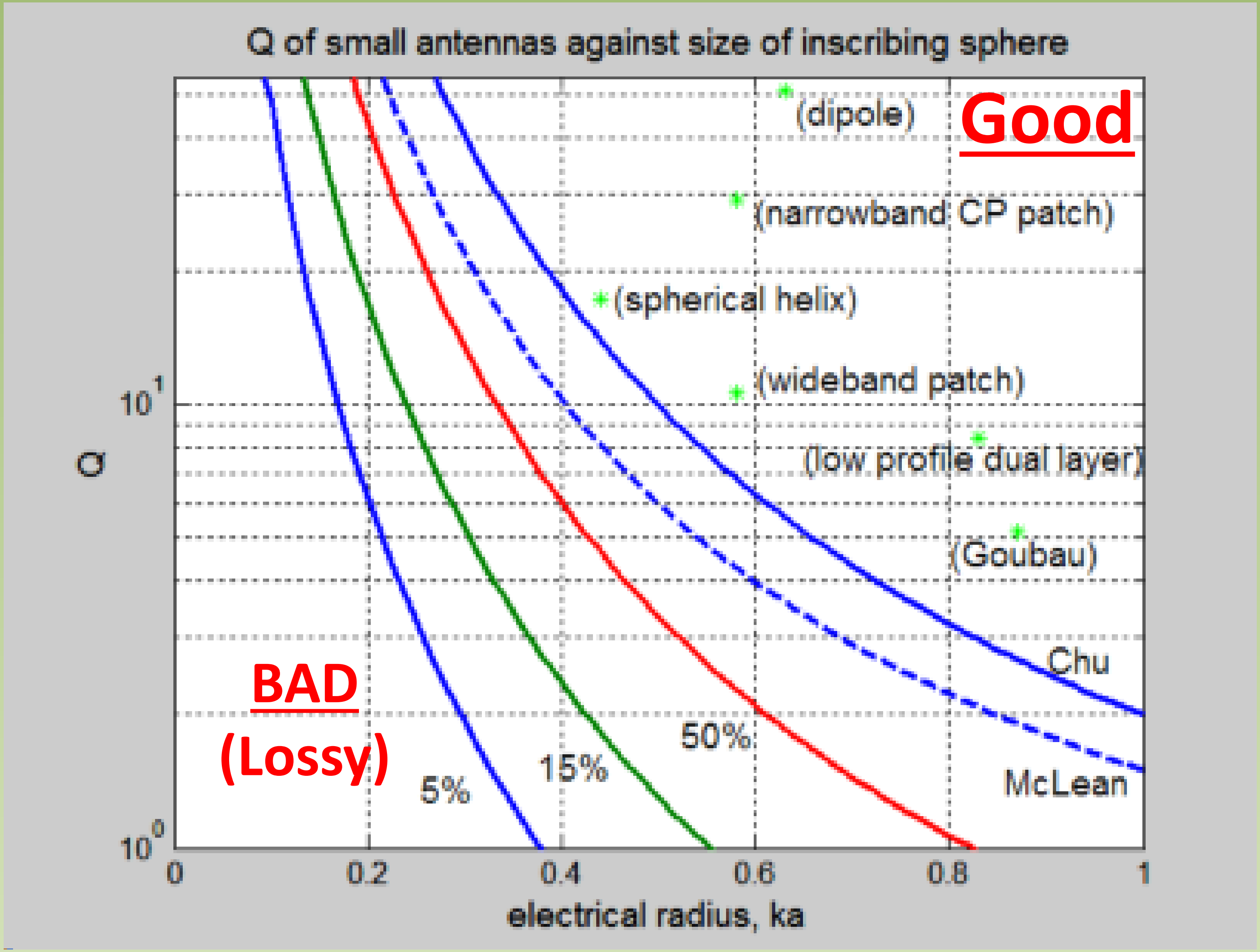
Spherical modes and arrays

Archimedean Polyhedral slot arrays

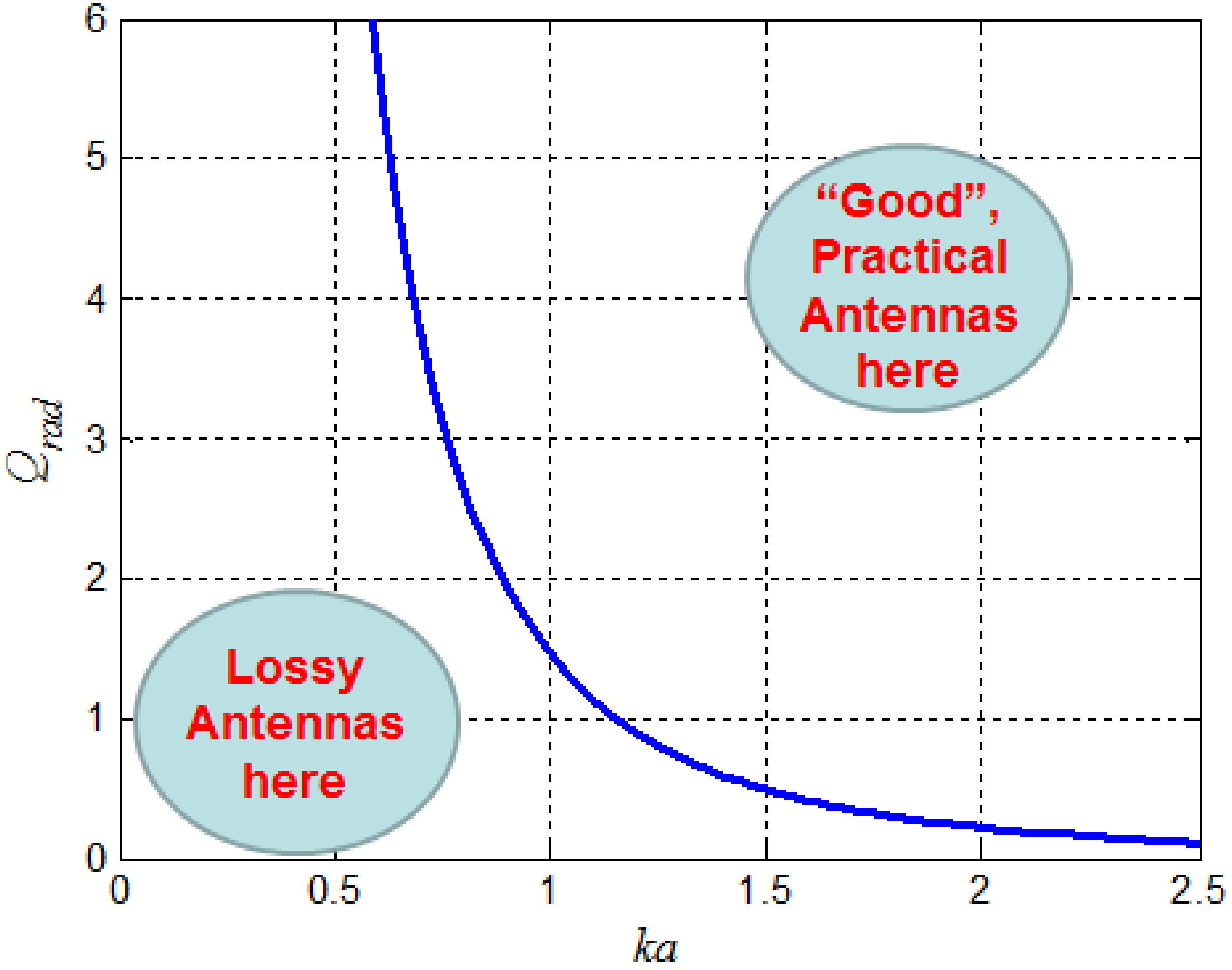


Multiport test set

Bandwidth-size of small antennas



Chu's first order limit : single element antenna spherical compactness

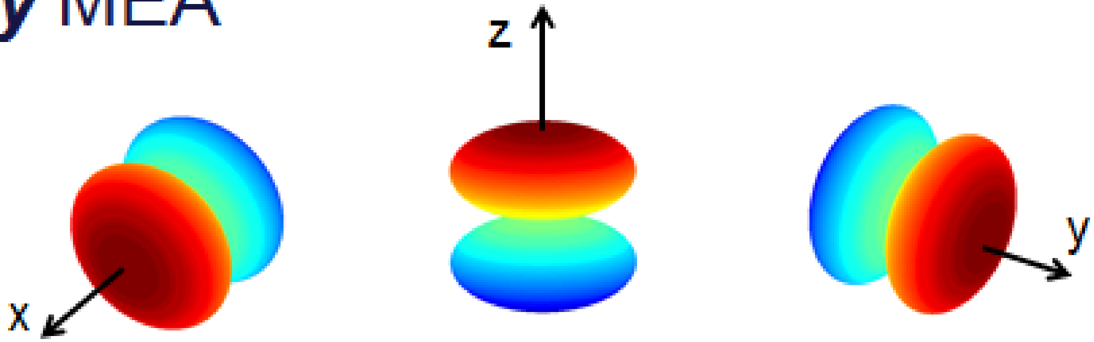


How many antenna elements can the Chu volume support?

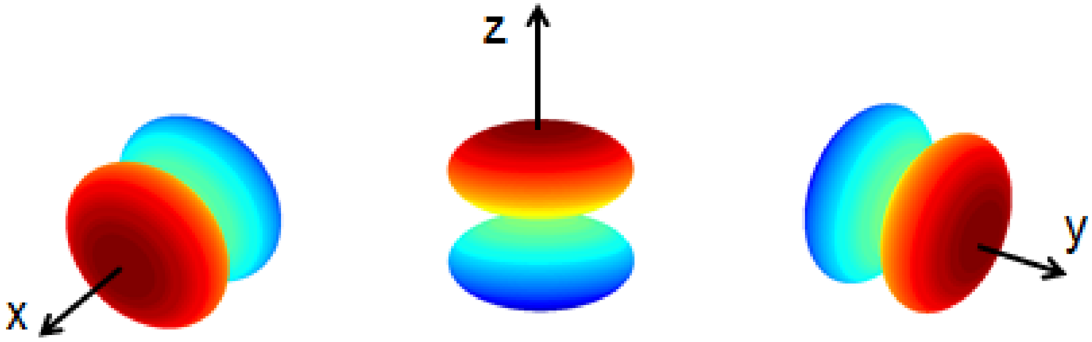
First order spherical wave expansion

6 modes correspond to the basic dipole modes of the ***energy density*** MEA

$TM_{1m\ (m=0,\pm1)}$

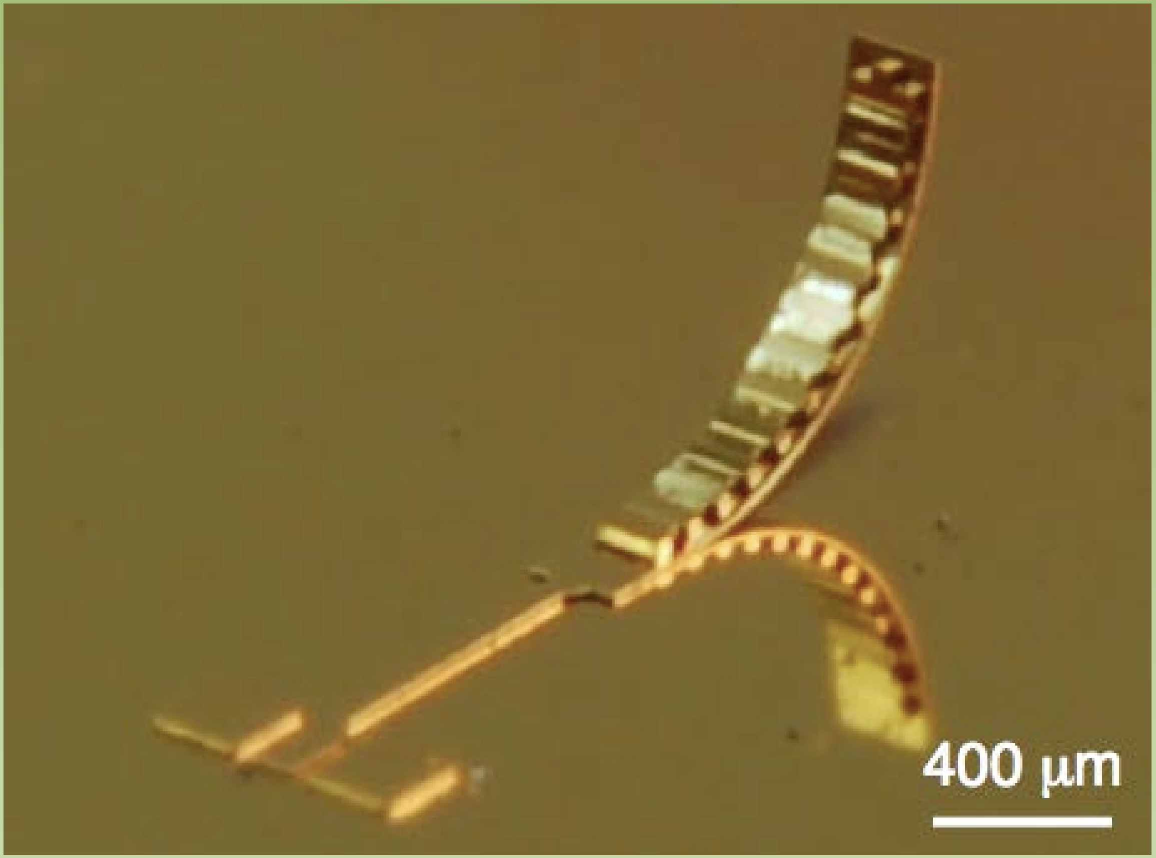


$TE_{1m\ (m=0,\pm1)}$



N.B. No zero mode.

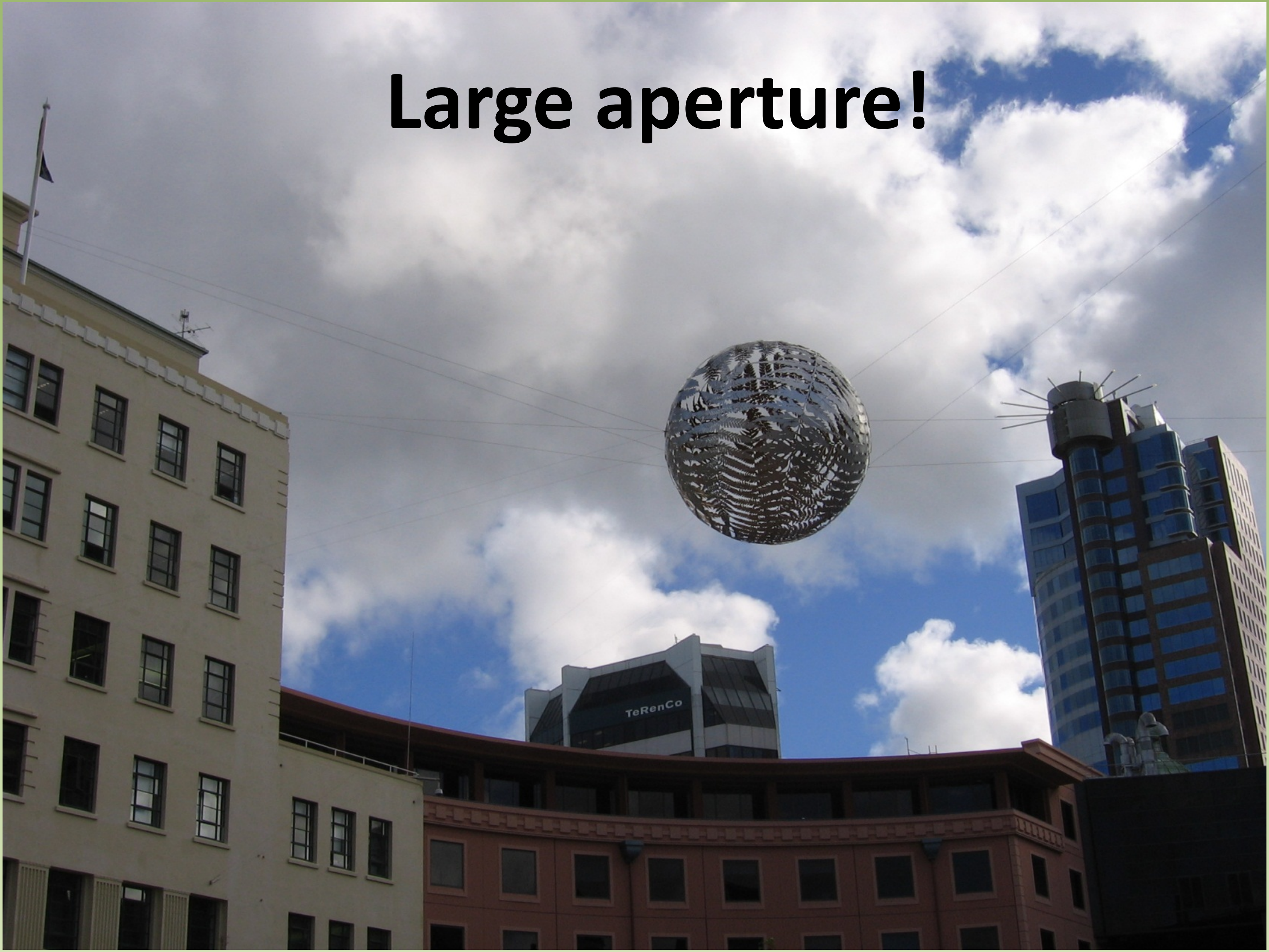
Dipole variation – realized as a self-erecting monopole for 60GHz antenna-on-a-chip



with Sae-Won Lee

A 5 meter by 1 meter aperture can support tens of thousands of elements

Large aperture!



Summary

- Part I looked at an alternative motivation for MEA antennas for MIMO communications, that of power efficiency, rather than just the capacity increase. The path forward from here has many seemingly impossible barriers
- Part II looked at the history of early wireless where seemingly impossible barriers were overcome
- Part III looked at some recent design aspects for communications-oriented compact MEA antennas. New metrics and standards are needed to assist with the ad-hoc design approach

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Compact Multiport Antennas for High Spectral Efficiency

Motivation from Energy Considerations, Lessons from Early Wireless History, and Design Aspects

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***Abstract*—The pursuit of wireless spectral efficiency draws on many different research areas. The area of largest potential impact is the deployment of multiport antennas. This is because it is the only technology that allows simultaneous sharing of the spectrum between many users, including full duplex operation in some circumstances. The spectral efficiencies of current communications system designs are still a long way from their information-theoretic limits, and similarly, current multi-element antenna designs seem to fall short of compactness limits. This invited paper, in tutorial style, touches on how wireless has reached this point, and the need to address grand challenges in information theory, communications techniques, networking, antenna elements and arrays, and signal theory. These aspects converge to set the scene for a new generation of adaptive antenna technology. The motivation is from basic energy and communications considerations. The design of compact multiport antennas requires an extension of classical performance metrics and new approaches to measurement and evaluation. Tools such as physics-based statistical channel and circuit models are likely to play a future role in the design of large-scale multiport antennas.**

Index Terms*— green wireless, wireless history, M2M, mobile antennas, MIMO antenna design, MEAs, arrays, mobile channels.

I. MOTIVATION FOR EFFICIENT MULTIPORT ANTENNAS

In much of the world there is public access to cellular or WiFi services. These forms of wireless illustrate how connectivity has extended from communications directly between people to communications for information access. To the user, wireless has become the main media for accessing the internet and the technologies of wireless and internet information have become inseparable. An emerging wireless market and technology challenge is the machine-to-machine (M2M) link, where devices, ranging from household appliances and computers to industrial sensors and alarms, communicate without human intervention. Current forecasts, e.g., [1], based on data from Beecham Research, Machina Research and ABI Research, suggest that some 50 billion M2M devices will be deployed by 2025. With such unprecedented numbers, networking-related issues arise, such as the need for an access scheme, and the need to share the spectrum. Currently, we do not have complete solutions for these issues. It is clear that the evolution of the required massive networks will be governed by pragmatic engineering, i.e., economically viable systems technology and economically viable implementation of the terminals. But in research, limitations of current technology do not suppress exploration of limiting, theoretical models. For example, many spectrally efficient wireless system proposals rely on accurate channel state information of all the channels to be available at all the transmitters and receivers. However, with current technology, the spectral overhead required to sound the channels and interchange the information overwhelms the efficiency gains available from MIMO systems, even in slowly changing channels, and especially in multi-user systems.

Further questions are now arising about power consumption in wireless. Wireless is viewed as a green technology because it can be used to coordinate industries for better energy efficiency. As a stand-alone technology, it can be viewed as extremely green in the sense of the extremely low energy required of a signal to be detected, and the energy-efficient basis used for deriving communications systems. However, the accumulated energy usage of large numbers (i.e., billions) of wireless devices is raising the awareness of the energy efficiency of wireless itself. For handsets, the consumed energy strictly includes that needed for the display and computation, but when actively wireless-linked, most of its energy is used for transmitting.

The unrelenting increase in demand for wireless services tends to be associated with increasingly compact antennas, and a more compact antenna typically means a lower efficiency. The low antenna efficiency contributes to a cascade of processes that consume much more energy than just that lost in the individual antenna. In short, an inefficient receive antenna causes a compensating increase in transmit power which incurs further losses in the transmitter and the propagation itself, and causes higher interference to other spectral users, leading to more power being transmitted in order to compensate for their decreased SINR, and so on. For every dB of power loss in all the mobile terminals, the cost of a large network increases sharply. Some handsets, developed more for retail appeal than efficiency, feature radio efficiencies 12dB below the best-in-class [2], and the best-in-class have far-from-ideal efficiency.

A simplistic example using a cascade of gain terms through a wireless link gives a feel for the situation. The example is the transmission of a small, low quality image (~10kbits).

From communications basics, an SNR of 6dB allows two bits/symbol at a modest error rate. ~~For a bandwidth of 10kHz, the Nyquist signaling rate is 20kS/sec and so the data rate can be up to 40kbits/sec. A low rate (1/4) code ensures a quasi-error-free 10kbits payload. So 40kbits need to be detected in 1 second~~.

From physical thermodynamics, the noise at room temperature ($k_{Boltzmann}T$) is often expressed as -174dBmW per Hz, and over the 10kHz (=40dBHz) bandwidth, this noise is (-174+40)dBmW = -164dBW. With the signal at the detector having to be 6dB above this, the signal level must be at least -158dBW, assuming no interfering signals from other spectral users are contributing to the noise. So the signal energy of the image required at the detector is $(10^{-(158)/10} \approx 10^{-4}\text{pW}) \times (1\text{sec}) \approx 10^{-16}$ Joules, an extremely low value simply stemming from the physics of thermal noise energy. In fact, the energy expended in the electronic decoding operations, which is also very small, well exceeds the signal energy required for detection. From the receiver viewpoint, the case for wireless being a green technology looks promising.

However, the wireless transmission process can be extremely inefficient. Some ballpark values for the cascade of gains at the terminals are as follows: transmit and receive antenna gains of unity (expressed in dB, $G_{Tx}=G_{Rx}=0\text{dB}$), an SNR gain of the receiver front-end (the inverse noise factor) expressed in dB, $G_{FRx}=-7\text{dB}$, and a transmitter efficiency at the base station (cable, power amplifier, combiners) of $G_{FTx}=-13\text{dB}$. The loss from the propagation path nearly always dominates these factors. For a 12GHz carrier, and a path length of d=20m, the free space path gain, i.e., the inverse of free space pathloss caused by spherical spreading of the energy, is $(4\pi d/\lambda)^{-2}$, or $G_{Path}= -80\text{dB}$. These three gains cascade to give a total link gain of -100dB. If the scenario is dense multipath (i.e., the majority of mobile wireless) then the mean path gain is modeled crudely by increasing the square law to a larger exponent, n. In low rise suburbia, $n \approx 2.6$, but for obstructed in-building paths, n is reported to be as high as 4 to 6. Taking a convenient reference distance of one wavelength, $d_r=\lambda$, the multipath gain is $G_{MP}=(4\pi d_r/\lambda)^{-2} \times (d/d_r)^{-n} = (4\pi)^{-2}(d/\lambda)^{-n}$, so for $n=4$, $G_{MP}= -140\text{dB}$. If the antennas are single port and the channel is narrowband, then the Rayleigh-like fades are some 30dB below the mean for a probability of 10^{-3}. A fade margin of $G_{FM} = -30\text{dB}$ ensures local coverage for all but 1 in 10^3 locations. The associated multipath link gain, i.e., the ratio of power at the detector to the radiated power, is now (-140dB-30dB) = -170dB, or 10^{-17}.

Link analysis gives an idea of how much of the transmitter power is wasted even when the electrical distance of transmission is modest (less than 10^3 wavelengths here). The radiated power is only for the single receiver in question, but also causes interference everywhere in the transmitter coverage.

This link gain states that, in order to transfer the image, about $(10^{-16} \times 10^{17} \approx 10)$ Joules is consumed at the transmitter. (Of course, even without transmission of payload, the power consumption at both terminals continues, and this overhead must be included in a more thorough calculation.)

From this viewpoint, wireless technology is not looking green. With "just" one billion (10^9) such links transferring a small image, each consuming 10 Joules, a total of 10GigaJoules is required. This corresponds to the output from several power stations (say ten 1GigaWatt nuclear stations), ignoring the power distribution efficiency, for the transmission duration of 1 second. So the total signal detection power required over all the receivers is a fraction of a milliWatt, but to get this delivered, some 10GigaWatts is required at the transmitters. The impact of the losses of the propagation, and to a lesser extent in the electronics, is devastating for the energy efficiency of wireless, and this is exposed when wireless deployment becomes large-scale. More efficient electronics can offer relatively modest incremental improvement, and this remains an important research and development topic for exactly this reason.

The only technology that can directly tackle the energy loss of the propagation is multiport (or array) antennas, comprising a large number of elements with associated sophisticated electronic signal processing. Such antennas enable higher signal gains and interference suppression. Their potential remains largely untapped owing to the relative immaturity of the technology (despite the presence of adaptive antennas of various sorts for well over a half century) and the required complexity of the signal processing. Again, ignoring interference allows a simple, albeit optimistic, energy analysis. The potential increase in capacity, without using extra radiated energy, from using MIMO arrays can be modeled by the square of the number of idealized (lossless, uncoupled, uncorrelated) antennas at each end of the link. For 100 antennas at the terminals, the capacity increase is 10^4, and in the above example, this can be interpreted as "saving" about 10GigaWatt~~/~~10^{-4}=1~~0~~MegaWatt at the transmitters over the one-second duration of the signal.

In the above examples, interference was ignored, but the SNR performance of most links is limited by interference rather than by thermal noise. Many systems, such as cellular communications, have their electrical and geographic layout governed by interference considerations. The deployment of multiport antennas is the only technology that can disrupt such interference limitations to spectral efficiency.

The propagation loss will remain dominant in the above kind of energy efficiency analysis, and efficient multiport antennas can be considered as green because they tackle this loss. The use of high-gain pencil beam antennas from large aperture antennas for point-to-point, line-of-sight links, does exactly this. Here the idea of the large antenna aperture is to try to capture all of the transmitted power, and in a limiting case, the propagation loss is compensated by the antenna gains. At the same time, the pencil beams act to spatially filter out interference. The situation in multipath is not so easy. But the concept of high gain still holds, and this is achieved through the large aperture of a large number of elements working together in the multipath. A large aperture is also required at the base station, where different adaptive beams could focus on the different users as their locations change, and also spatially filter out interference. The use of large apertures in multipath is unlikely to be as effective as for the line-of-sight situation for compensating for the propagation loss.

Adaptive antenna technology still needs much development. For example, there is little in the way of formal standards for the performance evaluation of multiport antennas. In practice, current designs are often undertaken in an ad-hoc (or "unformalized") way, making use of basic antenna principles and a simple statistical model for the multipath propagation. In fact, single-port antenna design is also mainly ad-hoc, but at least there are standards for their evaluation and benchmarks for their compactness. The larger the number of elements, the more bulky and less efficient an antenna tends to be. In an analogous way to the capacity benefits of MIMO systems being compromised by the need for channel state information, the shortfalls in current antenna technology compromise the goal of the multiport antennas. Nevertheless, the lure of the potential benefit of tackling the propagation loss encourages exploration of antenna performance limits. Following a glimpse of the early history of propagation and wireless technology, which offers some clues about the future directions, the remainder of the presentation includes the case for multiport antennas from a communications basis, and concludes with comments on multiport antenna design and evaluation.

II. A Glimpse of an Extraordinary History

As wireless communications moves into its second century, a few highlights from the start of its first century give a taste of its extraordinary and rich story. The history of wireless cannot be separated from Marconi, who is often referred to as *the inventor of wireless*. But as so often is the case in scientific or engineering breakthroughs, there were many unsung lead-ups that paved the way in developing an understanding of propagation, antennas, and electronic radio components. Many other players bracketed Marconi's scientific role. The following set of highlights is a personal choice, with many of the dates approximate because of conflicting historic records and the date differences between discovery and reporting. The information is from multiple sources, too numerous to fully list here, but nowadays, the references in the pertinent entries of Wikipedia cover much of background, so this historic aspect is a presentation that anyone can readily create.

The first telecommunications were probably visible actions such as gesturing, waving, signal fires, smoke signals, and audio actions such as bullroarers (dated back to 17,000BC) and drums. In recorded history, the Greeks used light for signaling in ~405BC. Gauss's heliotrope, from ~1810, used light signals for surveying, and a later variation, the heliograph, was for signaling. Semaphore, followed by Morse code on telegraph lines, finally evolved to the use of radiowaves. The redundancy of the telegraph wires led to the name *wireless* being primarily associated with radiowave communication, and conveying a hint of mystery or even magic at the time (cf., *Clarke's third law*). Some current predictions are that telepathy and even quantum transportation will be the next steps. While these may seem far-fetched to pragmatic engineers, it is worth remembering that technologies such as signaling along wires, and then wireless signals bending over the horizon, were greeted with skepticism by many, including scientists, at the time.

The wireless era needed a new word, and *telecommunications* became accepted by the early 1900s. Its hybrid nature (Greek "remote" and Latin "common" or "shared") became a target, with tongue-in-cheek claims such as "as a cross-breed by name the act can never take off". Of course it did take off, both commercially and as a major driver for many areas of scientific research, and over a century later, this is still the case.

In the chicken-and-egg situation of discovering propagation and antennas, it is evident that understanding propagation had a strong lead on understanding antennas. Some electromagnetic and propagation highlights were:

~1820 in Denmark, Ørsted noted that an electric current influenced a magnetic compass needle.

~1825, in Britain, Faraday publishes his law of induction linking electric and magnetic fields.

~1849 in France, Fizeau and Foucault measure the speed of light to be $2.98(10)^8$m/s. (It must be added that Rømer reported a measurement method in ~1676, and Huygens made a ballpark estimate at about the same time.)

~1864 in Scotland, building on Faraday's work from ~1855, Maxwell published *A dynamical theory of the electromagnetic field,* noting that light and radiowaves were the same thing (from this point, the wonderful history of optics intersects with radiowave propagation science); that both have a speed of $3.1074(10)^8$m/s in *lumniferous aether*; and in ~1873 his four equations presented a compact description the field relations.

~1878 in America, Hughes transmitted and received radiowaves, some 14 years after Maxwell's theoretical discovery of them. Hughes' transmission may been inadvertent, and was not fully appreciated by others when it was presented formally in 1890, but he well understood the significance, and also went on to make several radio component inventions.

~1886 in Germany, Hertz is widely regarded to be the first to intentionally and systematically transmit and receive radiowaves. When asked about the significance, Hertz is reported to have said that they were of no use whatsoever, simply noting that *Maestro Maxwell was right.* Hertz's experiments showed nearly all the properties of waves: propagation, reflection, refraction, polarization, and speed.

~1896 in Germany, Sommerfeld published his half plane diffraction analysis, which later became a foundation for multipath propagation;

~1905 in Switzerland, Einstein's special theory of relativity showed that neither Maxwell's equations nor the lumniferous aether are needed for describing radiation. (Unfortunately, the special theory did not seem easier than Maxwell's equations.)

By this time, a more marked separation seems to have developed between the theory-based efforts and the practically-oriented efforts. Some practical highlights were:

~1884 in Italy, Onesti noted radio-frequency current induction in iron filings, leading much later to the coherer, i.e., the receiver, developed by Branly and Lodge, *et al.*

~1885 in America, Edison applies for a wireless communications patent although this was an induction mechanism, probably developed by Tesla who worked for Edison until this time.

~1890 in France, Branly develops the coherer which was used for wireless reception for the following decade.

~1893 in America, Tesla demonstrated wireless signaling, and this was likely by induction, although he later invented components for radiating waves. Tesla's inventions were used to turn over Marconi's patents much later in ~1943.

~1894 in Britain, Lodge demonstrated Hertz's transmissions, and patented his system, and also improved Branly's coherer and patented that as well (Lodge later attacked Marconi viciously in the press, but in ~1911, he sold his patents to him).

~1894 in New Zealand, Rutherford transmitted across a room including through or around obstacles. Rutherford took his equipment to Britain, and in 1895 set a world record for transmission distance, for ship-to-shore. Although he seemed aware of the commercial significance, a research offer from JJ Thompson drew him to a career in nuclear physics.

~1894 in Russia, Popov developed a working radio, and set propagation distance records ~1895 and ~1897.

~1895 in India, Bose demonstrated wireless signaling, including recognition the advantages of experimenting with more optical-like frequencies (about 60GHz);

~1900 in Brazil, de Moura demonstrated wireless voice transmissions.

On the antenna aspects, Hertz's diagrams, including field lines, demonstrate that he had a clear understanding of dipole radiation mechanisms (and optics). The purely experimental approach of Marconi seems to have yielded the first tie between antenna aperture and transmission quality, and he later wrote [3]

> I then began to examine the relation between the distance at which the transmittor could affect the receiver and the elevation of the capacity aereas above the earth, and I very soon definitely ascertained that the higher the wires or capacity aereas the greater the distance over which it was possible to telegraph.

Marconi's lack of an advanced education may have helped focus his scientific research on commercialization. By ~1894, he had read Hertz's work and appreciated what was known about practical aspects of propagation, but his vision also required an understanding of antennas and electronic radio components. By ~1896, well after Lodge, Tesla, Rutherford, Popov, and Bose (not to mention Hughes and Hertz, much earlier), Marconi also succeeded with transmission experiments. Marconi's Irish mother had contacts which lead Marconi to the British Post Office's Chief Engineer, W.H.Preece, who was considered the most important man in the world in telecommunications. Agreements were made, the experiments were shifted to Britain, and as soon as ~1897, Marconi started to set transmission distance records.

Marconi became aware that propagation occurred in a non-line-of-sight fashion (e.g., ~1899, he transmitted across the English channel which is over-the-horizon). It was known that waves travelled in straight lines, and with the ionosphere and surface waves still undiscovered, Marconi's ambitions to go further looked unlikely. Unburdened by needing to know why the propagation behaved unexpectedly, Marconi's new knowledge surely gave him the confidence to tackle trans-Atlantic experiments against the tide of conventional wisdom. Marconi filed wireless patents, and his ambition caused a major fall out with Preece and the British government. By ~1901, Marconi was claiming trans-Atlantic transmissions. This led to turmoil amongst the 'straight-liners", resulting in international research efforts to try to better understand radiowave propagation (a wonderful story in itself), and was the catalyst for the formation of URSI. The success of the technology upset more players still, in particular those with vested interests such as American cable companies (which had spent a fortune on trans-Atlantic cabling), and other inventors. Marconi's inventions and patents seem to have been widely considered as 'familiar", and this, probably along with his commercial success with one of the most disruptive technologies ever, attracted conflict for much of his career. The reported success of Marconi's first trans-Atlantic experiment is still under suspicion. But at the end of the day, Marconi delivered both in the experimental science and its commercialization. His success is partly because he found solutions that went against the conventional thinking of the day. Examples include: his banking on propagation not being restricted to follow single straight lines; and his infamous 7777 patent on tuned circuits (the first spectrum sharing technology) which was forged from necessity.

The development of early wireless demonstrates that a significant technology is seldom the invention of one person or one group. Key wireless discoveries and developments were made in several, well spread countries, at about the same time. The disruptive nature of the technology brought conflict which seems to blur who was really the first with specific breakthroughs. Since the discovery of electromagnetic propagation and antennas, wireless technology has further developed through: new and improved communications techniques, including for spectral sharing such as cellular and multiple access, and more recently using MIMO; the electronic technology to make these techniques feasible in mass produced, small terminals; and a better understanding of propagation, not just for long distance, but also of scattering mechanisms and ways to exploit them; and finally administrative structures for spectrum sharing around the world. Each of these has its own fascinating history. Antenna technology, *per se*, has not evolved at the pace of the signal processing electronics, and Moore's law does not yet apply to MIMO because of the lack of integration of the antennas. Dipoles and horns, essentially similar to Hertz's and Bose's, and optical systems (like the parabolic reflector used by Hertz), are still mainstay antenna elements. In looking at today's systems, the obvious developments in elements are patches and slots. There is also an understanding of array mechanisms. The unrivalled potential of the spectral and energy efficiency of MIMO is widely appreciated, but the technology seems to be at the equivalent stage of Marconi's *capacity aereas*. The feasibility of MIMO which is sufficiently large-scale to have a truly significant impact depends on the development of high efficiency antenna systems with large numbers of elements. Deploying large-scale MIMO systems requires new technology from the areas of: elements and arrays, communications techniques; and signal processing. Conventional thinking may be that such complexity is unlikely. But history suggests that breakthroughs, perhaps against conventional thinking, will come to the rescue.

III. Communications Basis

Shannon's law offers a limiting transmission rate, relating the capacity in bits per channel use (also called the capacity efficiency, in bits/sec/Hz) to the basic digital communications parameter, energy-per-bit over noise; which using the usual notation, is $(C/B)=\log_2(1+(C/B)(\varepsilon_b/N_o))$. For MIMO, when the channels are known at the transmitter, the eigen-channels can be combined using Gallagher's parallel channels formula [4]. The unknown channels formula, with its different systems architecture, is [5] $(C/B)=\log_2|I_M+(SNR_{Ant}/M)\Sigma HH^H|$, and gives values close to the eigen-MIMO bound. These formulas are information-theoretic limits for a simplex transmission rate. But the impact of digital communications techniques, such as the use of digital constellations instead of Gaussian-distributed signals, finite length codes instead of idealized (i.e., non-existent), infinitely long ones, and the need for channel overhead for synchronization and multiple access, makes these theoretic limits hard to relate to what can be achieved. Practicable limits need to be developed that relate to the capacity seen at the receiver, rather than the information theoretic limits which relate more to the transmitter. Such limits would account for the inherent shortfalls imposed by current communications techniques. For example, the throughput (bits/sec/Hz) of correctly detected bits is a step in the right direction [6-8]. This throughput can be calculated for a link that is block-coded (which allows an error rate can be calculated) but otherwise uncoded (i.e., no forward error-correction coding). The behaviour of this limit can be reasonably independent of the block size, and at best, it falls short of the single channel Shannon limit by about 7dB SNR. Its behaviour also highlights the sensitivity of digital modulation to the optimal SNR - just a few dB of change in SNR rapidly causes a loss of capacity efficiency. When the SNR drops a few dB too low, the throughput collapses catastrophically, and when the SNR increases to be too high, the throughput stays the same, resulting in more wasted energy, and interference to other users. Adaptive coding and modulation is for tracking the best available capacity efficiency, but as with MIMO, the spectral overhead required in coordinating the adaptation for the changing channels can spoil the improvement. For analyzing the impact of coding, Monte Carlo simulations are currently needed. However, Reed-Solomon codes, with their closed-form error expression, allow progress [8]. For optimization, the Shannon-based limits are convenient cost functions, but they behave differently to practicable limits, and are therefore a questionable optimality criterion. For example, optimizing a multiport antenna for capacity, or for SNR, will not, in general, yield the same design.

The capacity efficiency also raises the question of to how to tally the bandwidth, B. The use of an idealized bandwidth does not account for all communications techniques. A practicable bandwidth should include implementation limitations including the channel resource needed to run a link, especially in multi-user systems; and a practicable capacity should incorporate this.

The set of channels for pairs of MIMO terminals that communicate independent data using simultaneously shared spectrum has been coined the K-user MIMO channel, so-called because it supports K pairs of terminals. An example could be a set of M2M links in close proximity. The mathematical method to set the antenna weights to suppress interference is called interference alignment. Each terminal must know all the channels (which also need to be sounded) which uses spectral resource. Optimization of the antenna weights is an open problem (there is no proof of an optimum solution available at the time of writing), but a best-available solution [9] yields such a finely tuned system that even adding an extra antenna - which is widely regarded as always helping with spectral efficiency - actually degrades the sum capacity. In the spectral efficiency sense, the K-user channel represents a limiting solution of MIMO. But the spectral cost of the channel overhead required using current technology, suggests that the application can only be for a static channel where the overhead is negligible. Despite these hurdles for deploying large scale MIMO, other digital communications techniques (coding, modulation) cannot offer the same potential for improving spectral or energy efficiency.

IV. MULTI ELEMENT ANTENNAS

For a fixed antenna aperture, more elements can be accommodated if the carrier frequency, f, is increased. With lossless antennas, the antenna gain (e.g., the number of elements in a planar array) of a fixed aperture is proportional to f^2, so the antennas' gain contribution to the link gain is $\propto f^4$. Taking the propagation gain as $\propto f^{-n}$, (Section I), then the total link gain becomes $\propto f^{4-n}$, and if $n<4$, then higher the frequency the better the link. Unfortunately, antenna loss increases with frequency. For example, for thin (radius=$10^{-4}\lambda$), metallic dipoles, then the loss from the antenna pair is about -3dB at 60GHz [10]. Moving to higher frequencies needs to be accompanied by lower loss components, perhaps dielectric antennas. The feed lines are also lossy, so amplifiers need to be close to the elements. The array configuration depends on the range of radiation directions, and the need for minimal mutual coupling [11] between the elements. At mobile terminals, spherical-coverage distributions and apertures may be required [12]. At the other extreme, for a small angular coverage, a planar aperture would be best.

To be able to compare the compactness of MEAs in a similar way to using the Chu limits for elements, a first step is to seek a spatial efficiency [13]. Performance evaluation of the antenna radio structure (i.e. not including specific electronics) in an environment looks to be possible using simulation. Physics-based simulation (ray tracing, *et al*) can generate distributions of waves at the antenna for a specific environment, and measured antenna parameters can be included. The antenna adaptation, as it moves through the environment, can be by using simulated communications algorithms. Different antenna and algorithmic designs can be compared for specific environments in this way [14]. The computation cost is high, and better accuracy is still required, but these drawbacks seem temporary.

REFERENCES

[1] W.Waung, "M2M Trends and Challenges", presentation at Wavefrontac, Vancouver, Canada, 20 November 2012. (www.wavefrontac.com)

[2] G.F.Pedersen, “Limit values for downlink mobile telephony in Denmark”, Version 3.0, Aalborg university report, November 2012.

[3] G.Marconi, *Original-Manuskriptet till Marconis NobelPris-Föredrag*, p.6, 11 December 1909. (Courtesy Fondazione Gugliemo Marconi)

[4] R.G.Gallager, *Information theory and reliable communications*, Wiley, 1968.

[5] J.H.Winters, “On the capacity of radio communications systems with diversity in a Rayleigh fading environment”, *IEEE JSAC*, Vol.5, 5, pp.871-878, June 1987.

[6] S.Catreux, P.F.Driessen, L.J.Greenstein, “Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment”, *IEEE Trans. Wireless Communications,* Vol. 1, 2, pp. 226-235, April 2002.

[7] S.A.Mirtaheri, R.G.Vaughan, “Practicable MIMO capacity in ideal channels”, *Proc. IEEE 63rd VTC*, Vol.4, pp.1620-1624, May 2006.

[8] S.A.Banani, R.G.Vaughan, “Capacity maximisation in eigen-MIMO using adaptive modulation and Reed-Solomon coding”, *IET Communications*, Vol.6, 15, pp.2413-2424, October 2012.

[9] M.Toutounchian, A.H.Sayed, R.G.Vaughan, ”Multi-objective, multi-variable optimization for the *K*-user MIMO channel”, SFU-ENSC Report 2012-9, 2012.

[10] M. Dehghani Estarki and R.G.Vaughan, “A study of the radiation efficiency of a half wavelength dipole”, Proc 14th ANTEM, July 2010.

[11] J.X. Yun and R.G.Vaughan, “Multiple element antenna efficiency and its impact on diversity and capacity,” *IEEE Transactions on Antennas and Propagation*, Vol.60, No. 2, pp.529-539, February 2012.

[12] J.X.Yun, R.G.Vaughan, “Slot MIMO cube,” *Proc. IEEE APS International Symposium*, Toronto, ON, Canada, July 2010.

[13] J.X.Yun and R.G.Vaughan, “Space efficiency of multiple element antennas”, *IEEE Transactions on Antennas and Propagation*, Vol.60, 6, pp.3066-3071, June 2012.

[14] M. Dehghani Estarki, R.G.Vaughan, “On the power delay profile and delay spread for physics-based simulated mobile channel”, Eucap2013.