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Wireless Personal Area Networks

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Abstract	[This paper presents a theoretical analysis of the near field channel in free space. Then this document offers a reasonable strawman channel model for purposes of comparison of near field location systems: (1) Assume attenuation no worse than 20 dB below the free space near field channel model and (2) Assume phase deviations consistent with the delay spread measured at microwave frequencies.]
Purpose	[The purpose of this document is to provide IEEE P802.15 with a near field channel model for evaluating near field location aware wireless systems.]
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Release	

Near Field Channel Model

This paper presents a theoretical analysis of the near field channel in free space. Then this document offers a reasonable strawman channel model for purposes of comparison of near field location systems: (1) Assume attenuation no worse than 20 dB below the free space near field channel model and (2) Assume phase deviations consistent with the delay spread measured at microwave frequencies.

Outline

I. Introduction

The purpose of this document is to lay out a near field channel model. This document presents a theoretical analysis of the near field channel. A reasonable strawman channel model for purposes of comparison of near field location systems is to assume attenuation no worse than 20 dB below the free space near field channel model and phase deviations consistent with the delay spread measured at microwave frequencies.

Accuracy achievable by a low frequency tracking system will naturally depend upon the specific implementation and the corresponding range algorithm. For the special case of a "near field electromagnetic ranging" tracking system a range algorithm and associated error relations has been presented elsewhere.[1]

Additionally, though not required for a channel model, this document also includes information on the relationship between antenna size and performance. in conjunction with these antenna relations, performance of a near field ranging system is fully quantified.

II. Pathloss

This section will discuss the pathloss for traditional far field links and summarize the differences between far field and near field links. Then, this section will introduce a near field link equation that provides path loss for low frequency near field links.

[1] H. Schantz, "*Near Field Ranging Algorithm*," IEEE 802.15-04-0438-00-004a, 17 August, 2004.

A. The Friis Law and Far Field Pathloss

The relationship between transmitted power (P_{TX}) and received power (P_{RX}) in a far-field RF link is given by "Friis's Law:"

$$PL(f,d)=\frac{P_{RX}}{P_{TX}}=\frac{G_{TX}G_{RX}\lambda^2}{(4\pi)^2 d^2}=\frac{G_{TX}G_{RX}}{4}\frac{1}{(kd)^2} \tag{1}$$

where G_{TX} is the transmit antenna gain, G_{RX} is the receive antenna gain, λ is the RF wavelength, $k = 2\pi/\lambda$ is the wave number, and d is the distance between the transmitter and receiver. In other words, the far-field power rolls off as the inverse square of the distance ($1/d^2$). Near-field links do not obey this relationship. Near field power rolls off as powers higher than inverse square, typically inverse fourth ($1/d^4$) or higher.

This near field behavior has several important consequences. First, the available power in a near field link will tend to be much higher than would be predicted from the usual far-field, Friis's Law relationship. This means a higher signal-to-noise ratio (SNR) and a better performing link. Second, because the near-fields have such a rapid roll-off, range tends to be relatively finite and limited. Thus, a near-field system is less likely to interfere with another RF system outside the operational range of the near-field system.

B. Near Field Link Equations

Electric and magnetic fields behave differently in the near field, and thus require different link equations. Reception of an electric field signal requires an electric antenna, like a whip or a dipole. Reception of a magnetic field signal requires a magnetic antenna, like a loop or a loopstick. The received signal power from a co-polarized electric antenna is proportional to the time average value of the incident electric field squared:

$$P_{RX(E)}\sim\left\langle|\mathbf{E}|^2\right\rangle\sim\left(\frac{1}{(kd)^2}-\frac{1}{(kd)^4}+\frac{1}{(kd)^6}\right), \tag{2}$$

for the case of a small electric dipole transmit antenna radiating in the azimuthal plane and being received by a vertically polarized electric antenna. Similarly, the received signal power from a co-polarized magnetic antenna is proportional to the time average value of the incident magnetic field squared:

$$P_{RX(H)}\sim\left\langle|\mathbf{H}|^2\right\rangle\sim\left(\frac{1}{(kd)^2}+\frac{1}{(kd)^4}\right). \tag{3}$$

Thus, the "near field" pathloss formulas are:

$$PL_E(d,f)=\frac{P_{RX(E)}}{P_{TX}}=\frac{G_{TX}G_{RX(E)}}{4}\left(\frac{1}{(kd)^2}-\frac{1}{(kd)^4}+\frac{1}{(kd)^6}\right) \tag{4}$$

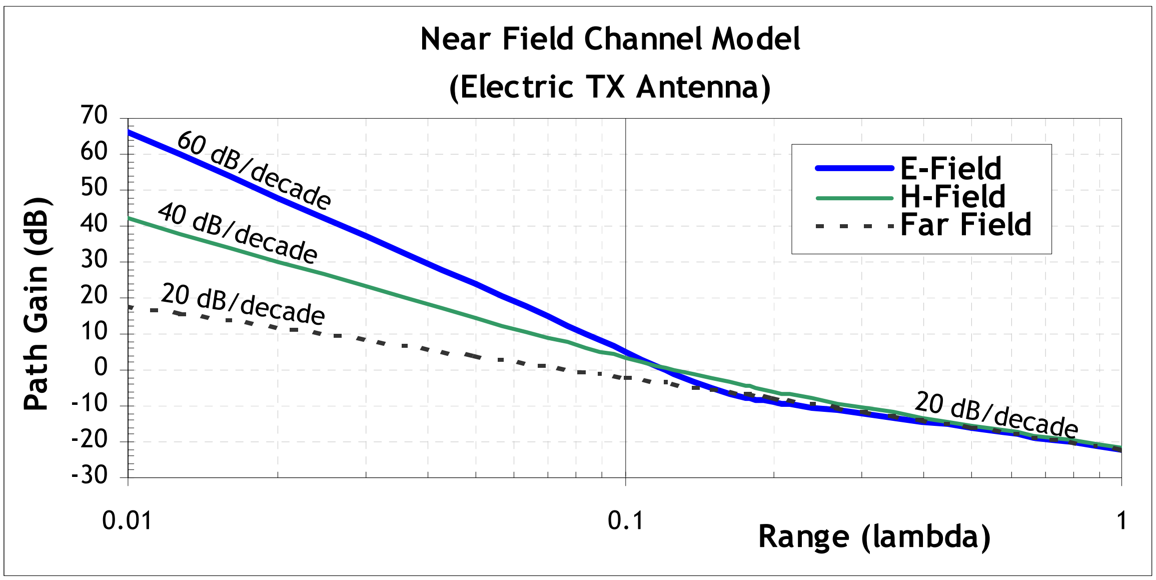
for the electric field signal, and:

$$PL_H(d,f) = \frac{P_{RX(H)}}{P_{TX}} = \frac{G_{TX}G_{RX}}{4}\left(\frac{1}{(kr)^2} + \frac{1}{(kr)^4}\right) \quad (5)$$

for the magnetic field signal. At a typical near field link distance where $kd \cong 1$ ($d \cong \lambda/2\pi$), a good approximation is:

$$PL(d,f) \cong \tfrac{1}{4}\, G_{TX} G_{RX}. \quad (6)$$

In other words, the typical pathloss in a near field channel is on the order of –6 dB. At very short ranges, pathloss may be on the order of 60 dB or more. At an extreme range of about one wavelength the pathloss may be about 18 dB. This behavior is summarized in the figure below:



Behavior of a Typical Near Field Channel

Experimental data showing the accuracy of a near field ranging system is available elsewhere.[2]

III. Near Field Phase Equations

The near field phase behavior was derived elsewhere.[3] For an electric transmit antenna, the magnetic phase is:

$$\phi_H = -\frac{180}{\pi}\left[kr + \left(\cot^{-1} kr + n\pi\right)\right], \quad (7)$$

and the electric phase varies as:

[2] Kai Siwiak, "*Near Field Electromagnetic Ranging*," IEEE802.15-04/0360r0, 13 July 2004.
[3] Hans Schantz, "*Near Field Ranging Algorithm*," IEEE802.15-04/0438r0, 17 August 2004.

$$\phi_E = -\frac{180}{\pi}\left\{kr + \left[\cot^{-1}\left(kr - \frac{1}{kr}\right) + n\pi\right]\right\}. \tag{8}$$

IV. Attenuation and Delay Spread:

The near field link and phase equations above describe free space links. In practice, the free space formulas provide an excellent approximation to propagation in an open field environment. In heavily cluttered environments, signals may be subject to additional attenuation or enhancement. Attenuation or enhancement of signals may be included to match measured data. Even in heavily cluttered environments, low frequency near field signals are rarely attenuated or enhanced by more than about 20 dB. In most typical indoor propagation environments, results are comparable to free space results and attenuation or enhancement are not necessary for an accurate model. The key complication introduced by the indoor environment is phase distortions caused by the delay spread of multipath.

The concept of a delay spread is not directly applicable to a near field channel because the wavelength of a low frequency near field system is much longer than the propagation environment. Instead, a near field channel in a complex propagation environment is characterized by phase distortions that depend upon the echo response of the environment. Since this echo response is largely insensitive to frequency, delay spread measurements at higher frequencies provide an excellent indication of the phase deviation magnitude to expect at lower frequencies.

In propagation testing of near field systems indoors, typical delay deviations are on the order of τ_{RMS} = 30-50 ns, consistent with what might be expected for a microwave link. For instance, a system operating at 1 MHz with an RF period of 1 μs will experience phase deviations of 11–18 degrees. The worst case near field delay observed to date has been an outlier on the order of 100 ns corresponding to a 36 degree deviation at 1 MHz.

The delay spread tends to be distance dependent:[4]

$$\tau_{RMS} = \tau_0 \sqrt{\frac{d}{d_0}}, \tag{9}$$

where d is the distance, d_0 = 1 m is the reference distance, and the delay spread parameter is τ_0 = 5.5 ns. [5] In the limit where the RMS delay spread is much smaller than the period of the signals in questions, the RMS phase variation is:

$$\phi_{RMS} = \omega\tau_{RMS} = 2\pi f\tau_{RMS}, \tag{10}$$

[4] Kai Siwiak et al, "On the relation between multipath and wave propagation attenuation," Electronic Letters, 9 January 2003 Vol. 39, No. 1, pp. 142-143.

[5] Kai Siwiak, "UWB Channel Model for under 1 GHz," IEEE 802.15-04/505r0, 10 October, 2004.

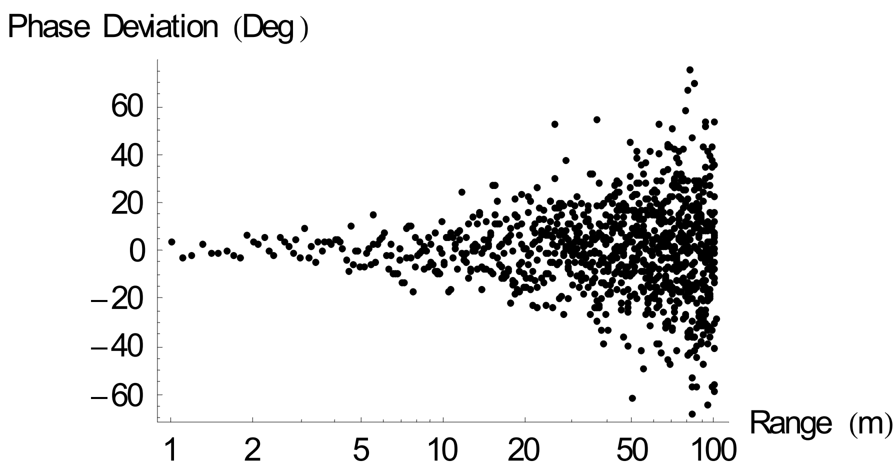
where f is the operational frequency. Thus, a good model for phase behavior is to add a normally distributed phase perturbation with zero mean and a standard deviation equal to the RMS delay spread. Thus:

$$\phi_H = -\frac{180}{\pi}\left[kr + \left(\cot^{-1} kr + n\pi\right)\right] + Norm[0, \phi_{RMS}] \tag{11}$$

and

$$\phi_E = -\frac{180}{\pi}\left\{kr + \left[\cot^{-1}\left(kr - \frac{1}{kr}\right) + n\pi\right]\right\} + Norm[0, \phi_{RMS}] \tag{12}$$

The figures below show randomly generated phase deviations and phase response.



Typical Phase Deviations (τ_0 = 5.5 ns; f = 1.3 MHz)

In summary, to a reasonable approximation, signal power in a near field link follows from the free space model. Further, one may assume that the delay spread as measured at microwave frequencies is typical of the phase deviation to be expected at low frequencies.

Appendix 1: Code and Sundry Trials

This appendix presents Mathematica code to generate typical near field channels.

■ Load Packages:

```
In[1]:= << Graphics`Graphics`

In[2]:= << Statistics`NormalDistribution`
```

■ Independent Parameters:

```
In[3]:= c := 299.79        (* MHz m - Speed of Light *)
        f0 := 1.3           (* MHz - Operational Frequency *)
        τ0 := 5.5          (* ns - RMS Delay Spread Parameter *)
        d0  := 1           (* m - RMS Delay Reference Distance *)
        Ptx := 0.1         (* W - TX Power *)
        Gtx := 10^(-52/10)        (* N/A - Transmit Gain *)
        GrxE := 10^(-65/10)       (* N/A - E Receive Gain *)
        GrxH := 10^(-63/10)       (* N/A - H Receive Gain *)
```

■ Derived Parameters:

In[11]:= $k := \frac{2\pi\, f0}{c}$ (* $\frac{1}{m}$ - Wave Number *)

■ Near Field Power Relations:

In[12]:= $PrxE := Ptx\,\frac{Gtx\,GrxE}{4}\left(\frac{1}{(k\,d)^2} - \frac{1}{(k\,d)^4} + \frac{1}{(k\,d)^6}\right)$

$PrxH := Ptx\,\frac{Gtx\,GrxH}{4}\left(\frac{1}{(k\,d)^2} + \frac{1}{(k\,d)^4}\right)$

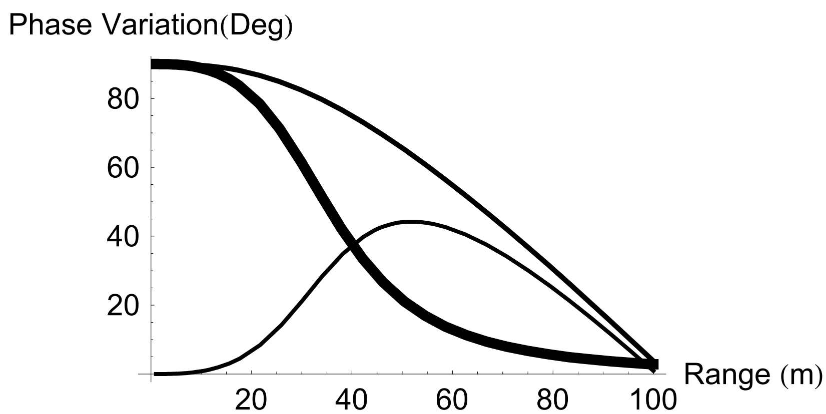
■ Free Space Near Field Phase Relations:

In[33]:= $\varphi E := -\frac{180}{\pi}\,(k\,d + (\mathrm{ArcCot}[k\,d]) - \pi)$

$\varphi H := -\frac{180}{\pi}\left(k\,d + \left(\mathrm{ArcCot}\left[k\,d - \frac{1}{k\,d}\right] + \mathrm{If}[k\,d > 1, -\pi, 0]\right)\right)$

(* Note: Must correct branch cut at kd = 1 *)

```
In[40]:= Show[{Plot[φH, {d, 1, 100}, PlotStyle → Thickness[0.008]],
           Plot[φE, {d, 1, 100}, PlotStyle → Thickness[0.01]],
           Plot[φE - φH, {d, 1, 100}, PlotStyle → Thickness[0.02]]},
          TextStyle → {FontFamily -> "Helvetica",
            FontSize → 14},
          AxesLabel → {"Range (m)", "Phase Variation(Deg)"}]
```




```
Out[40]= - Graphics -
```

■ Delay Spread:

In[41]:= $\tau RMS := \tau 0 \sqrt{\frac{d}{d0}}$ (* ns - RMS Delay Spread *)

$\varphi RMS := 2\,\pi\,\tau RMS\,\frac{f0}{1000}$ (* rad - RMS Delay Spread *)

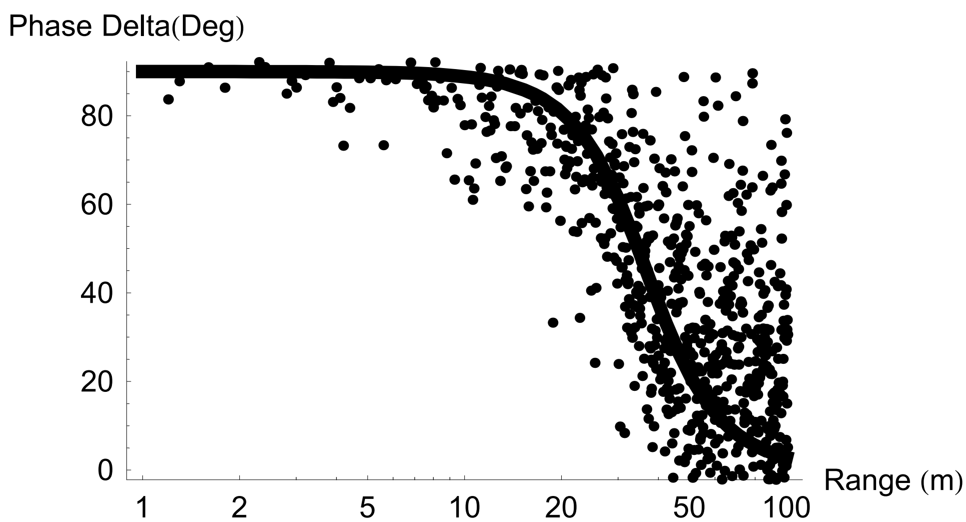
■ Plots:

■ Phase Plot

In[44]:= LogLinearListPlot[Table[{d, $\left(\varphi E + \text{Random}\left[\text{NormalDistribution}\left[0, \frac{180}{\pi}\,\varphi RMS\right]\right]\right) - \left(\varphi H + \text{Random}\left[\text{NormalDistribution}\left[0, \frac{180}{\pi}\,\varphi RMS\right]\right]\right)$}, {d, 1, 101, .1}],

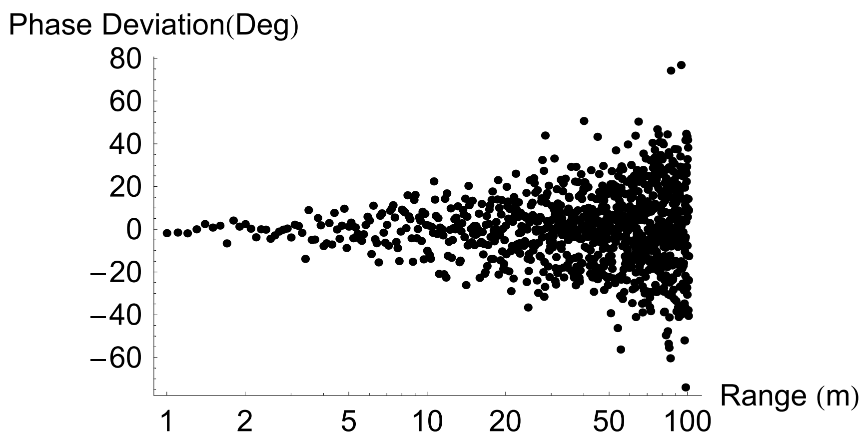
```
PlotStyle → PointSize[0.015],
TextStyle → {FontFamily -> "Helvetica",
  FontSize → 14},
AxesLabel → {"Range (m)", "Phase Deviation(Deg)"}]
```

```
In[48]:= Show[{LogLinearPlot[φE - φH, {d, 1, 100},
    PlotStyle → Thickness[0.02], TextStyle → {FontFamily -> "Helvetica",
      FontSize → 14},
    AxesLabel → {"Range (m)", "Phase Delta(Deg)"}],
   LogLinearListPlot[Table[{d, (φE + Random[NormalDistribution[0, 180/π φRMS]])
       - (φH + Random[NormalDistribution[0, 180/π φRMS]])}, {d, 1, 101, .1}],
    PlotStyle → PointSize[0.015],
    TextStyle → {FontFamily -> "Helvetica",
      FontSize → 14},
    AxesLabel → {"Range (m)", "Phase Delta(Deg)"}]}]
```




```
Out[48]= - Graphics -
```

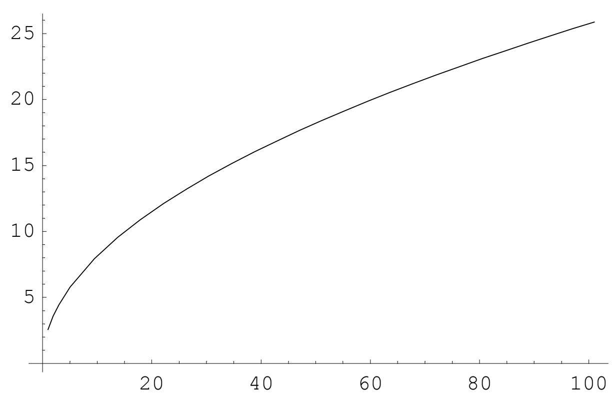
```
In[43]:= LogLinearListPlot[
    Table[{d, Random[NormalDistribution[0, 180/π φRMS]]}, {d, 1, 101, .1}],
    PlotStyle → PointSize[0.015],
    TextStyle → {FontFamily -> "Helvetica",
      FontSize → 14},
    AxesLabel → {"Range (m)", "Phase Deviation(Deg)"}]
```




```
Out[43]= - Graphics -
```

■ RMS Delay Plot

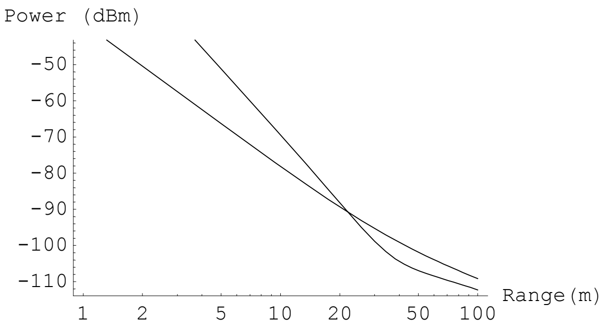
```
Plot[180/π φRMS, {d, 1, 101}]
```




```
- Graphics -
```

■ Power Plot

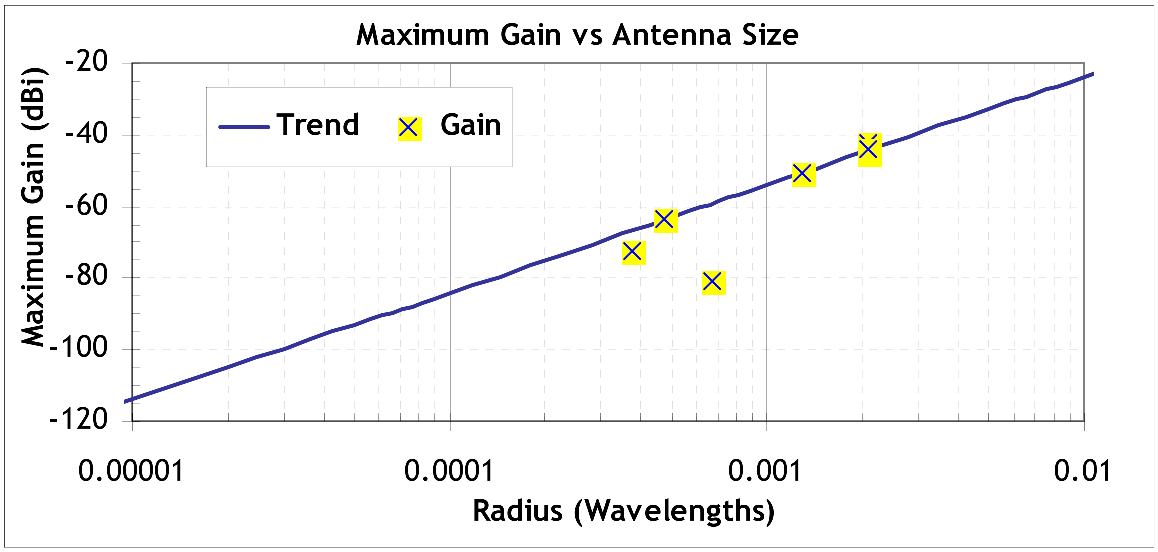
```
Show[{LogLinearPlot[10 Log[10, PrxE] + 30, {d, 1, 100}],
  LogLinearPlot[10 Log[10, PrxH] + 30, {d, 1, 100}]},
 AxesLabel → {"Range(m)", "Power (dBm)"}]
```



- Graphics -

Appendix 2: Additional Background on Antenna Size vs Performance:

This section presents some results from antennas constructed by the Q-Track Corporation. The figure below shows gain vs. size for Q-Track's antennas as well as a trend line.



Gain vs Size for Selected Electrically Small Antennas

For instance at the 1.3 MHz frequency used by Q-Track's prototype antenna, a typical receive antenna occupies a boundary sphere of radius 11 cm and has a gain of –63.6 dB. A typical transmit antenna is a thin wire whip occupying a boundary sphere of radius 30 cm and having a gain of –51 dB.