Today's Electrically Small Antennas: Over 100 Years of Development

Steven R. Best

MITRE

srbest@ieee.org

Small Antenna Background

The performance of any ESA is characterized and understood through the following:

- Impedance Match and Matching Technique
- Radiation Efficiency
- Directivity (Radiation Pattern Shape)
- Quality Factor - Q (bandwidth)

Impedance Matching

- Any electrically small antenna can be matched at any single frequency
  - Short vertical radiator
  - Horizontal radiator very close to metal ground
- Trade-offs with decreasing size
  - Bandwidth
  - Radiation efficiency
- Generally, the first objective is to tune the antenna's reactance as this facilitates easier and more effective matching
- Generally, the second objective is to match or transform the antenna's small resistance to the system characteristic resistance (typically 50Ω)

Impedance Matching

- Oftentimes, we try to impedance match with the greatest radiation efficiency – not always a practical option
  - Repeatability issues in manufacturing
  - Detuning effects in surrounding environment
  - Bandwidth may not meet system requirements
- Many small antenna designs successfully achieve wider bandwidths with decreased efficiency – typically with lower gain at the lower operating frequencies

Tuning – Achieving Self Resonance

Inductive Loading

Lumped element

Distributed (e.g. - increasing conductor length)

Capacitive Loading

Lumped element

Distributed (e.g. - top-hat, disk loading)

Combined Inductive/Inductive Loading

Lumped element

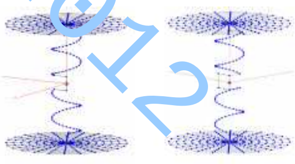
Distributed

Material Loading

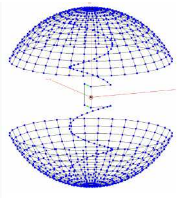
Tuning – Achieving Self Resonance

Capacitive

Inductive

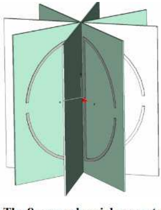


(a) Tuned disk-loaded dipole. (b) Matched disk-loaded dipole.



(a) The spherical-cap dipole.

H. Stuart

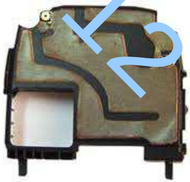


(a) The 8-arm sphercial resonator.

Matching Techniques

- Shunt (parallel) stub or post (e.g. Inverted-F, PIFA)
- Elevated feed point
- Lumped element reactive matching at feed point
- Near-field reactive transformer
- Increasing turns (e.g. loop)
- Folding (e.g. dipole, monopole)

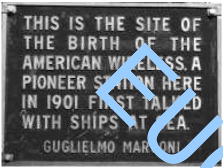
Questions

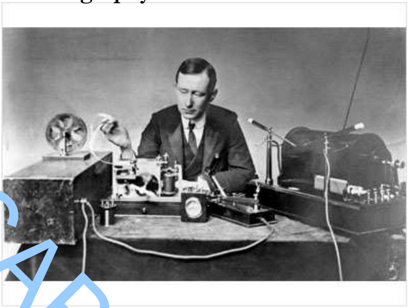


- After 100+ years, where do today's antenna engineers derive their design building blocks?
- What are some of today's engineering design challenges?

Wireless Telegraphy

"To Whom it May Concern: Be it known that I, Guglielmo Marconi, a subject of the King of Italy, and a resident of London, England, have invented certain new and useful Improvements in Wireless Telegraphy….."

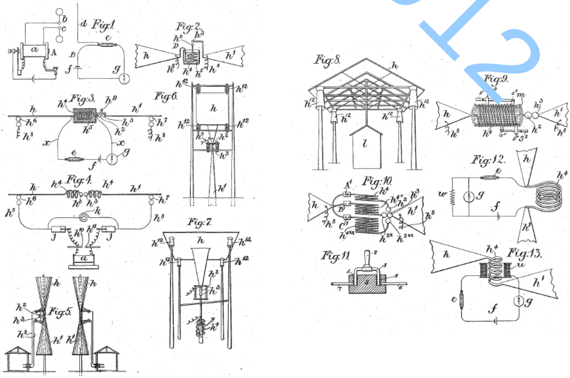




1901

Wireless Telegraphy - 1898

Oliver Lodge's 609,154 patent (1898) – *Electric Telegraphy*

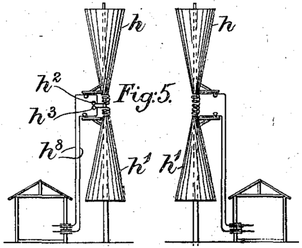


Wireless Telegraphy - 1898

Oliver Lodge's 609,154 patent (1898) – *Electric Telegraphy*

As charged surfaces or capacity areas spheres or square plates or any other metal surfaces may be employed; but I prefer, for the purpose of combining low resistance with great electrostatic capacity, cones or triangles or other such diverging surfaces with the vertices adjoining and their larger areas spreading out into space; or a single insulated surface may be used in conjunction with the earth, the earth or conductors embedded in the earth constituting the other oppositely-charged surface.

Radiation from an oscillator consisting of a pair of capacity areas is greater in the equatorial than in the axial direction, and accordingly when sending in all directions is desired it is well to arrange the axis of the emitter vertical. Moreover, radiation polarized in a horizontal plane—that is, with its electric oscillations vertical—is less likely to be absorbed during its passage over partially-conducting earth or water. A pair of insulated capacity areas arranged for long-distance signaling is shown on the left-hand side of Fig. 5. Fig. 6 shows a single insu-



Wireless Telegraphy - 1904

"According to my present invention I connect to the vertical elevated conductor which, as shown, is in the form of a wire or rod, one or more members consisting of wires or rods extending there from in a lateral or outward direction. The vertical portion of the aerial may then, if desired, be made comparatively short, and the necessary length and capacity secured by lateral extension."

No. 760,463. PATENTED MAY 24, 1904.

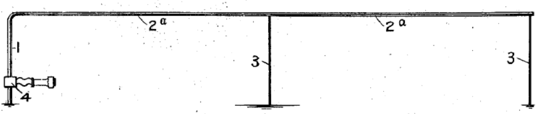
G. MARCONI.

WIRELESS SIGNALING SYSTEM.

APPLICATION FILED SEPT. 10, 1903.

NO MODEL.

FIG. I.



Marconi patented the Inverted-L antenna in 1904

Wireless Telegraphy - 1904

"According to my present invention I connect to the vertical elevated conductor which, as shown, is in the form of a wire or rod, one or more members consisting of wires or rods extending there from in a lateral or outward direction. The vertical portion of the aerial may then, if desired, be made comparatively short, and the necessary length and capacity secured by lateral extension."

FIG. 2.

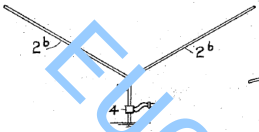
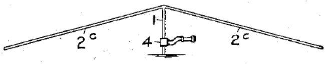


FIG. 3.

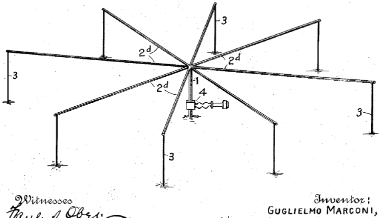


Marconi patented the Top-Loaded antenna in 1904

Wireless Telegraphy - 1904

"According to my present invention I connect to the vertical elevated conductor which, as shown, is in the form of a wire or rod, one or more members consisting of wires or rods extending there from in a lateral or outward direction. The vertical portion of the aerial may then, if desired, be made comparatively short, and the necessary length and capacity secured by lateral extension."

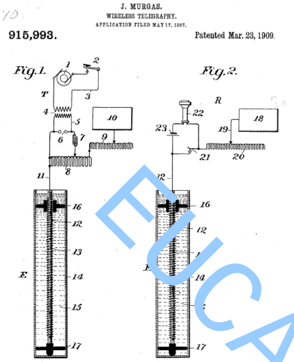
FIG. 4.



Marconi patented the Top-Loaded antenna in 1904

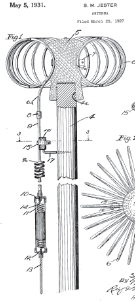
Wireless Telegraphy - 1909

J. Murgas' 915,993 patent (1909) – *Wireless Telegraphy*

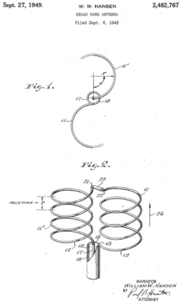


"My present improvement is directed to rendering the apparatus equally sensitive to waves of any length and any frequency and also to **reducing the length** or depth of the well or hole for the antenna and therefore its cost. I accomplish these objects by **coiling the antenna into a helix having an axis much shorter than the straight antenna** of the application mentioned.

Small Antennas



Filed 1927

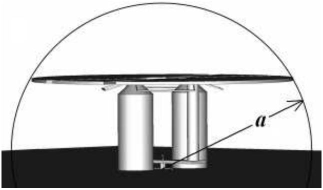


Filed 1943

Short "stubby" helical coil

Helical Coil Antennas

Small Antennas



$$k = \frac{2\pi}{\lambda}$$

a is the radius of a sphere circumscribing the maximum dimension of the antenna.

Electrically Small: ***ka*** < 1 (Wheeler – 1947); ***ka*** < 0.5 (Best – 2003)

$$Q_{lb} \approx \frac{1}{(ka)^3}$$

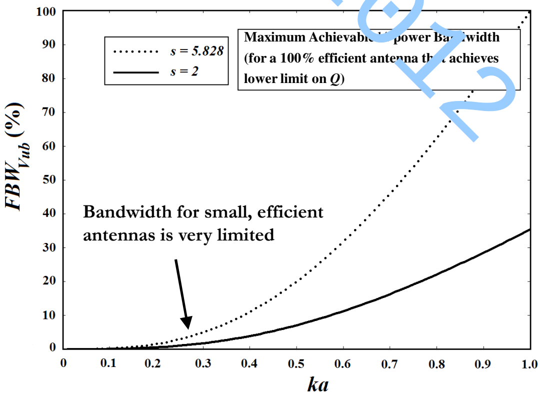
Wheeler – 1947

$$Q_{lb} = \frac{1}{(ka)^3} + \frac{1}{ka}$$

Chu – 1948; McLean - 1996

Fundamental Limits Defined for Small Antennas (1947-1948)

Small Antennas

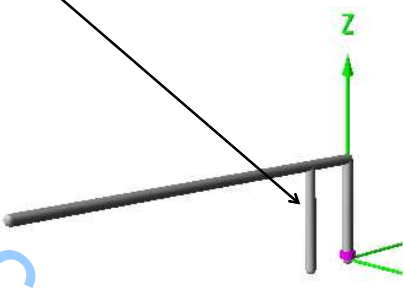


Upper Bound on Bandwidth

Small Antennas

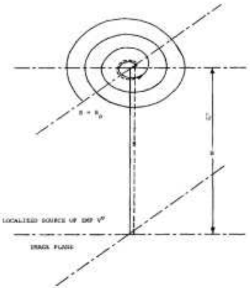
"Post" or "stub" to facilitate impedance matching of the Inverted-L

R. W. P King - 1960

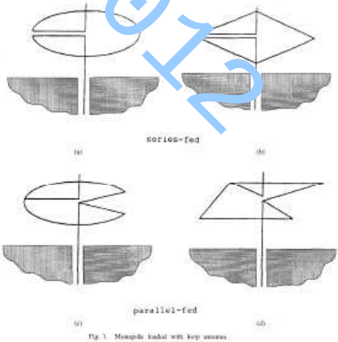


Inverted-F Antenna

Small Antennas



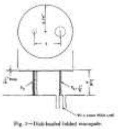
Bhojwani, 1973



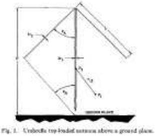
Altshuler, 1996

Inductive and Capacitive Loading

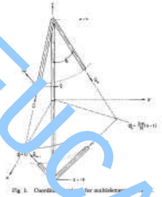
Small Antennas



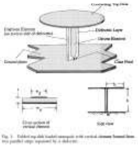
Seeley, 1956



Gengi, 1965



Simpson, 19



McLean, 1998

Inductive and Capacitive Loading

Small Antennas

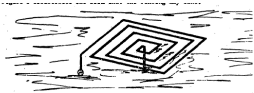


Figure 3. Electrically small antenna with simple flat spiral winding, an electrical half wave long

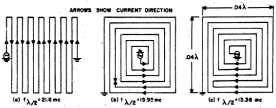


Figure 7. Three windings of same dimensions and containing the same length of wire, with their resonant frequencies

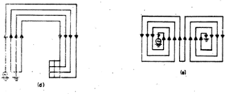
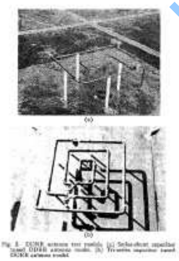
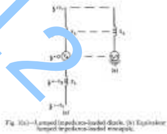


Figure 8. Windings in which mutual inductances between adjacent wires are positive

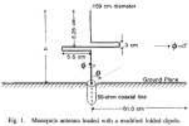
Fenwick, 1965



Wanselow, 1966



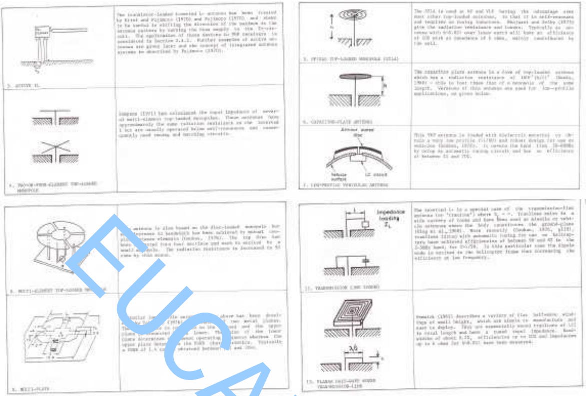
Harrison, 1963



Altshuler, 1993

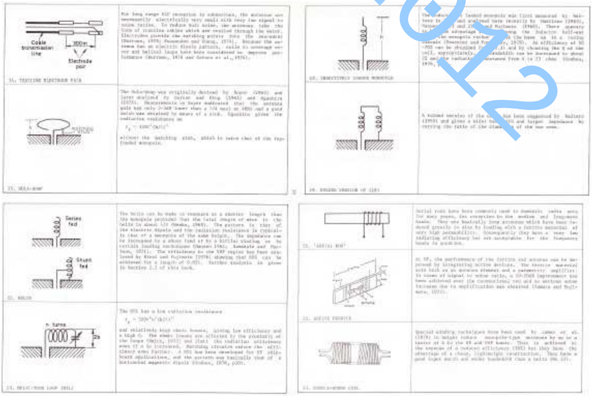
Inductive and Capacitive Loading

Small Antennas



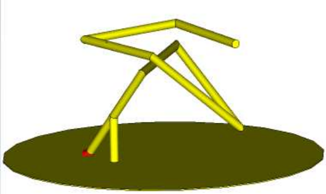
Inductive and Capacitive Loading

Small Antennas



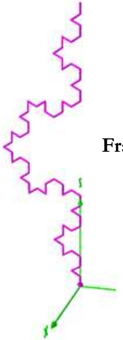
Inductive and Capacitive Loading

Recent Activities



Optimization Algorithms:

Genetic Algorithms
Particle Swarm Optimization
Others

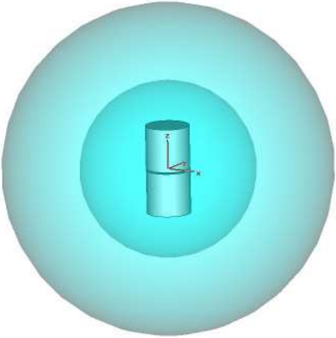


Koch Fractal

Fractal Antennas

Mid to Late 1990's: Geometric Considerations

Recent Activities



Many definitions of "Metamaterial" within the community

No electrically small, isotropic, homogeneous material with negative permittivity or permeability exits

"Metamaterial-Inspired"

Ziolkowski R. W. and Erentok A., "Metamaterial based efficient electrically small antennas," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 7, pp. 2113-2130, July 2006.

Mid 2000's – Present: Metamaterial Antennas

Today's Building Blocks

Liu, Hall and Wake – 1997

Offers advantages of wider bandwidth and multiple operating bands.

Inverted-L (1904)

Inverted-F (1960 or before?)

PIFA (1980's or before?)

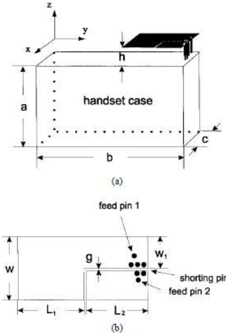
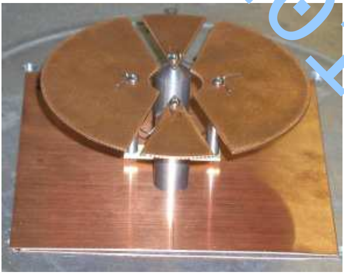


Fig. 1. (a) Geometrical arrangement of the dual-band antenna mounted on the conducting telephone case. (b) Top view of the dual-band antenna.

Planar Inverted-F Antenna (PIFA)

Today's Small Antenna Perspective



While today's small antennas may be sophisticated, unique and exhibit near optimum performance, today's antenna engineers must move beyond the concept and design of the isolated antenna in free space or an isolated antenna on a ground plane Today's antenna engineers must understand and design the antenna as part of a much larger system.

Today’s Wireless Communications

- ❑ Software Defined Radio
- ❑ Radio on a Chip
- ❑ Small Form Factor
- ❑ Wideband/Multiband
- ❑ Reconfigurable

Today’s Wireless Communications

Nokia 8390/8310

(Early Internal Antenna)

GSM Bands
GPS
UMTS
WiFi (802.11)
Bluetooth
LTE
FM Radio

[illegible]yste[illegible]	Band	Uplink (MHz)	Downlink (MHz)	Channel number
T-GS[illegible]80	38[illegible]	380.2–389.8	390.2–399.8	dynamic
[illegible]SM-410	410	[illegible]–419.8	420.2–429.8	dynamic
GSM-450	450	[illegible]0.4–457.6	460.4–467.6	259–293
G[illegible]-480	[illegible]	478.8–486.0	488.8–496.0	306–340
GSM-[illegible]	710	698.0–716.[illegible]	[illegible]8.0–746.0	dynamic
GSM-750	[illegible]50	747.0–762.0	77[illegible]0–792.0	438–511
T-GSM-810	810	[illegible]	[illegible].0–866.0	dynamic
GSM-850	850	[illegible]4.0–849.0	869.0–894.0	128–251
P-GSM-900	900	890.[illegible]914.8	935.2–959.8	1–124
E-GSM-900	900	880.0–914.8	925.2–959.8	975–1023, 0-124
R-GSM-900	900	876.0–914.8	921.0–959.8	955–1023, 0-124
T-GSM-900	900	870.4–876.0	915.4–921.0	dynamic
DCS-1800	1800	1710.2–1784.8	1805.2–1879.8	512–885
PCS-1900	1900	1850.0–1910.0	1930.0–1990.0	512–810

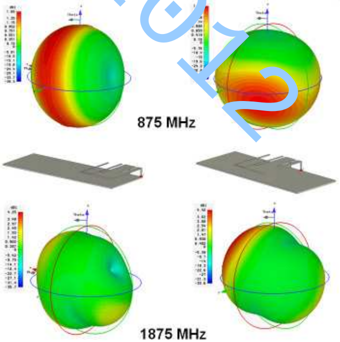
- ❑ Internal Device Dependent Designs
- ❑ Wideband/Multiband
- ❑ Small Form Factor
- ❑ User Dependent Effects
- ❑ MIMO
- ❑ Reconfigurable

Today's Small Antenna Challenges

Today's wireless devices come in many different form factors. While meeting required performance properties, the antenna must be designed to fit within the electrical and mechanical constraints of the device.

Today's Small Antenna Challenges

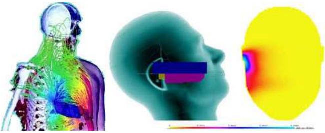
The front of the circuit board



Time-varying current within the device (ground plane, circuit board, etc) radiate and become part of the antenna system.

Today's Small Antenna Challenges

Introduction of iPhone 4



Performance and design of the wireless system must include the affects of the user.

Today's Small Antenna Challenges

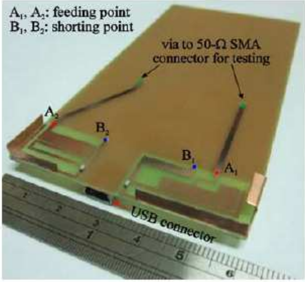


Fig. 2 Photo of the fabricated antenna array (handset casing not included in the photo).

"Internal Handset Antenna Array for LTE/WWAN and LTE MIMO Operations," Ting-Wei Kang*, Kin-Lu Wong, Ming-Fang Tu, *EuCap 2011*

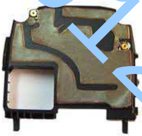
Antenna engineers must do more than just design an "antenna". Oftentimes, the antenna engineer must focus on optimizing system performance.

Today's Small Antenna Designs

100+ years of fundamental design approaches allows today's antenna engineers to develop sophisticated antennas as part of designing and optimizing a complete wireless system

- Design antennas within the mechanical constraints of the device
- Design the antenna to operate at multiple communication bands
- Optimize the antenna while considering user dependent effects
- Understand the propagation environment and channel
- Understand that the device is part of the radiating structure
- Optimize system performance/capacity using reconfigurable antennas, MIMO antennas, etc.

Today's Small Antenna Designs



What's Next/Current Activities?

- High permeability, low loss materials
- Non-Foster Impedance matching
- Small multi-resonant/wideband antennas
- Smart, reconfigurable small antenna – tunes and matches itself depending on waveform bandwidth, operating frequency, changes in surrounding environment, etc.

Today's Small Antenna Designs

What is certain: Not considering the wireless device as a complex, integrated system operating in a complex environment - an optimum system design may not be achieved