1. Intro. to UWB Comm. Systems

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1. Intro. to UWB Comm. Systems

- 1.1 UWB Comm.: Concepts & Advantages
- 1.2 UWB Pulse Modulation
- 1.3 UWB Pulse Detection
- 1.4 UWB Multiple-Access Techniques
- 1.5 UWB Channel Models
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1.1.1 Low duty cycle UWB pulses

- Very short pulses of ns duration and nwatt power
- Low average transmission power
- Longer battery life for handheld devices (UWB devices power requirements 1000 times lesser than mobile headsets)

Fig. 1.1.1 A low-duty-cycle (<0.5%) pulse
1.1 UWB Comm.: Concepts & Advantages

1.1.2 Ability to share spectrum

FCC UWB power requirement <-41.3 dBm/MHz  
(approx. 75nW/MHz) ➔ Below noise floor level for narrowband receivers

- Narrowband: FBW<1%
- Wideband: 1%<FBW<20%
- UWB: FBW>20%

FBW=(BW/f_c)*100%=200*(f_H-f_L)/(f_H+f_L)

f_H, f_L are 10-dB cut-off frequencies
1.1 UWB Comm.: Concepts & Advantages

FCC: slice available spectrum into slots for various applications
UWB huge spectrum 7.5 GHz (an overlay system)

![Frequency Spectrum Diagram]

-41 dBm/MHz

Fig. 1.1.2 Coexistence of UWB signals with narrowband and wideband signals
1.1 UWB Comm.: Concepts & Advantages

1.1.3 Large channel capacity

- Channel capacity: max data that can be transmitted per sec over a comm channel
- Hartley Shannon’s capacity formula
  \[ C = B \log_2 (1+SNR) \]
  (What is C? max. zero-free or reliable comm.)
where C is the max channel capacity, B is bandwidth, SNR is signal-to-noise power ratio
  C increases linearly with B
FCC allocation UWB 3.1-10.6 GHz \( \rightarrow \) Gbps data rate easily achievable
1.1.4 Future wireless communications: wire free

- Imagine your computer and HDTV connections without any wire transferring data at the same or higher data rate
- UWB make this possible
- UWB device low power emission ⇒ harmless
1.1 UWB Comm.: Concepts & Advantages

- UWB systems for short-range, high-data rate wireless communications (WPANs) up to 10 m

Fig. 1.1.3 Future Wireless Communications [1]
1.1 UWB Comm.: Concepts & Advantages

Fig. 1.1.4 Model of a single-link communication system

Major blocks for communication: transmitter, channel, and receiver
1.1 UWB Comm.: Concepts & Advantages

Fig. 1.1.5 Block diagram of a typical (a) narrowband and (b) UWB transmitter
1.1 UWB Comm.: Concepts & Advantages

Fig. 1.1.6 Block diagram of a typical (a) narrowband and (b) UWB receiver
1.1 UWB Comm.: Concepts & Advantages

1.1.5 Simplified UWB transceivers

- Transmission of low-powered pulses ➔ No need for power amplifier (PA)
- Carrierless transmission ➔ No need for mixers & local oscillators, carrier recovery at the receiver
- Less analog front-ends, possible to make an all complementary metal-oxide semiconductor (C-MOS) transceiver
1.1 UWB Comm.: Concepts & Advantages

1.1.6 Single band and multiband: two contending technologies for WPAN

- Single Band (IR or DS-UWB or Zero-carrier radio technology)
- Multiband (OFDM based)

IEEE 802.15.3a WPANs
1.1 UWB Comm.: Concepts & Advantages

- Single band/impulse radio (Send information using a single narrow pulse, occupy the whole UWB spectrum in the freq. domain)
- Supported by Motorola, XtremeSpectrum
- Multiband approach divides the UWB spectrum (3.1-10.6GHz) into smaller, non-overlapping sub-bands whose BW>500MHz
- Supported by Staccato Communications, Intel, Texas Instruments, General Atomics, and Time Domain Corporation
Fig. 1.1.7 A Gaussian doublet (2\textsuperscript{nd} derivative of Gaussian pulse) in time domain
1.1 UWB Comm.: Concepts & Advantages

Fig. 1.1.8 A Gaussian doublet in freq domain
(Dispersion: major disadvantage)
Fig. 1.1.9 The multiband approach divides the available UWB spectrum into several non-overlapping smaller bands [2]
1.1 UWB Comm.: Concepts & Advantages

1.1.5 FCC emission limits:
Different Emission Limits for different applications
1.1 UWB Comm.: Concepts & Advantages

Fig. 1.1.10 UWB emission limits for indoor communications systems
### 1.1 UWB Comm.: Concepts & Advantages

Table 1.1.1 Emission Limits for UWB communication devices in each operational band

<table>
<thead>
<tr>
<th>Applications</th>
<th>0.96-1.61 (GHz)</th>
<th>1.61-1.99 (GHz)</th>
<th>1.99-3.1 (GHz)</th>
<th>3.1-10.6 (GHz)</th>
<th>10.6-29.0 (GHz)</th>
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</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>75.3 (dBm/MHz)</td>
<td>53.3 (dBm/MHz)</td>
<td>51.3 (dBm/MHz)</td>
<td>41.3 (dBm/MHz)</td>
<td>51.3 (dBm/MHz)</td>
</tr>
<tr>
<td>Outdoor</td>
<td>75.3 (dBm/MHz)</td>
<td><strong>63.3</strong> (dBm/MHz)</td>
<td><strong>61.3</strong> (dBm/MHz)</td>
<td>41.3 (dBm/MHz)</td>
<td><strong>61.3</strong> (dBm/MHz)</td>
</tr>
</tbody>
</table>

GPS Band
1.2 UWB Pulse Modulation

- UWB pulse modulation [3]-[4]: baseband modulation \( \rightarrow \) information modulated into amplitudes, phases, or positions of pulses

  - Pulse-amplitude modulation (PAM),
  - On-off keying (OOK),
  - Phase shift keying (PSK),
  - Pulse-position modulation (PPM)
1.2 UWB Pulse Modulation

Fig. 1.2.1 Some UWB Pulses $p(t)$
(a) Square
(b) Gaussian
(c) Monocycle
(d) Doublets
1.2 UWB Pulse Modulation

1.2.1 PAM

- Information conveyed in the amplitudes of pulses
- M-ary PAM signal: sequence of modulated pulses with M different amplitude levels

\[
s(t) = \sum_{k=-\infty}^{\infty} a_m(k) p(t - kT_f)
\]

\(a_m(k)\) amplitude of the \(k^{th}\) pulse, depends on the M-ary information symbol \(m \in \{0, 1, \ldots, M-1\}\).

\(T_f\) frame interval also known as pulse repetition time
1.2 UWB Pulse Modulation

Fig. 1.2.2 2-ary PAM Signals

Higher amplitude pulse $\rightarrow 1$

Lower amplitude pulse $\rightarrow 0$
1.2 UWB Pulse Modulation

- PAM signal, simple to generate, vulnerable to channel noise, may cause false detection
- Pulse transmitted periodic, discrete lines on the PSD of UWB signals (see Fig. 1.2.3)
- Discrete spectral lines interfere to systems sharing a frequency spectrum
- Overcomed by using spectrum-whitening or time dithering techniques
1.2 UWB Pulse Modulation

Fig. 1.2.3 PSD of UWB PAM Signals [2]
1.2 UWB Pulse Modulation

Fig. 1.2.4 PSD UWB PAM Signals after time dithering [2]
1.2 UWB Pulse Modulation

1.1.2 OOK

- Special case of PAM $m \in \{0,1\}$; pulse amplitude $a_m(k) = m(k)$
- Simplest to implement, poor performance, noise & interference cause false detection

$$s(t) = \sum_{k=-\infty}^{\infty} m(k) p(t - kT_f)$$
1.2 UWB Pulse Modulation

Fig. 1.2.5 OOK Signals

Pulse transmitted for information bit is 1
Absent for information bit 0
1.2 UWB Pulse Modulation

- Simple RF Switch (OOK)
- Synchronization major issue for streams of zero transmission
- Multipath, echoes of original or other pulses, difficult to determine absence of pulse
1.2 UWB Pulse Modulation

1.2.3 PSK

- Binary PSK or biphase modulation, binary data carried in the polarity of the pulses
- Pulse with positive polarity $\rightarrow$ information bit 1 \( \{d(k)=1\} \), Pulse with negative polarity $\rightarrow$ information bit 0 \( \{d(k)=0\} \)
- Better performance than OOK: twice pulse amplitude level difference

\[
s(t) = \sum_{k=-\infty}^{\infty} d(k) p(t - kT_f)
\]
1.2 UWB Pulse Modulation

- Fewer discrete lines on the PSD, change of polarity of pulses $\rightarrow$ zero mean
- Implementation more difficult: requires one transmitter for positive pulses, another for negative pulses

![BPSK Signals](image)

Fig. 1.2.6 BPSK Signals
1.2 UWB Pulse Modulation

1.2.4 PPM

- Popular UWB comm. systems modulation technique
- Information carried in the fine time shift of pulse
- Less sensitive to noise than PAM or PSK signals
- Pseudorandom code sequence of pulse positions
  → reduce discrete lines in the PSD
1.2 UWB Pulse Modulation

$$s(t) = \sum_{k=-\infty}^{\infty} p(t - kT_f - m(k)T_d)$$

$m(k) \in \{0, 1, \ldots, M-1\}$ the $k$th M-ary symbol, $T_d$ modulation delay, provides time shift to represent each M-ary symbol.

2-ary PPM shown in Fig. 1.2.7

Vulnerable to random collisions caused by multiple-access channels, timing synchronization issues
1.2 UWB Pulse Modulation

Fig. 1.2.7 2-ary PPM Signals
1.3 UWB Pulse-detection

- Pulse-detection techniques: Energy detectors (ED) and Classical matched filters (CMF)
- Most UWB receivers use for data demodulation

1.3.1 Energy Detectors

- Energy detectors: simple, non-coherent receivers detect the energy of a signal, compare with threshold level to demodulate data bits
1.3 UWB Pulse-detection

- ED: squaring device, finite integrator and decision threshold comparator (Fig. 1.3.1)
- Energy above threshold $\rightarrow$ data demodulated 1
- Data not present or energy below the threshold $\rightarrow$ received data demodulated 0
1.3 UWB Pulse-detection

1.3.1 Energy detector receiver
1.3 UWB Pulse-detection

3.2.2 Classical Matched Filters

- CMF: simple, optimal method for detecting signal in random noise (correlation process)

- Correlation: mathematical operation, provides measure of similarity between two signals

- Multiply the two waveforms at different points in time, find the area under the curve formed by multiplication using integration in finite time
1.3 UWB Pulse-detection

\[ R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t) y(t - \tau) \, dt \]

- Two signals compared \( x(t) \) and \( y(t) \), \( \tau \) the time shift to provide sliding of \( y(t) \) on \( x(t) \), \( R_{xy}(\tau) \) the correlation function

- Large value of correlation function (negative or positive) \( \Rightarrow \) strong resemblance between the two waveforms

- Small value close to zero \( \Rightarrow \) low correlation or slight similarity between the two waveforms
1.3 UWB Pulse-detection

- CMF: received signal correlated with template signal matched to the transmitted signal
- Received signal similar to the template $\rightarrow$ high correlation values and signal can be detected
- CMF (Fig. 1.3.2): correlation on the received signal $r(t)$ (transmitted signal $s(t)h(t) +$ channel noise $w(t)$)
- Correlation: multiply the received signal with a predefined template (similar to the transmitted signal $s(t)$), integrate over a finite period of time
- Maximize the received signal’s SNR, detects the desired signal from the background random noise
1.3 UWB Pulse-detection

1.3.2 Classical matched filter (For simpler analysis, neglect channel effect on the received signal, UWB channels will be discussed in section 1.5)

\[ r(t) = s(t) * h(t) + w(t) \]
1.3 UWB Pulse-detection

\[ r(t) = s(t) + w(t); \hat{s} = \int_0^T [s(t) + w(t)] \cdot s(t) \, dt \]
\[ \hat{s} = \int_0^T s^2(t) \, dt + \int_0^T w(t) \cdot s(t) \, dt = E_p + 0 \]

- Integral produces two terms
- First term: signal energy \( E_p \), correlation of the transmitted signal with the similar template signal
- Second term: correlation of the signal with noise, ignored due to poor correlation between the transmitted signal and the random noise
1.3 UWB Pulse-detection

Performance of CMF in a two-user scenario

\[ r(t) = s_1(t) + s_2(t) + n(t) \]

\[ \hat{s} = \int_{0}^{T} \left[ s_1(t) + s_2(t) + w(t) \right] \bullet s_1(t) dt \]

\[ \hat{s} = \int_{0}^{T} s_1^2(t) dt + \int_{0}^{T} s_1(t) \bullet s_2(t) dt + \int_{0}^{T} w(t) \bullet s_1(t) dt \]

\[ = E_p + MAI + 0 \]

Ignore correlation between the desired signal and random noise
Multiple access interference (MAI) can’t be disregarded: correlation between \( s_1(t) \) and \( s_2(t) \)
1.4 UWB Multiple Access Techniques

- UWB deliver large amounts of data with low PSD, useful for short-range, high-data-rate applications
- Require several transmitters in an area
- Require proper multiple-access techniques, proper channelization of multiple users
- Typical multiple-access communications: several users transmit information simultaneously, independently over a shared channel
1.4 UWB Multiple Access Techniques

Fig. 1.4.1 A typical multiple-access communication system
1.4 UWB Multiple Access Techniques

- Received signal, combination of desired signal, MAI and AWGN
  \[ r(t) = s(t) + MAI + w(t) \]
- Deteriorating effect of MAI severe in UWB systems (strict transmit power limitation)
- Two common multiple-access techniques:
  (a) Time-hopping (TH) UWB: theoretically sound, difficult practical implementations
  (b) Direct-sequence (DS) UWB: promising scheme for IR UWB
1.4 UWB Multiple Access Techniques

1.4.1 TH-UWB

- Divide frame interval into multiple smaller chip intervals, one segment carries the transmitted monocycle or doublets
- Unique TH code assigned to each user, specify which segment in each frame interval is used for transmission
- Fig. 1.4.2: Frame interval $T_f$ divided into $N_c$ segments of $T_c$ seconds where $N_cT_c < T_f$. 
Notation: TH sequence \{c(k)\}, 0 \leq c(k) \leq N_c - 1.

Provides additional time shift of \(c(k)T_c\) seconds to the \(k^{th}\) monocyle or doublet, allow multiple access without catastrophic collisions

Pulse train with TH sequence \(c(k) = \{1,0,3,\ldots\}\) (Fig. 1.4.2)

\[
s(t) = \sum_{k=-\infty}^{\infty} p(t - kT_f - c(k)T_c)
\]
1.4 UWB Multiple Access Techniques

Fig. 1.4.2 Pulse train with TH sequence \( \{1,0,3, \ldots \} \)
1.4 UWB Multiple Access Techniques

- Synchronized network: orthogonal TH sequence satisfies $c^u(k) \neq c^{u'}(k)$ for all k’s and for any two users $u \neq u'$ adopted to minimize interference between the users.

- Asynchronous system: orthogonal TH sequence do not guarantee collision free transmission.

- TH technique used PAM, PSK or PPM
1.4 UWB Multiple Access Techniques

Fig. 1.4.3 TH-UWB Signal with PAM Modulation

\[ s(t) = \sum_{k=\infty}^{\infty} a_m(k) p(t - kT_f - c(k)T_c) \]
1.4 UWB Multiple Access Techniques

Fig. 1.4.4 TH-UWB Signal with PSK Modulation

\[ s(t) = \sum_{k=-\infty}^{\infty} d(k) p(t - kT_f - c(k)T_c) \]
1.4 UWB Multiple Access Techniques

$$s(t) = \sum_{k=-\infty}^{\infty} p(t - kT_f - c(k)T_c - m(k)T_d)$$

Fig. 1.4.5 TH-UWB Signal with PPM Modulation
1.4 UWB Multiple Access Techniques

1.4.2 DS-UWB

- DS-UWB employs a train of high-duty-cycle pulses whose polarities follow pseudo-random code sequences.
- Specifically, each user in the system is assigned a pseudo-random sequence that controls pseudorandom inversions of the UWB pulse train.
1.4 UWB Multiple Access Techniques

In a DS-UWB with BPSK modulation, the binary symbol $d(k)$ to be transmitted over a $k^{th}$ frame interval is spread by a sequence of multiple monocycles or doublets

\[
\left\{ c(n_c) p(t - kT_f - n_c T_c) \right\}_{n_c=0}^{N_c-1}
\]

whose polarities are determined by the spreading sequence

\[
\left\{ c(n_c) \right\}_{n_c=0}^{N_c-1}
\]
1.4 UWB Multiple Access Techniques

- A different spreading code is assigned to each user.
- Similar to TH-UWB, an orthogonal spreading sequence may be used to mitigate MAI in a synchronous network.

\[
x(t) = \frac{1}{\sqrt{N_c}} \sum_{k=-\infty}^{\infty} d(k) \sum_{n_c=0}^{N_c-1} c(n_c) p(t - kT_f - n_cT_c)
\]

A pulse has positive polarity if the information bit is 1 \{d(k)=1\}, whereas it has negative polarity if the information bit is 0 \{d(k)=0\}.
1.4 UWB Multiple Access Techniques

Sequence of data \[ \sum_{k=-\infty}^{+\infty} b_m(k) \]

Pulse train with a pseudo-random code

\[ \frac{1}{\sqrt{N_c}} \sum_{n_c=0}^{N_c-1} c(n_c) p(t-n_c T_c) \]

Fig. 1.4.6 DS-UWB Signal with BPSK Modulation [5]
1.4 UWB Multiple Access Techniques

\[
\frac{1}{\sqrt{N_c}} \sum_{k = -\infty}^{+\infty} b_m(k) \sum_{n_c = 0}^{N_c - 1} c(n_c) p(t - kT_f - n_c T_c)
\]

Fig. 1.4.7 DS-UWB Signal with BPSK Modulation
1.5 UWB Channel Models

Fig. 1.5.1 Block diagram of a UWB comm. system
1.5 UWB Channel models

- UWB systems: ultra-large BW of UWB signals
  - increased ability of the receiver to resolve the multipath components
- Multipath components resolved on very fine time duration
  - time of arrival of the multipath components not continuous.
- Empty delay bins (bins containing no energy) between the arriving multipath components
- UWB systems channel measurements: multipath arrivals in clusters not in continuum unlike NB channels
- Rayleigh fading may not perfectly match the amplitude of the signal received
1.5 UWB Channel models

- Very fine resolution of UWB waveforms \( \rightarrow \) different objects/walls in room \( \rightarrow \) different clusters of multipath components
- Reliable UWB channel model: captures such important characteristics of UWB channel, required for critical analysis, design of UWB systems
- IEEE 802.15.3a standards task group’s subgroup establishing common UWB channel model
1.5 UWB Channel models

- Three main indoor channel models considered in the standard:

1.5.1 Tap-Delay-Line Fading Model

- Simple model for characterization of UWB channel
- Channel impulse response (CIR) expressed as

\[ h(t) = \sum_{l=0}^{L-1} \alpha(l) \delta(t - \tau_l) \]

\(\alpha(l)\) multipath gain coefficient of the \(l^{th}\) path, \(L\) number of resolvable multipath components, \(\tau(l)\) path delay of the \(l^{th}\) path
1.5 UWB Channel models

- NB systems: amplitude of the $l^{th}$ path $|\alpha(l)|$ is modeled Rayleigh r.v. with pdf

$$f_{|\alpha(l)|}(x) = \frac{x}{\Omega_l} e^{-\frac{x^2}{\Omega_l}}$$

$$\Omega_l = E[|\alpha(l)|^2] \text{ average energy of } l^{th} \text{ path}$$

- UWB systems: number of components falling within each delay bin much smaller $\Rightarrow$ change in statistics
1.5 UWB Channel models

1. Lognormal distribution

$$f_{|\alpha(t)|}(x) = \frac{20}{(\ln 10)x\sqrt{2\pi \Omega_l}} \cdot e^{-\frac{\left(10\log_{10}(x^2)-\mu_l\right)^2}{2\Omega_l}}$$

- Advantageous that the fading statistics, same form for small-scale and large-scale.
- Superposition of two lognormal distributions approximated by a log normal distribution
1.5 UWB Channel models

- Drawback it is difficult to use for analysis of MIMO systems
- M. Z. Win suggested that amplitude of a multipath coefficient can be modeled by *Nakagami-m distribution*
- Turin (1972) and Suzuki (1977) have also shown that the Nakagami-m distribution provides the best fit for data signals received in urban radio multipath environments

\[
f(x) = \begin{cases} 
\frac{2}{\Gamma(m)} \left( \frac{m}{\Omega} \right)^m x^{2m-1} e^{-\frac{mx^2}{\Omega}} & , \quad x > 0 \\
0, & \text{otherwise}
\end{cases}
\]

*where* \( \Omega = E[X^2] \), \( m = \frac{\Omega^2}{E[(X^2 - \Omega)]} \), \( m \geq \frac{1}{2} \)
1.5 UWB Channel Models

- Nakagami-$m$ is a two parameter distribution, involving the fading figure $m$ and the mean square value $\Omega$.
- The smaller the $m$, the more severe the fading, with $m=1$ and $m=\infty$ corresponding to Rayleigh fading and non-fading channels respectively.
- To capture the clustering property, an approach that models multipath arrival times using a statistically random process based on Poisson process has been considered.
- Specifically, the multipath arrival times $\tau_i$ can be characterized by a Poisson process with constant arrival rate $\lambda$. 
In other words, the inter-arrival time is exponentially distributed, i.e., given a certain arrival time for the previous time $\tau_{l-1}$, the PDF for the arrival of path $l$ can be written as

$$P_r(\tau_l - \tau_{l-1} > t) = e^{-\lambda t}$$

$$\Rightarrow f_{\tau_l}(\tau_l | \tau_{l-1}) = \lambda e^{-\lambda(\tau_l - \tau_{l-1})}, l > 0$$

Two mathematical models that reflect this clustering are the $\Delta$–K model and the Saleh-Valenzuela (SV) model.
1.5 UWB Channel models

1.5.2 Δ-K model (Modified Poisson Distribution)

- This model defines two states: state A, where the arrival rate of paths is $\lambda$, and state B, where the rate is $K\lambda$.
- The process starts with a pure Poisson with parameter $\lambda$, state A.
- If a path exists at time $t$ then the process will switch to another Poisson process with parameter $K\lambda$, state B.
- If no path arrives during the time interval $[t,t+\Delta]$, the model reverts back to state A at the end of the interval; otherwise it remains in state B.
1.5 UWB Channel models

- This model is described by a series of transitions between two states A and B.
- With $K=1$ and $\Delta=0$ this process is the standard Poisson process.
- This model takes into account the clustering properties of multipath components and was first suggested by G. L. Turin and was successfully used in analysis and simulation of mobile and indoor propagation channels.
1.5 UWB Channel models

Mean-arrival time

Fig. 4.10 Δ-K or modified Poisson Process
1.5 UWB Channel models

1.5.3 Saleh-Valenzula Model or Double Poisson Distribution [3]

- Another method to characterize the arrival times in UWB channels is the double Poisson process, first proposed by Saleh and Valenzula (SV) for indoor channels.
- According to this model, multipath arrivals occur in clusters and the rate of arrival of clusters is \( \Lambda \).
- Within each clusters, rays (multipath) arrive according to Poisson process with \( \lambda \).
1.5 UWB Channel models

- When arrival process is Poisson, inter-arrival times are exponentially distributed
- If $T_c$ denotes the arrival time of the $c^{th}$ cluster and $\tau_{c,l}$ is the delay of $l^{th}$ ray or path arrival in the $c^{th}$ cluster relative to the cluster arrival time, then

\[
 f_{T_c}(T_c \mid T_{c-1}) = \Lambda e^{-\Lambda(T_c - T_{c-1})}, c > 0 \\
 f_{\tau_{c,l}}(\tau_{c,l} \mid \tau_{c,l-1}) = \lambda e^{-\lambda(\tau_{c,l} - \tau_{c,l-1})}, l > 0
\]
1.5 UWB Channel model

Accordingly, impulse response of SV model becomes

$$h(t) = \sum_{c=0}^{C} \sum_{l=0}^{L} \alpha_{c,l} \exp(j\phi_{c,l}) \delta(t - T_c - \tau_{c,l})$$

- Arrival time of the $c^{th}$ cluster
- Delay of the $l^{th}$ ray in the $c^{th}$ cluster
- Tap weight of the $l^{th}$ multipath component of the $c^{th}$ cluster

The path amplitude $\alpha_{c,l}$ follows Rayleigh distribution and phase $\phi_{c,l}$ is uniformly distributed over $[0,2\pi)$
1.5 UWB Channel model

Two Poisson model:
- Clusters
- Paths within each cluster

Several power delay profile:
- For clusters
- Paths within each cluster

Fig. 4.10 S-V model
where \( \alpha_{cl} \) and \( \varphi_{cl} \) denotes the amplitude and phase of the \( l^{th} \) multipath component in the \( c^{th} \) cluster, \( C \) is the total number of clusters, \( L \) is the total number of rays within each cluster.

With this model, power delay profile can be expressed by two negative exponential functions as

\[
P_{c,l} = P_{0,0} e^{\frac{T_c}{\Gamma}} e^{-\frac{\tau_{c,l}}{\gamma}}
\]
1.5 UWB Channel models

- $P_{0,0}$ is the received power at delay 0 of the 0\textsuperscript{th} cluster
- The parameter $\Gamma, \gamma$ are the cluster and ray time decay constants (TDC) of the power delay profiles
- The four main parameters: the cluster arrival time ($T_c$), the ray arrival delay within cluster ($\tau_{c,l}$), the cluster decay factor ($\Gamma$) and the ray decay factor ($\gamma$) can be changed for various environments which provide great flexibility to model different environments
### 1.5 UWB Channel models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UWB (Win model)</th>
<th>UWB (Intel model)</th>
<th>Wideband (S-V model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC of clusters ($T$ in ns)</td>
<td>27.9</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>TDC within clusters ($\gamma$ in ns)</td>
<td>84.1</td>
<td>1.6</td>
<td>28.6</td>
</tr>
<tr>
<td>Cluster arrival rate ($\Lambda$ in 1/ns)</td>
<td>1/45.5</td>
<td>1/60</td>
<td>1/300</td>
</tr>
<tr>
<td>Intra-cluster arrival rate ($\lambda$ in 1/ns)</td>
<td>1/2.3</td>
<td>1/0.5</td>
<td>1/5</td>
</tr>
</tbody>
</table>

Table 4.1 Double exponential model of UWB and conventional wideband systems
1.5 UWB Channel models

1.5.4 IEEE UWB channel model

- The path loss, shadowing and small-scale fading models of the standard UWB channel are given below:

- **Path loss**: The path loss specified is free-space path loss, with the center frequency $f_c$ given $f_c = \sqrt{f_L f_H}$, where $f_L$ and $f_H$ are obtained at the -10dB edges of the waveform spectrum.

- **Shadowing**: The shadowing is assumed lognormally distributed with standard deviation of 3 dB, i.e.,
1.5 UWB Channel models

- The shadowing is $X_\sigma (\text{dB}) \sim \mathcal{N}(0, \sigma^2)$ with a $\sigma$ value of 3dB
- Small-scale fading: The small scale fading model is based on S-V model
- Although the path amplitude $\alpha_{c,l}$ may follow lognormal distribution, the Nakagami distribution (Win, 2002), or the Rayleigh distribution (Cramer, 2002), the lognormal distribution is employed in the standard with mean $\mu_{c,l}$ and variance $(\sigma_1)^2 + (\sigma_2)^2$
- IEEE 802.15.3a proposed by TG3 in July 2003
1.5 UWB Channel models

Shadowing

\[ h(t) = X_\sigma \sum_{c=0}^{C} \sum_{l=0}^{L} \alpha_{c,l} \exp(j\phi_{c,l}) \delta(t - T_c - \tau_{c,l}) \]

\[ = X_\sigma \sum_{c=0}^{C} \sum_{l=0}^{L} \text{sgn}_{c,l} \zeta_{c,l} \beta_{c,l} \exp(j\phi_{c,l}) \delta(t - T_c - \tau_{c,l}) \]

Sign (accounts for signal inversion) \( l \)th ray of \( c \)th cluster fading

\[ E\{|\alpha_{c,l}|^2\} = E\{|\zeta_{c,l} \beta_{c,l}|^2\} = P_{0,0} e^{\frac{T_c}{\Gamma}} e^{\frac{-\tau_{c,l}}{\gamma}} \]

Cluster arrival time \((T_c)\), the ray arrival delay within cluster \((\tau_{c,l})\), the cluster time decay constant \((\Gamma)\) and the ray time decay constant \((\gamma)\)
1.5 UWB Channel models

\[ \mu_{c,l} = \frac{10 \ln P_{0,0} - 10T_c}{\Gamma} - \frac{10 \tau_{c,l}}{\gamma} - \frac{\ln 10}{20} \left( \sigma_1^2 + \sigma_2^2 \right), \sigma_1 = \sigma_2 = 3.3941dB \]

Inter arrival times of clusters (\( \Lambda \)) and (\( \lambda \)) rays

\[ f_{T_c}(T_c | T_{c-1}) = \Lambda e^{-\Lambda(T_c - T_{c-1})}, c > 0; f_{\tau_{c,l}}(\tau_{c,l} | \tau_{c,l-1}) = \lambda e^{-\lambda(\tau_{c,l} - \tau_{c,l-1})}, l > 0 \]

\( T_c \) denotes the arrival time of the \( c^{th} \) cluster and \( \tau_{c,l} \) is the delay of \( l^{th} \) ray or path arrival in the \( c^{th} \) cluster relative to the cluster arrival time
1.5 UWB Channel models

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<td>γ(ns)</td>
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<td>6.7</td>
<td>7.9</td>
<td>12</td>
</tr>
</tbody>
</table>
1.6 UWB Interference

- Two important aspects of interference: (1) the interference caused by the NB and WB systems on the victim UWB system and (2) the interference caused by UWB systems on the victim NB and WB systems

- Both interferences are important and should be considered in the design, evaluation and implementation of the systems
1.6 UWB Interference

Fig. 1.6.1 UWB Spectrum and Other Wireless Services
In Fig. 1.6.2, the spectrum of UWB systems with other wireless systems are shown.

As seen from this figure, several other services exist in or in the neighborhood of the UWB band.

For example, IEEE 802.11-a which works at 5.2 GHz is a main source of interference to indoor UWB communication systems.

Other systems such as 2.4 GHz band WLANs as well as GPS system at 1.5 GHz, mobile cellular system at 800 MHz and 1800 MHz are also source of interference to UWB systems.
1.6 UWB Interference

1.6.1 IEEE 802-11.a interference (UWB victim)

- To understand the effect of wideband interference on the UWB system, as example, an IEEE 802-11.a interference source stationed at 5.25 GHz with a BW of 200 MHz is considered.
- The interference set up is shown in Fig. 1.6.2
- The channel is assumed to be AWGN
- To gauge the propagation loss and the effect of interference, Friis transmission formula in free space is used:
1.6 UWB Interference

\[
\frac{P_{\text{desired}}}{P_{\text{interference}}} = \frac{P_t}{P_{t_i}} \left( \frac{\lambda_{\text{UWB}}}{r_U} \right)^2 \left( \frac{\lambda_i}{r_i} \right)^2
\]

where, \( P_{\text{desired}} / P_{\text{interference}} \) gives the ratio of the desired signal power to the interference power based on FCC emission limit

\( P_{t_i} \) is the transmission power of the interferer (IEEE 802.11a) available from the specifications of these systems

The UWB \( \lambda_{\text{UWB}} \) wavelength is obtained from the geometrical mean between the highest and lowest freq and \( \lambda_i \) is the interferer wavelength calculated from the center freq of the interferer
1.6 UWB Interference

Fig. 1.6.2 Block diagram of the UWB system with IEEE 802.11-a interferer
Parameters $r_u$ and $r_i$ are the distances between UWB transmitter to UWB receiver and interferer to UWB receiver, respectively.

The above equation can be rewritten as

\[
\frac{r_i}{r_U} = \sqrt{\frac{P_{desired}}{P_{interf.}} \frac{P_{t_i}}{P_{t_{UWB}}} \frac{\lambda_i}{\lambda_{UWB}}}
\]
1.6 UWB Interference

- Using the expression for $P_{\text{desired}}/P_{\text{interf.}} = 0\text{dB}$, $P_{tUWB} = 1\text{mW}$, $P_{t_i} = 100\text{mW}$ and $r_U = 1\text{m}$, the value of $r_i$ is obtained as 10m.

- If $P_{\text{desired}}/P_{\text{interf.}} = 10\text{dB}$, then the interferer distance $r_i$ is obtained as 30m.

- Which means that if 10 times larger power is desired at the UWB receiver side, assuming the same interferer power, the distance between the interferer and UWB receiver should be 3 times larger.
1.6 UWB Interference

1.6.2 General method of Signal to Interference Ratio Calculation:

- In the previous section, a simple case of only one interferer was considered
- Moreover, the propagation channel considered was a simplistic free space loss model
- In the actual case, the situation is much more complex
- More interferer may be present and interfering with the UWB signal
1.6 UWB Interference

- The channel between each transmit and receive point may be more complex as well.
- A block diagram of a general interference scenario is shown in Fig. 1.6.3.
- As seen from the figure a UWB communication link is between the UWB transmitter and receiver.
- A general transmitter and receiver pair is in the neighborhood of the UWB system.
1.6 UWB Interference

Fig. 1.6.3 A block diagram of a general interference scenario
1.6 UWB Interference

Fig. 1.6.4 Interference on IEEE 802.11a WLAN receiver system [6]
1.6 UWB Interference

- **Interference by single UWB transmitter**
- Consider a single UWB interferer for IEEE 802.11a downlink
- Quasi free space propagation model is assumed
- The interference power is calculated by assuming an UWB interfering source at different distance from the WLAN transmitter
- **Breakpoint model:** For distances $d<d_0$ (breakpoint distance in the far-field of the antenna), the power is proportional to $d^{-2}$ and beyond that point, the power is proportional to $d^{-n}$, where $n$ typically lies between 3.5 and 4.5 $P_{RX}(d) = P_{RX}(d_0) (d/d_0)^{-n}$ for $d>d_0$
1.6 UWB Interference

- Assuming $d^{-4}$ power law for PL model (a direct wave and a ground reflected wave), the interference power generated by a UWB interferer, $P(d)$, is given by:

$$P(d) = P_{UWB} \left( \frac{\lambda}{4\pi d} \right)^2 \left( \frac{d_0}{d_0 + d} \right)$$

- $P_{UWB}$ is the UWB EIRP in dBm
- $\lambda$ is the wave length
- $d_0$ is the breakpoint distance ($d_0 = 12h_T h_R / \lambda$)
- $d$ is the distance between UWB transmitter and WLAN receiver
1.6 UWB Interference

- **Multiple UWB interference scenario**
- We assume that the victim receiver is located in a 3-D room around which the multiple UWB interferer exists.
- This 3-dimensional scenario is depicted as shown in below figure.
- The receiver is located at the centre of two concentric spheres of radius $r_{\text{min}}$ and $r_{\text{max}}$.
- $r_{\text{min}}$ is the minimum radius of the sphere within which there are no UWB transmitters.
1.6 UWB Interference

Fig. 1.6.5 3-D hemispherical distribution of UWB devices around the victim NB system [7]
1.6 UWB Interference

- Uniform distribution of the UWB devices between the two concentric spheres is assumed with $N$ total number of UWB transmitters.
- The corresponding probability density function of the UWB transmitters as a function of the radius $r$ is:

$$\text{pdf} (r) = \begin{cases} 
0, & r < r_{\text{min}} \text{ and } r > r_{\text{max}} \\
\frac{3r^2}{r_{\text{max}}^3 - r_{\text{min}}^3}, & r_{\text{min}} < r < r_{\text{max}}
\end{cases}$$
1.6 UWB Interference

- The mean interference level is obtained by summing up the mean received power from all the interfering UWB transmitters, i.e., given by equation:

\[ E\{P\} = P_R = N \int_{r=r_{\text{min}}}^{r=r_{\text{max}}} P(r) \frac{3r^2}{r_{\text{max}}^3 - r_{\text{min}}^3} \, dr \]

where \( P(r) \) is the received signal power of one UWB transmitter at the victim receiver as a function of the distance between them.
1.6 UWB Interference

- The total interference received by the victim is obtained as:

\[
P_R(r) = 2\pi \rho \cdot P_{UWB} \cdot \left(\frac{\lambda}{4\pi}\right)^2 \int_{r=r_{\min}}^{r_{\max}} \frac{d_0^2}{(d_0 + r)^2} dr
\]

\[
\rho = \frac{N}{2\pi \left(\frac{r_{\max}^3 - r_{\min}^3}{3}\right)}
\]

is density of UWB transmitters per unit volume
1.6 UWB Interference

To accommodate all the UWB interferers,

\[ I_{\text{UWB}} = P_R(r) \bigg|_{r_{\text{max}} \to \infty} = 2\pi \rho P_{\text{UWB}} \left( \frac{\lambda}{4\pi} \right)^2 \left[ \frac{d_0^2}{r_{\text{min}} + d_0} \right] \]
1.6 UWB Interference

Fig. 1.6.6 Cumulative UWB interference at an IEEE 802.11a victim receiver with $d_0 = 1\text{m}$
1.6 UWB Interference

Now, considering the hemispherical distribution, the variation in the UWB interference power on the NB victim receiver system with the distance is shown in Figure 1.6.6 for various minimum separation distance between the victim receiver and the nearest UWB interferer.

It implies that as $r_{min}$ increases i.e, the distance between the WLAN receiver and the nearest UWB transmitter, the interfering power from UWB transmitters decreases.

$$SINR = \frac{Useful\,\,Received\,\,Power}{Interference\,\,+\,\,Noise\,\,Power}$$
1.6 UWB Interference

Fig. 1.6.7 Effect on the signal to noise ratio of WLAN system.
1.6 UWB Interference

- Considering the above described three dimensional cumulative UWB interference model, the effect of UWB interference on the SINR of the IEEE 802.11a WLAN system is depicted in Fig. 1.6.7.

- It can be observed that the SINR of the victim IEEE 802.11a WLAN system increases with the increase of the minimum distance between the WLAN receiver and the UWB transmitters.

- It is highest for the case when there are no UWB transmitters in the vicinity of NB victim receiver in accordance with our intuition.

- As the distance $r$ increases, SINR decreases for all the three cases plotted in figure 1.6.7.
1.6 UWB Interference

Fig. 1.6.8 Interference scenario of multiple UWB sources on a GPS receiver (crosses → UWB transmitters and black dot → GPS receiver victim) [2]
1.6 UWB Interference

\[ I_{UWB} = \int_{R_L}^{\infty} P_r \rho 2\pi r dr \]

- The total interference at the receiver from the UWB transmitters \( I_{UWB} \) can be calculated by evaluating the above integral.
- \( P_r \) is the received power from a UWB transmitter located at a distance \( r \) from the receiver.
- The distance from the receiver to the nearest UWB transmitter is \( R_L \), which can be expressed in terms of the average distance between the UWB transmitters \( R_0 \) by \( R_L = R_0 / \sqrt{2} \).
1.6 UWB Interference

- The received power can be approximated by
  \[ P_r = P_0 \left( \frac{r}{d_0} \right)^n \]

- where \( P_0 \) is the power received at a free space reference point \( d_0 \) in the far field region of the UWB transmitting antenna and \( n \) is the path loss coefficient.

- It is appropriate to assume a \( d_0 \) of 100m for urban macrocells.

- \( P_0 \) can be expressed as
  \[ P_0 = G_p B_{Rx} \lambda^2 / \{(4\pi)^2(d_0)^2\} \]

  where \( G_p \) is the UWB PSD, \( B_{Rx} \) is the victim receiver’s BW.
1.6 UWB Interference

\[ I_{UWB} = \int_{R_L}^{\infty} \frac{G_P B_{RX} \lambda^2 r^{-n} d_o^{n-2} \rho 2\pi r dr}{(4\pi)^2} \]

\[ = \frac{G_P B_{RX} \lambda^2 d_o^{n-2} \rho 2\pi}{(4\pi)^2} \int_{R_0/\sqrt{2}}^{\infty} r^{1-n} dr \]

\[ = \frac{G_P B_{RX} \lambda^2 d_o^{n-2} \rho 2\pi}{(4\pi)^2} \left[ \frac{r^{2-n}}{2-n} \right]_{R_0/\sqrt{2}}^{\infty} \]

For \( n > 2 \)

\[ I_{UWB} = \frac{G_P B_{RX} \lambda^2 d_o^{n-2} \rho \left( \frac{R_0}{\sqrt{2}} \right)^{2-n}}{(8\pi)(2-n)} \]
The average distance between UWB transmitters is related to the density of UWB transmitters by $R_0 = \frac{1}{\sqrt{\rho}}$.

Hence the interference power $I_{UWB}$ can be expressed as a function of the density of the UWB transmitters

$$I_{UWB} = \frac{G_P B_{RX} \lambda^2 d_o^{n-2} \sqrt{2^n} \sqrt{\rho^n}}{(16\pi)(2-n)}$$
1.6 UWB Interference

- For UWB transmitters distributed with density \( \rho \) such that \( \frac{R_0}{\sqrt{2}} \) is less than or equal to \( d_0 \), then free-space propagation can be assumed from the UWB transmitters within a distance of \( d_0 \) from the GPS receiver.

- The preceding condition can be written as \( \frac{R_0}{\sqrt{2}} \leq d_0 \) can be rewritten as \( \rho \geq \frac{1}{2(d_0)^2} \).

- When this condition is true.
1.6 UWB Interference

\[ I_{UWB} = \int_{\frac{R_0}{\sqrt{2}}}^{d_0} \frac{G_p B_{RX} \lambda^2 \rho 2\pi rdr}{(4\pi r)^2} + \int_{d_0}^{\infty} \frac{G_p B_{RX} \lambda^2 d_0^{n-2} r^{-n} \rho 2\pi rdr}{(4\pi)^2} \]

\[ = \frac{G_p B_{RX} \lambda^2 \rho}{(8\pi)} \left[ \ln \left( \frac{\sqrt{2}d_0}{R_0} \right) + d_0^{n-2} \int_{d_0}^{\infty} r^{1-n} dr \right] \]

\[ = \frac{G_p B_{RX} \lambda^2 \rho}{(8\pi)} \left[ \ln \left( \sqrt{2} \rho d_0 \right) + \frac{1}{(n-2)} \right] \]

\[ I_{UWB} = G_p B_{RX} F(\lambda, \rho, d_0, n); \]

\[ F(\lambda, \rho, d_0, n) = \begin{cases} \frac{\lambda^2 \rho}{(8\pi)} \left[ \ln \left( \sqrt{2} \rho d_0 \right) + \frac{1}{(n-2)} \right] & \text{for } \rho \geq \frac{1}{2d_0^2} \\ \frac{\lambda^2 d_0^{n-2} \sqrt{2^n \sqrt{\rho^n}}}{(16\pi)(2-n)} & \text{for } \rho < \frac{1}{2d_0^2} \end{cases} \]
1.6 UWB Interference

1.6.4 CDMA-based cellular systems

- In CDMA, the uplink is generally the limiting link in terms of capacity.
- Consider \( N \) mobiles communicating to a single isolated base station.
- Assuming perfect power control, the signal from each mobile is received at the base station at its target power, \( S \).
- Therefore, the interference from \( N-1 \) interfering mobile stations is \( I_{\text{CDMA}} = (N-1)S + N_0(W) \).
1.6 UWB Interference

- Now the interference due to the UWB transmitters can be introduced to modify $I_{\text{CDMA}}$ to

$$I_{\text{CDMA}} = (N-1)S + N_0(W) + I_{\text{UWB}}$$

- The SINR for a particular user arriving at the base station is

$$\text{SINR} = \frac{S}{I_{\text{CDMA}}} = \frac{S}{(N-1)S + N_0(W) + I_{\text{UWB}}}$$

- The total interference can be expressed as

$$J_0B_{Rx} = (N-1)S + N_0(W) + I_{\text{UWB}}$$

$$J_0 = \frac{1}{B_{Rx}} \times \{(N-1)S + N_0(W) + I_{\text{UWB}}\}$$

where $J_0$ is the combined PSD of the interference and receiver noise.
1.6 UWB Interference

- The power $S$ received from each mobile station is the product of the energy per bit $E_b$ and the transmission bit rate $R_b$

  $$S = E_b R_b; \frac{S}{R_b} = E_b$$

- Therefore, we can calculate $E_b/J_0$ as

  $$E_b/J_0 = \frac{G}{[(N-1) + \{N_0(W) + I_{UWB}/S\}/S]}$$

  where $G$ is the processing gain $B_{Rx}/R_b$

- This equation is based on the analysis of a single isolated cell
1.6 UWB Interference

- Factors such as imperfect power control, voice activity and inter-cell interference have not been considered in this analysis.

- The above equation can now be rearranged to calculate the target received power $S$ which we now denote as $S_{UWB}$.

- \[ S_{UWB} = \frac{(N_0(W) + I_{UWB})}{\left\{ \frac{G}{(E_b/J_0)} \right\} - (N-1)} \]

- A similar expression can be written for the target received power $S_{NO_{-UWB}}$, when the CDMA base station receives no interference from UWB transmitters.
1.6 UWB Interference

- \( S_{\text{NO\_UWB}} = \frac{N_0(W)}{\{G/(E_b/J_0)\} - (N-1)} \)

- The received powers \( S_{\text{UWB}} \) and \( S_{\text{NO\_UWB}} \) required to maintain a target \( E_b/J_0 \) can be calculated and the UWB interference that makes \( S_{\text{UWB}} \) greater than \( S_{\text{NO\_UWB}} \) by \( M \) dB can be evaluated.

- In this way the UWB PSD that increases the received power by a particular amount, \( M \) dB, can be identified:

\[
M = 10\log\left(\frac{S_{\text{UWB}}}{S_{\text{NO\_UWB}}}\right)
= 10\log\left\{\frac{N_0(W)}{N_0(W)} + \frac{I_{\text{UWB}}}{N_0(W)}\right\}
= 10\log\left[1 + \frac{I_{\text{UWB}}}{N_0(W)}\right]
\]
1.6 UWB Interference

\[ M = 10 \log \left( 1 + \frac{I_{UWB}}{N_0(W)} \right) \]

\[ I_{UWB} = G_p B_{RX} F(\lambda, \rho, d_0, n); \]

\[ F(\lambda, \rho, d_0, n) = \begin{cases} 
\frac{\lambda^2 \rho}{(8\pi)} \left[ \ln(\sqrt{2\rho d_0}) + \frac{1}{(n-2)} \right] & \text{for } \rho \geq \frac{1}{2d_0^2} \\
\frac{\lambda^2 d_o^{n-2} \sqrt{2^n \sqrt{\rho^n}}}{(16\pi)(2-n)} & \text{for } \rho < \frac{1}{2d_0^2}
\end{cases} \]

The above two equations can be combined to derive the UWB PSD \( G_p \) that increases the mobile station transmit power in a CDMA by \( M \) dB as
1.6 UWB Interference

\[ G_p = \frac{10^{\left(\frac{M}{10}\right)} - 1}{F(\lambda, \rho, d_0, n)} \cdot kT \]

k is Boltzmann constant = 1.38 \times 10^{-23} Joules/Kelvin and T is the temperature in Kelvin approximately (300K) for environmental temperature.

Note that noise power is \( P_n = kT_{B_{RX}} = N_0B_{RX} \)

The above equation gives the max. UWB PSD that degrades the performance of a cellular receiver by M dB.
1.6 UWB Interference

- The above analysis is for a cellular receiver operating in a noise limited environment.
- Thus we have considered the impact of the interference of UWB transmitters to the receiver noise power.
- Noise limited cellular systems are generally found in areas with low user density, such as rural areas.
- Cellular networks that are deployed in areas with high user density such as urban areas are generally interference limited and require an alternative equation for determining the maximum UWB PSD.
- In this case, a cellular receiver is subject to co-channel interference from the cellular system itself, in addition to the interference from UWB transmitters.
1.6 UWB Interference

Fig. 1.6.9 Illustration of the first tier of interfering cells of a sectorised cellular system, with 3 sectors per cell and 4 cells per cluster
1.6 UWB Interference

\[ G_p = \left[ \frac{M}{10^{10}} - 1 \right] \frac{I_T(W)}{B_{RX} F(\lambda, \rho, d_0, n)} \]

\[ I_T(W) = I_0(W) + N_0(W) \]

\[ I_0 = P_{c0} d_0^n \left( (\sqrt{13}R)^n + (\sqrt{19}R)^n + (\sqrt{31}R)^n \right) \]

\[ P_{c0} = \frac{P_t \lambda^2}{(4\pi)^2 d_0^2} \]

\[ I_0 = \frac{P_t \lambda^2 d_0^{n-2}}{(4\pi)^2} \left( (\sqrt{13}R)^n + (\sqrt{19}R)^n + (\sqrt{31}R)^n \right) \]


