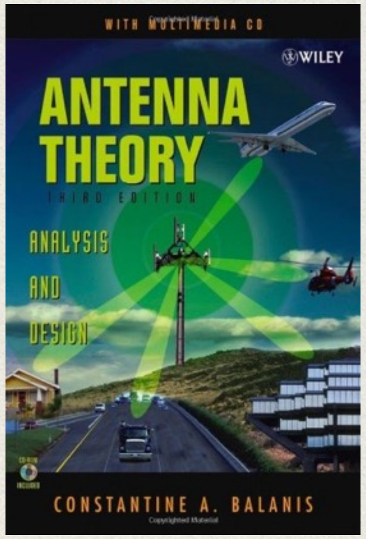
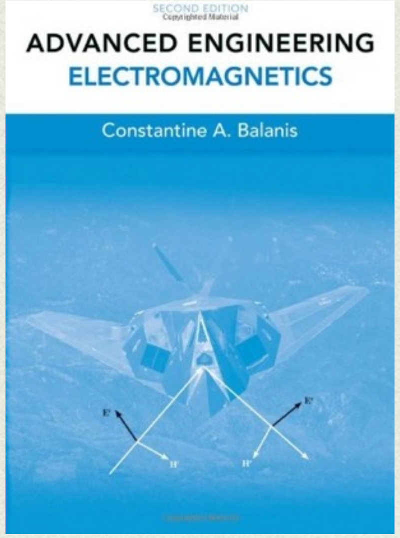
BLUETOOTH LOW ENERGY RANGING PRIMER

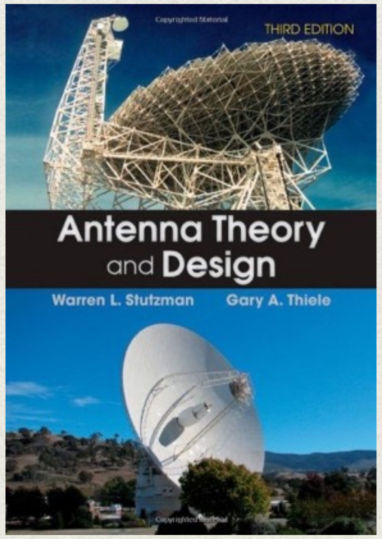
Tomáš Rosa

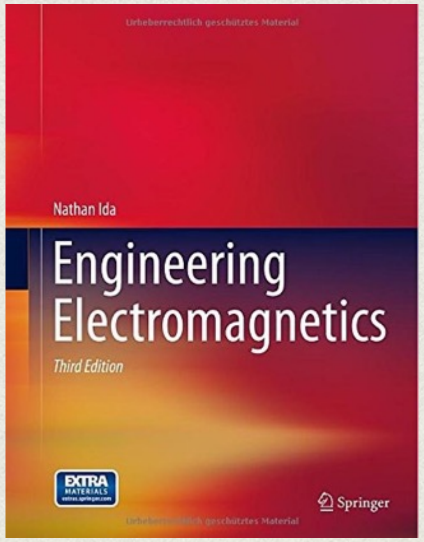
http://crypto.hyperlink.cz

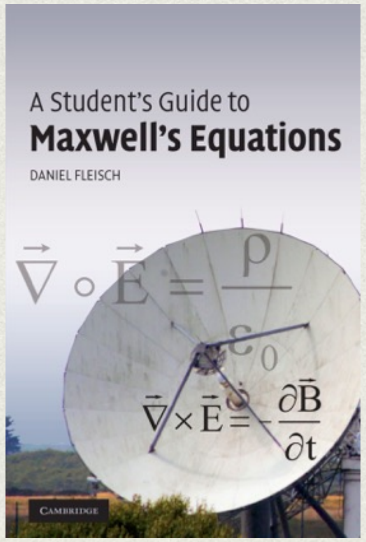
ANTENNA ESSENTIALS WITH NEAR AND FAR FIELDS DISCUSSION

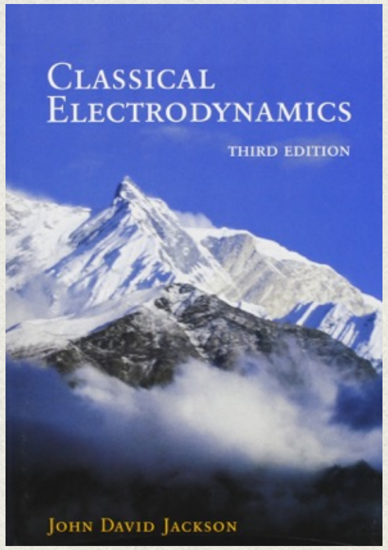












START WITH SOMETHING FAMILIAR

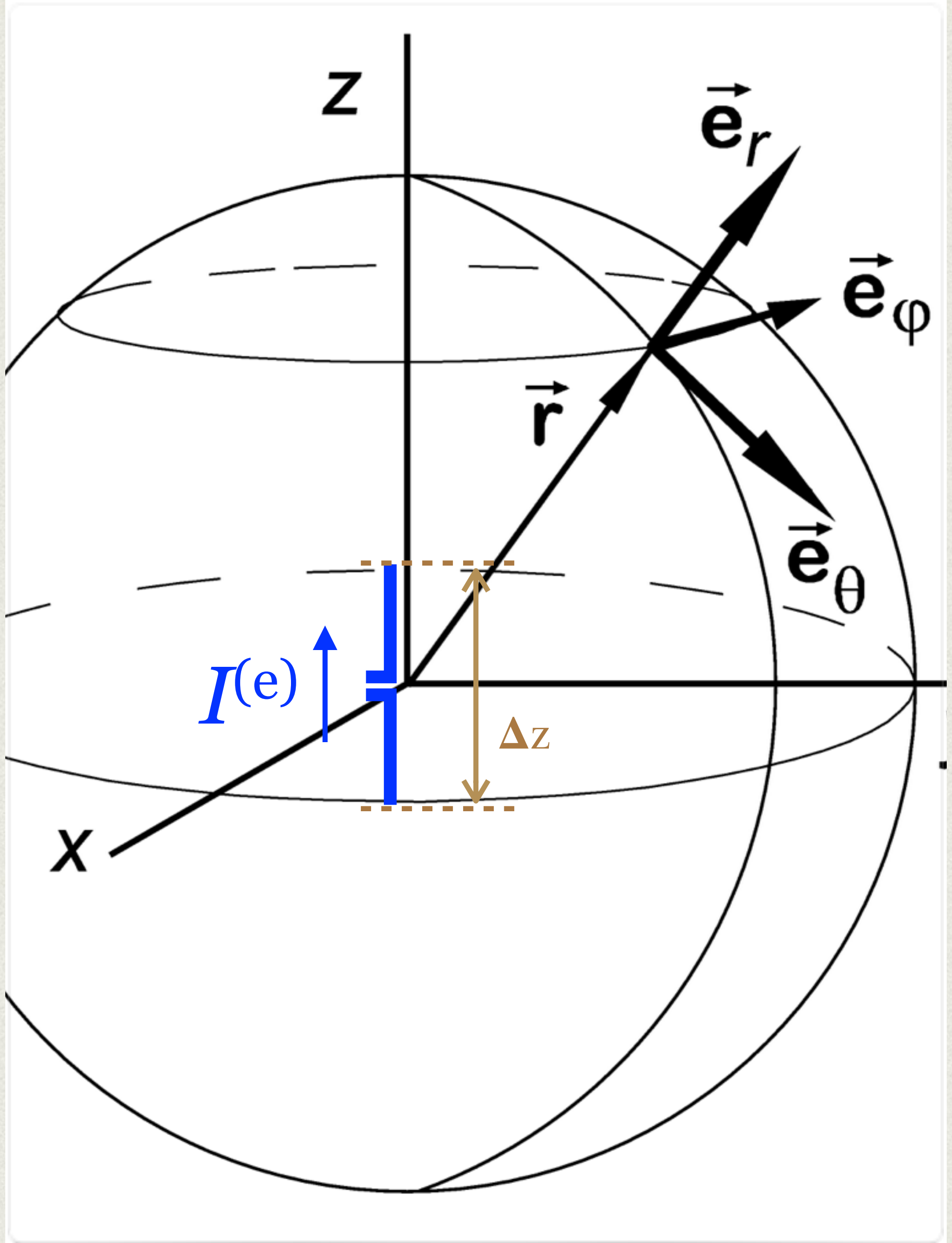
[Buddipole QRV by 5B8AP]

THE IDEAL ELECTRIC DIPOLE

- Electrically small, i.e. $\Delta z << \lambda$, uniform amplitude current element.
  - Ordinary dipole is covered by integration over these elements.
- In the far field, a donut-like pattern bearing the vertical polarisation is produced.
- In general, its field has the following components.

$$\overrightarrow{E}_{edp}(I^{(e)}) = E_{edp,\theta}(I^{(e)})\cdot\widehat{e_\theta} + E_{edp,r}(I^{(e)})\cdot\widehat{e_r}$$

$$\overrightarrow{H}_{edp}(I^{(e)}) = H_{edp,\phi}(I^{(e)})\cdot\widehat{e_\phi}$$



(illustration purpose only)

LONG STORY SHORT

$$\vec{H}_{edp}(I^{(e)}) = \frac{I^{(e)}\Delta z}{4\pi} j\beta(\frac{1}{r} + \frac{1}{j\beta r^2})e^{-j\beta r}\sin\theta \cdot \hat{e}_\phi$$

$$\vec{E}_{epd}(I^{(e)}) = \frac{I^{(e)}\Delta z}{4\pi} j\omega\mu(\frac{1}{r} + \frac{1}{j\beta r^2} - \frac{1}{\beta^2 r^3})e^{-j\beta r}\sin\theta \cdot \hat{e}_\theta$$

$$+\frac{I^{(e)}\Delta z}{2\pi} j\omega\mu(\frac{1}{j\beta r^2} - \frac{1}{\beta^2 r^3})e^{-j\beta r}\cos\theta \cdot \hat{e}_r$$

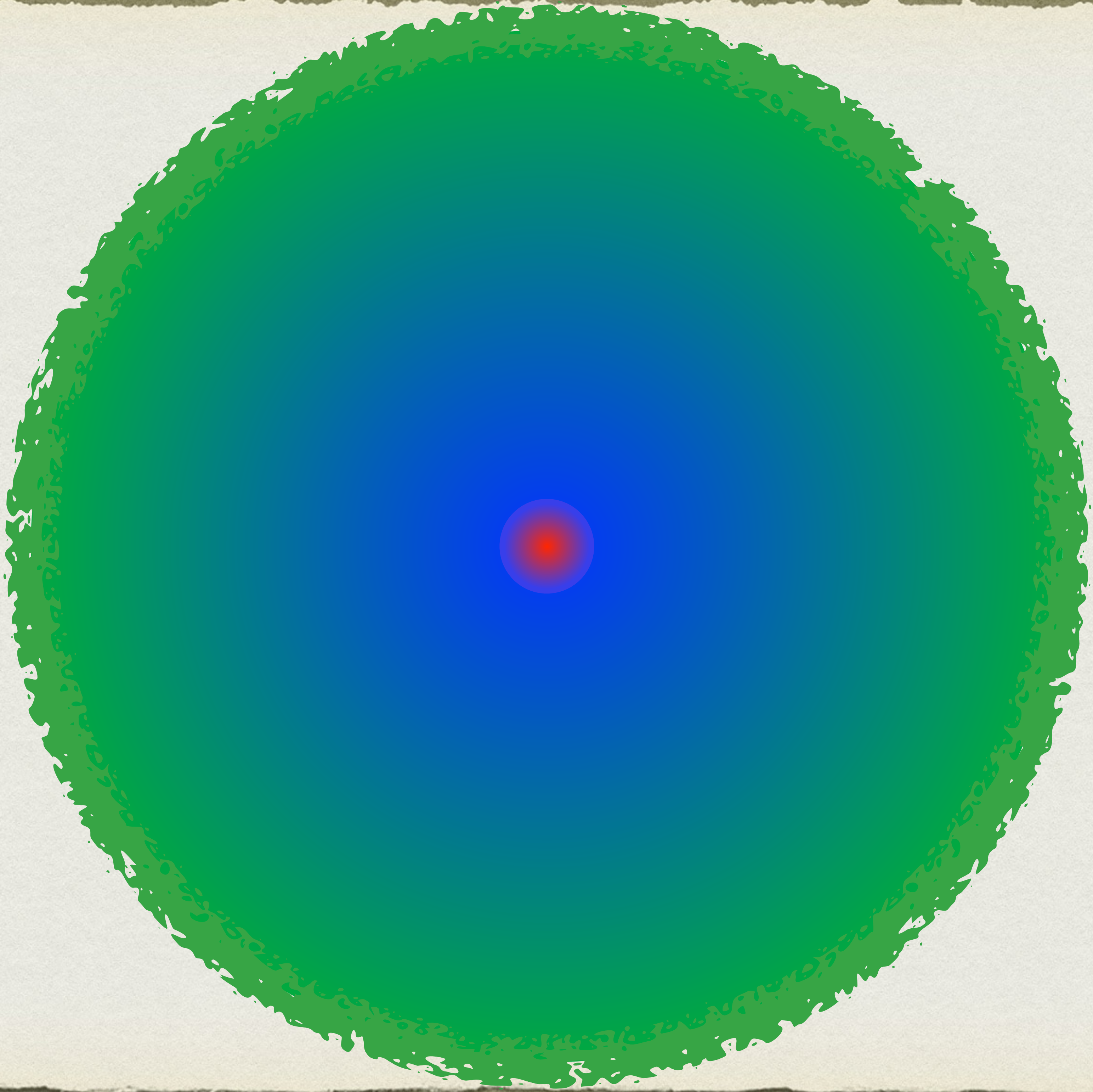
$$= \frac{I^{(e)}\Delta z}{4\pi} j\omega\mu(\frac{1}{r} + \frac{1}{j\beta r^2} - \frac{1}{\beta^2 r^3})e^{-j\beta r}\sin\theta \cdot \hat{e}_\theta$$

$$+\frac{I^{(e)}\Delta z}{2\pi} \eta(\frac{1}{r^2} - j\frac{1}{\beta r^3})e^{-j\beta r}\cos\theta \cdot \hat{e}_r$$

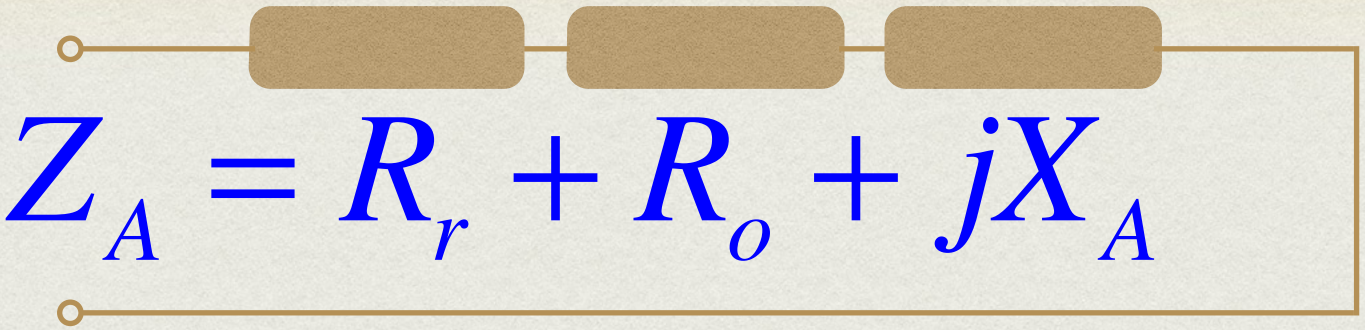
NEAR, FAR

- Basing on the dominating *E*, *H* field terms, it is useful to distinguish:
  - *Reactive near field* (XNF), where the terms with $1/r^2$ and $1/r^3$ dominate. Energy is mainly stored and exchanged between *E* and *H*.
  - *Radiating near field* (Fresnel region), where the $1/r^2$ terms start to dominate, i.e. $r > \lambda/2\pi$. Energy is mainly radiated with unstable patterns, however.
  - *Far field* (Fraunhofer region), where the $1/r$ terms remain to dominate and the plane wave model can be used. Several conditions shall be met: $r > 2D^2/\lambda$, $r > 5D$, $r > 1.6\lambda$, where D is the largest antenna dimension. Energy is radiated with a distance-independent field pattern.

WHEREVER YOU ARE



ANTENNA IMPEDANCE



$$Z_A = R_r + R_o + jX_A$$

- The input impedance Z_A describes the antenna from the lumped circuit parameters viewpoint.
  - R_r is the equivalent radiation resistance representing the energy emanated through the radio waves
  - R_o describes the dissipative energy loss
  - X_A reflects the energy exchanged back-and-forth with the reactive near field

EFFICIENCY ANALYSIS

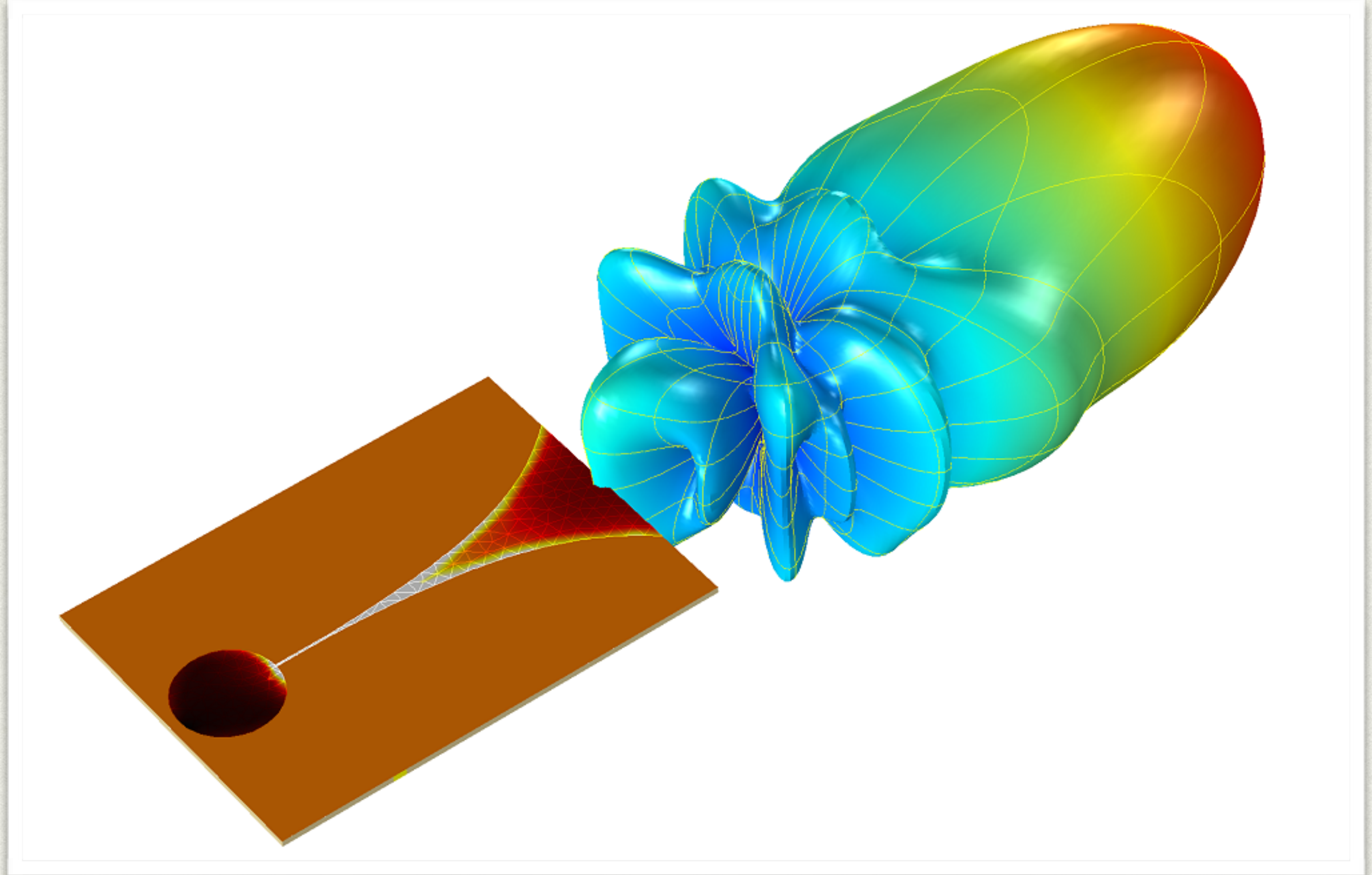
- To get a better overview, we can compute the radiation efficiency e_r that can be further used for gain estimation, etc.

- Especially, please see the relationship in between the gain G and directivity D below.

$$e_r = \frac{R_r}{R_o + R_r}$$

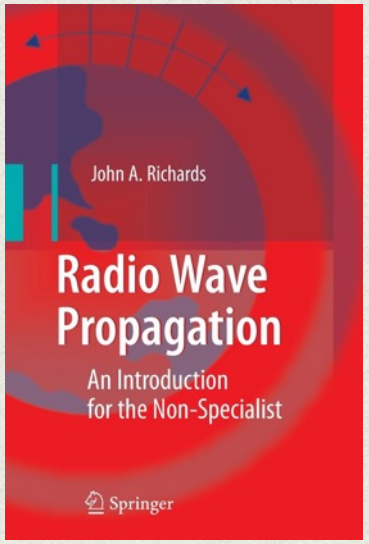
$$G = e_r D$$

UNDERSTANDING DIRECTIVITY AND GAIN



[Vivaldi Antenna Design Analysis by Caty Fairclough]

FREE SPACE PROPAGATION BASICS

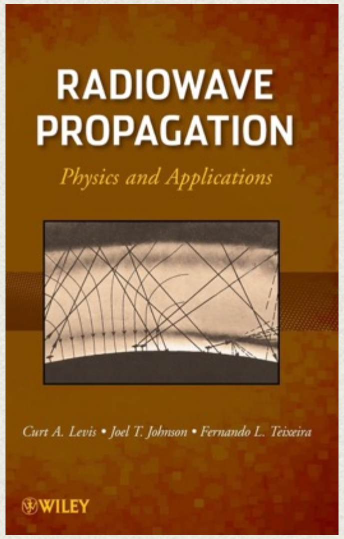


John A. Richards

Radio Wave Propagation

An Introduction for the Non-Specialist

Springer



RADIOWAVE PROPAGATION

Physics and Applications

Curt A. Levis • Joel T. Johnson • Fernando L. Teixeira

WILEY

TOWARDS FRIIS TRANSMISSION FORMULA

- Let P_t be the transmitter power delivered to an isotropic antenna,
  - e_rt the transmitter antenna radiation efficiency,
  - and d the target radial distance.
- The far-field power density p_iso at the distant place is then:

$$p_{iso} = \frac{e_{rt} P_t}{4\pi d^2}$$

INCLUDING ANTENNA DIRECTIVITY

- Furthermore, let D_t be the transmitter directivity
  - and G_t its gain (*we are in the far-field region!*).
- The power density p at the distant place in the direction of the maximum directivity/gain is then:

$$p = \frac{e_{rt} D_t P_t}{4\pi d^2} = \frac{G_t P_t}{4\pi d^2}$$

AVAILABLE RECEIVER ANTENNA POWER

- Let A_r be the receiver antenna effective aperture,
  - G_r its gain,
  - and λ the wavelength (c/f, in the free space).
- The available receiver antenna terminal power in the maximum directivity course is then given by:

$$P_r = \frac{A_r G_t P_t}{4\pi d^2} = G_r G_t P_t \left(\frac{\lambda}{4\pi d} \right)^2 ,$$

$$\text{where } A_r = \frac{\lambda^2 G_r}{4\pi}$$

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free space attenuation

$$\text{where } A_r = \frac{\lambda^2 G_r}{4\pi}$$

SPEAKING IN DECIBELS

- Let dBm denote decibels over 1 mW power and let dBi denote decibels of the antenna power gain over the isotropic source.
  - $[P]_{\text{dBm}} = 10\log(P/10^{-3}) = 10\log P + 30$
  - $[G]_{\text{dBi}} = 10\log(G/1) = 10\log G$
- The available receiver antenna terminal power is then:

$$[P_r]_{dBm} = [P_t]_{dBm} + [G_t]_{dBi} + [G_r]_{dBi} - 20\log\frac{4\pi d}{\lambda}$$

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free space loss

RECURRENT EQUATION

- With respect to a calibration distance d_0 (usually 1 metre), we can derive:

$$-\left[P_r(d_0)\right]_{dBm} = -[P_t]_{dBm} - [G_t]_{dBi} - [G_r]_{dBi} + 20\log\frac{4\pi}{\lambda} + 20\log d_0$$

$$\left[P_r(d)\right]_{dBm} = [P_t]_{dBm} + [G_t]_{dBi} + [G_r]_{dBi} - 20\log\frac{4\pi}{\lambda} - 20\log d$$

$$\left[P_r(d)\right]_{dBm} - \left[P_r(d_0)\right]_{dBm} = -20\left(\log d - \log d_0\right)$$

$$\left[P_r(d)\right]_{dBm} = \left[P_r(d_0)\right]_{dBm} - 20\log\frac{d}{d_0}$$

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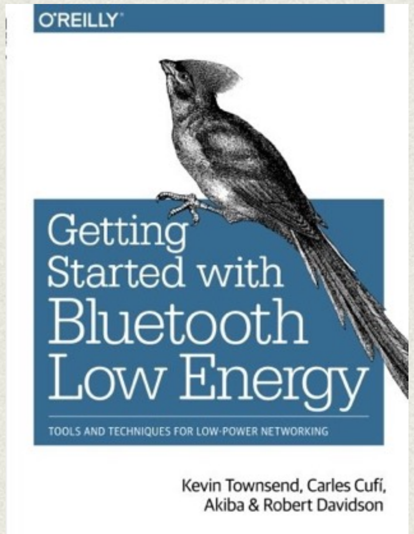
$$\left[P_r(d)\right]_{dBm} = [P_t]_{dBm} + [G_t]_{dBi} + [G_r]_{dBi} - 20\log\frac{4\pi}{\lambda} - 20\log d$$

$$\left[P_r(d)\right]_{dBm} - \left[P_r(d_0)\right]_{dBm} = -20\left(\log d - \log d_0\right)$$

$$\boxed{\left[P_r(d)\right]_{dBm} = \left[P_r(d_0)\right]_{dBm} - 20\log\frac{d}{d_0}}$$

our primary distance indicator

BLE
REAL PLAYGROUND



O'REILLY

Getting Started with Bluetooth Low Energy

TOOLS AND TECHNIQUES FOR LOW-POWER NETWORKING

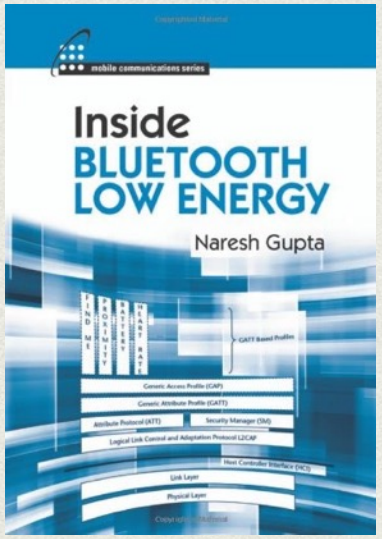
Kevin Townsend, Carles Cufí, Akiba & Robert Davidson

PRENTICE HALL

BLUETOOTH LOW ENERGY

THE DEVELOPER'S HANDBOOK

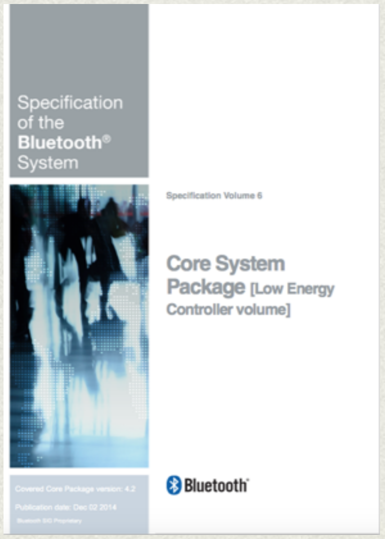
ROBIN HEYDON



mobile communications series

Inside BLUETOOTH LOW ENERGY

Naresh Gupta



Specification of the Bluetooth® System

Specification Volume 6

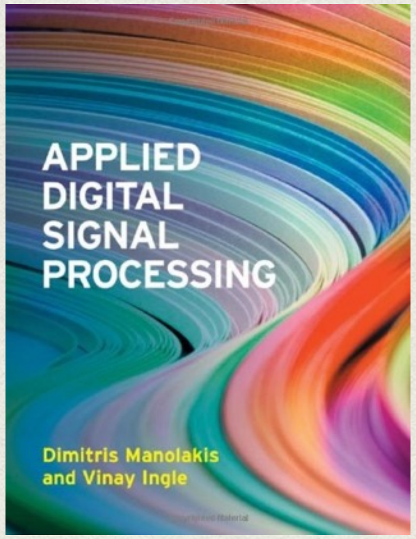
Core System Package [Low Energy Controller volume]

Covered Core Package version: 4.2

Publication date: Dec 02 2014

Bluetooth SIG Proprietary

Bluetooth



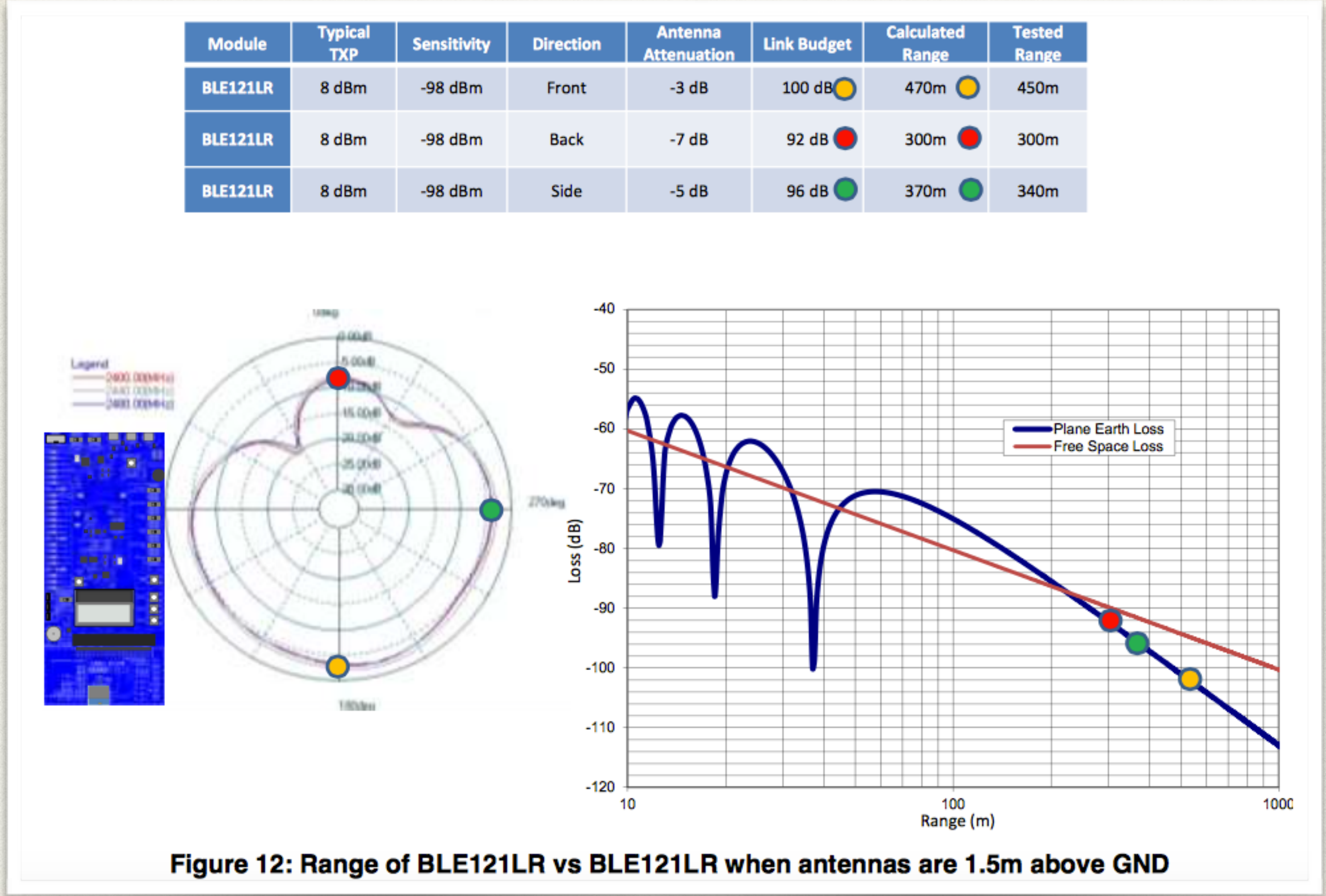
APPLIED DIGITAL SIGNAL PROCESSING

Dimitris Manolakis and Vinay Ingle

REAL WORLD OBSTACLES

- Multipath propagation fading
- Polarisation mismatch
- Field equations in a matter instead of the free space
- Radio channel interference in the 2.4 GHz ISM band
- RSSI measurement (in)accuracy

FADING ILLUSTRATION



Module	Typical TXP	Sensitivity	Direction	Antenna Attenuation	Link Budget	Calculated Range	Tested Range
BLE121LR	8 dBm	-98 dBm	Front	-3 dB	100 dB 🟡	470m 🟡	450m
BLE121LR	8 dBm	-98 dBm	Back	-7 dB	92 dB 🔴	300m 🔴	300m
BLE121LR	8 dBm	-98 dBm	Side	-5 dB	96 dB 🟢	370m 🟢	340m

Figure 12: Range of BLE121LR vs BLE121LR when antennas are 1.5m above GND

[BLE112, BLE113, and BLE121LR Range Analysis by Bluegiga Tech.]

GROUND PLANE EFFECTS

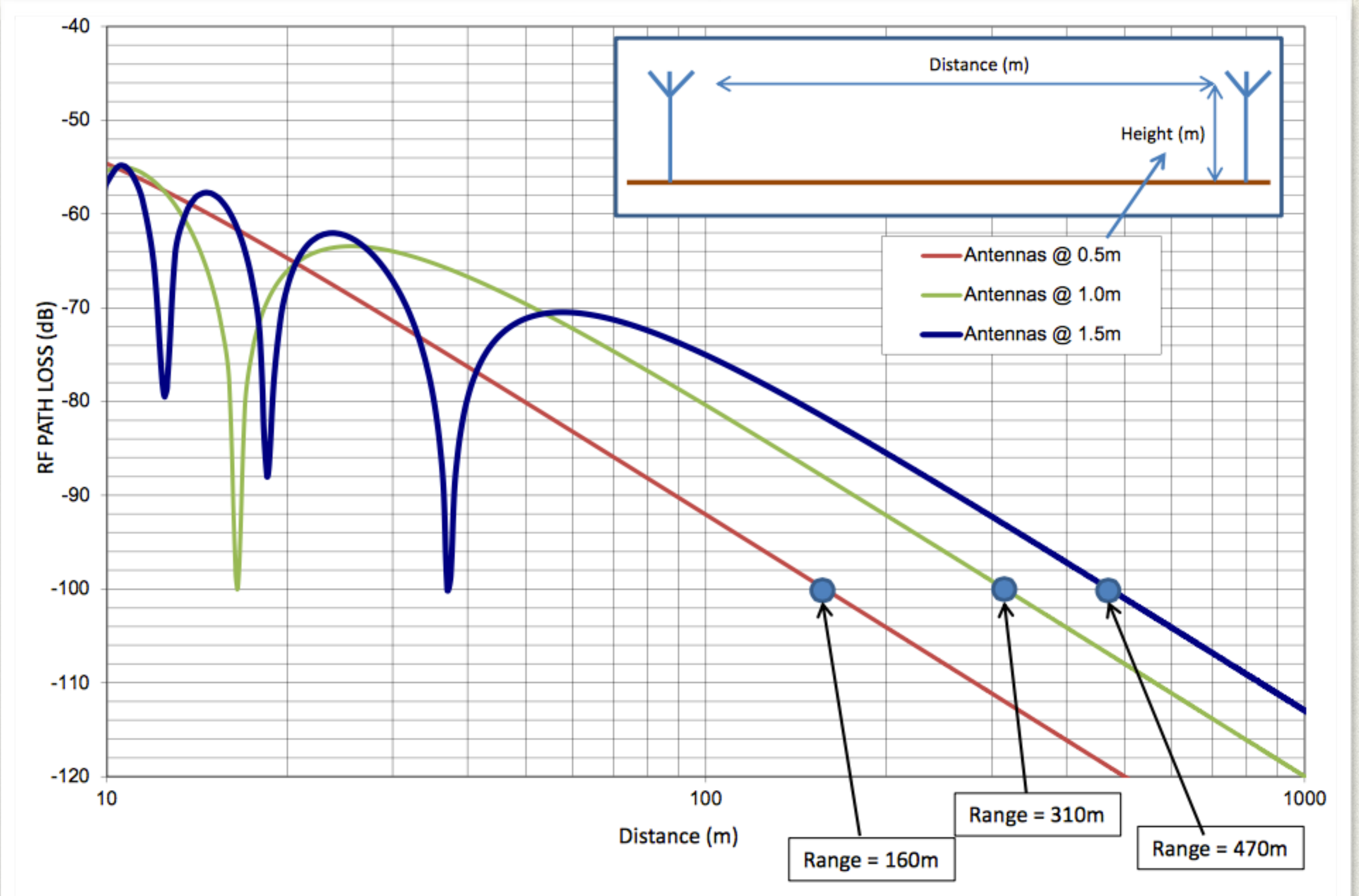


Figure 14: Impact of module height above GND to RF path loss

[BLE112, BLE113, and BLE121LR Range Analysis by Bluegiga Tech.]

GENERAL APPROACH

- Follow the idea of distance measurement principle suggested by the Friis transmission formula.
- Use a decent model parametrisation (development phase) and calibration (production phase) to cope with the predictable discrepancies.
- Deploy a simple statistical signal processing to filter out random disturbances.

POSITIONING VS. RANGING

- The indoor RF positioning and navigation applications can serve as an inspiration.
- We shall be careful, however, that the problem of BLE ranging in an ordinary environment is not the same as the positioning in a particular, well-measured environment.

RSSI MODEL

- Let RSSI denote the value provided by the Read RSSI Command via BLE HCI.
- Basing on the formula derived above, we can write:

$$RSSI(d) = RSSI(d_0) - 10n\log\frac{d}{d_0} + X$$

  - d_0 denotes the calibration distance,
  - n is a model parametrisation constant ($n = 2$ in the free space), referred to as the *attenuation factor*
  - X is a random variable covering fluctuations

1 METRE CALIBRATION

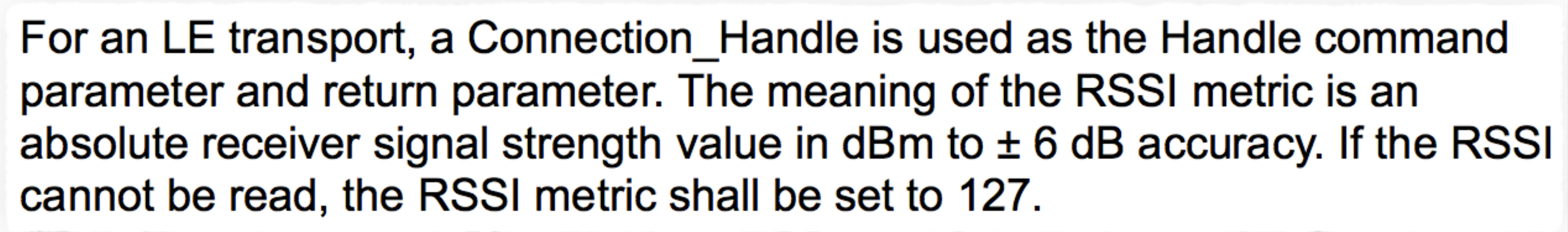
- Let d_0 = 1 m.
- The model can further simplified then as:

$$RSSI(d) = A - 10n\log d + X$$

  - *A* denotes the RSSI calibration at 1 m distance.

RSSI PRECISION

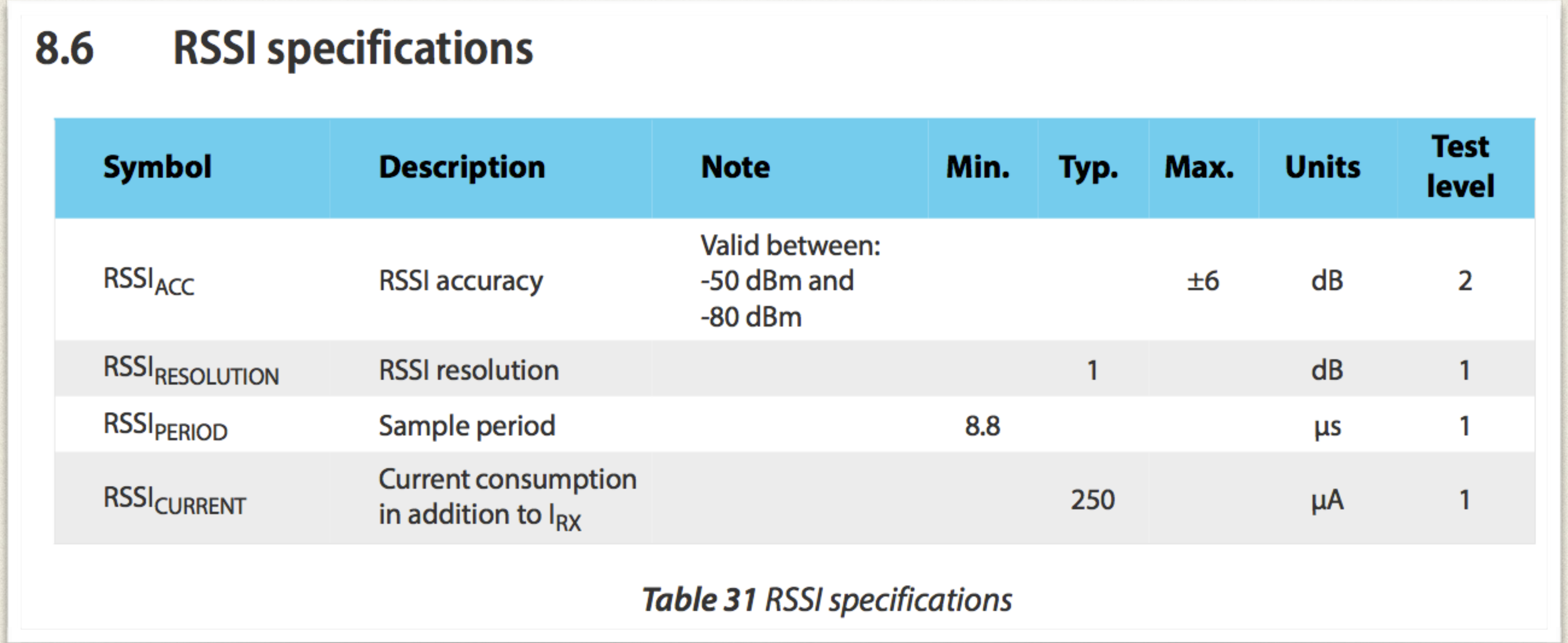
- The original BLE standard description of Read RSSI Command, accessible via HCI, states that:



For an LE transport, a Connection_Handle is used as the Handle command parameter and return parameter. The meaning of the RSSI metric is an absolute receiver signal strength value in dBm to ± 6 dB accuracy. If the RSSI cannot be read, the RSSI metric shall be set to 127.

    - Low-cost BLE controllers can be hardly expected to do any better than this…

nRF51822 EXAMPLE



8.6 RSSI specifications

Symbol	Description	Note	Min.	Typ.	Max.	Units	Test level
$RSSI_{ACC}$	RSSI accuracy	Valid between: -50 dBm and -80 dBm			±6	dB	2
$RSSI_{RESOLUTION}$	RSSI resolution			1		dB	1
$RSSI_{PERIOD}$	Sample period		8.8			µs	1
$RSSI_{CURRENT}$	Current consumption in addition to I_{RX}			250		µA	1

***Table 31** RSSI specifications*

[nRF51822 - Product Specification]

RSSI FILTRATION

- RSSI queries can be modelled as a random process sampling.
- Easy-to-implement (supposedly) IIR filter based on AR(*p*) all-pole model to smooth out the variation of data obtained was publicly suggested by Zhu et al.
  - In particular, it was advised to use $p = 3$ together with the following coefficients:

$$y[n] = 0.2 * y[n-1] + 0.2 * y[n-2] + 0.1 * y[n-3] \\ + 0.5 * RSSI[n]$$

[Based on Zhu, Chen, Luo, and Li, 2014]

CONCLUSIONS

- In the free space, the wave propagation problems are relatively easy to solve.
- However, a precise RSSI-to-distance transformation in the UHF band for the everyday environment is a long standing hard problem.
    - BLE in the 2.4 GHz ISM band adds a considerable amount of further practical difficulties.
- Anyway, under a reasonably simple model, we can get at least somewhere beyond the “mystery” of the trial and error approach.
    - For many practical applications, this can be fair enough.

REFERENCES

(BESIDES THE BOOKS NOTED ABOVE)

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