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§ Overview of High-Frequency Electronic Circuits

*補充.
- VLF: 3~30k.
- LF: 30k~300k.
- MF: 300k~3M.
- HF: 3M~30M
- VHF: 30M~300M
- UHF: 300M~3G.
- SHF: 3G~30G.
- EHF: 30G~300G.

微波 microwave, $\lambda = 10^{-3}$ m.

millimeter wave

目前通訊頻帶

4G. LTE.
1.71G~2.71 GHz.
(bandwidth = 700M~960M)

Wifi, BlueTooth.
2.4G, 5.8G.

GPS. 1.575 GHz.

Satellite 11.7 GHz.

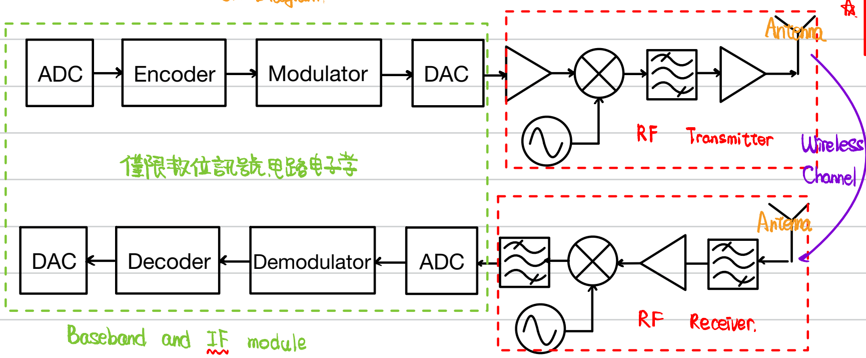
1.1 Transceiver Architecture (transceiver ⇒ transmitter + receiver)

• Typical Microwave Communication System.

Definition of Radio frequency ⇒ $A\cos(\omega t+\phi)$, $\omega = 2\pi f$. 其中, $3k \le f \le 300G$ Hz.

$10^{-3} \le \lambda \le 10^{5}$ m.

Block Diagram.



Baseband and IF module
Intermediate frequency (中介頻率)

• TX Baseband : Encoding Input Information.

ADC → Encoder (components)

• ADC : Convert analog data to digital formats

• Coding Process.

1. Source Encoder : eliminating redundancy in information bits (將訊號壓縮成小資訊)
2. Channel Encoder : minimizing probability of error in transmission. (避免將資訊傳錯) error detection, error correction.
3. Encoding System.

eg. B_1 B_2 B_3 原本資訊 → Free Space → 錯誤

Parity Bit ⇒ $P_1 = \mathrm{mod}(B_1, B_2)$, $P_2 = \mathrm{mod}(B_2, B_3)$, $P_3 = \mathrm{mod}(B_1, B_3)$

B_1 B_2 B_3 P_1 P_2 P_3

錯誤. 看到 parity 錯誤, 找最接近的.

中間有 125 channel.
channel 1 860~860.2
channel 2 860.2~860.4
guard band.

860 — 960
uplink user to base station
downlink. base station to user.

- 1980~1990 1G FDMA ⇒ frequency division multiple access
- 1990~2000 2G TDMA ⇒ time " " "
- 2000~2010 3G CDMA ⇒ code " " "
- 2010~2020 4G OFDM
- 2020~2030 5G SDMA.

但 ∵ 125 channel 不夠用
∴ 在 channel 間依 time frame (使用時間時段) 給不同使用者 (μs)
但 就算切割 time frame 不夠用.
∴ 用 code 將需要同一channel, 同一frame 歸類在一起.

eg. CDMA System.

Spread Signal.

每位 user 有不同 "orthogonal code"

∵ 各 code 正交. ∴ 資訊經 orthogonal 編碼
並不會互相影響.

· TX Baseband : Modulation Idea

- transforming baseband signal to intermediate frequency (several KHz → hundreds MHz)

- Modulation process :

Basic Method. — Advanced Method.

$$V_c(t) = A\cos(\omega_c t + \phi) \Rightarrow \begin{cases} \text{Amplitude Shift Keying.} \\ \text{Phase Shift Keying.} \\ \text{Frequency Shift Keying} \end{cases}$$

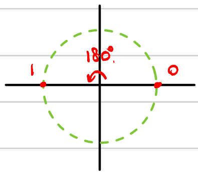
Amplitude Shift Keying / Phase Shift Keying → Quadrature Amplitude Modulation.

- Phase Shift Keying (PSK)

BPSK.

constellation chart

Digital	Modulated Carrier
0	$A\cos(\omega t + 0^\circ)$
1	$A\cos(\omega t + 180^\circ)$



⚠ 8-PSK.

000	$A\cos(\omega t + \phi_1)$
001	$A\cos(\omega t + \phi_2)$
010	$A\cos(\omega t + \phi_3)$
011	⋮
100	
101	
110	
111	$A\cos(\omega t + \phi_8)$

⇒角度 $(\phi_i - \phi_j) = \frac{360}{8} = 45$

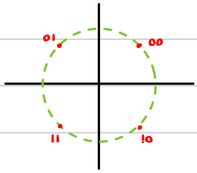
可利用phasor transform轉成

$A \angle \phi_i$

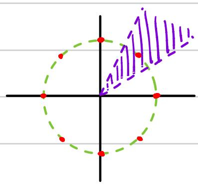
QPSK

constellation chart

Digital	Modulated Carrier
00	$A\cos(\omega t + 45^\circ)$
01	$A\cos(\omega t + 135^\circ)$
10	$A\cos(\omega t - 45^\circ)$
11	$A\cos(\omega t - 135^\circ)$



constellation chart



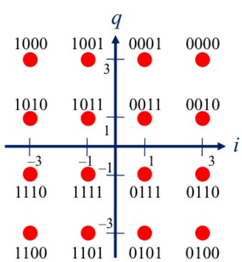
8-psk可容許錯誤範圍

∴分越多點容錯率愈低

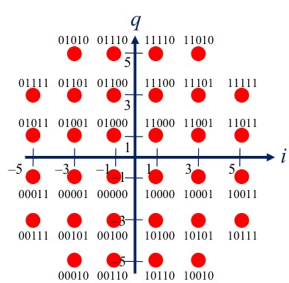
⇒不建議 high order.

- Amplitude Shift Keying ⇒ usually don't use this method

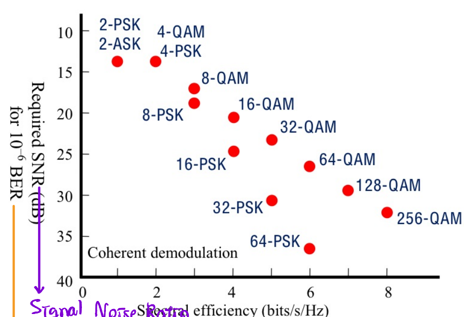
- Quadrature amplitude modulation ⇒ using Amplitude . Phase



16-QAM



32-QAM

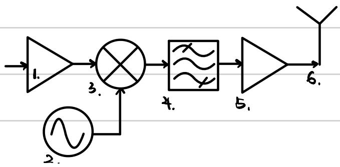


Signal Noise Ratio

Bit Error Rate

∴可得知傳輸bit↑,其訊號功率>雜訊功率 其 BER 才會得到 10^{-6} 之錯誤率

• TX RF Band.



1. IF Amplifier. : Enhance Signal Level. with modulator produce insertion loss

2. Oscillator: Generate precise controlled carrier frequency "f_{LO}"
控制任意頻率.產生該頻率的 sinusoidal wave

3. Mixer : Up-converting intermediate signal to RF.

output of idealized mixer

frequency convergent　　oscillator 的頻率.　　原中介頻率放大器

$$V_{RF}(t) = K \underline{V_{LO}(t) V_{IF}(t)} = K\cos(2\pi f_{LO} t)\cos(2\pi f_{IF} t)$$

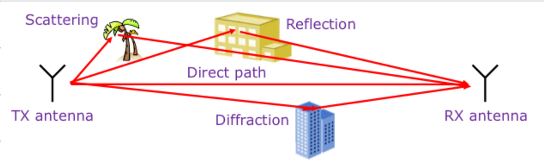
積化和差. $= \frac{K}{2}\left[\cos 2\pi(mf_{LO}+nf_{IF})t + \cos 2\pi(mf_{LO}-nf_{IF})t\right]$

4. RF Filter. : frequency conversion result from nonlinearity of transistor or diode
generate wide variety of harmonic wave
↳ select the wave only $f_{LO}+f_{IF}=f_{RF}$.

5. Power Amplifier : Increasing output power of transmitter.

6. TX Antenna : Converting modulated carrier signal from transmitter to propagating EM plane wave.
↳ PA傳遞 $V(x.t).I(x.t)$ 給 Antenna 化成 Electromagnetic Wave. (傳送至 channel) $E(t,r)=\frac{E_0}{\underset{\text{signal fading}}{r}}\cos(\omega t-\underset{\text{propagates}}{kr}+\phi)$

- Channel.
  - Wireless Propagation (considering free space)



令 $f = 2.4\ \text{GHz}$, $\lambda = 12.5\ \text{cm}$.

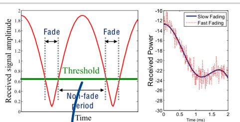
by considering size of Object

1. $O >> \lambda$ ($O \ge 10\lambda$): reflection ⇒ 反射.
   $\underbrace{O}_{\text{size of object}}$
2. $\frac{\lambda}{10} < O < 10\lambda$: scattering ⇒ 散射.
3. $\lambda >> O$. ($O < \frac{\lambda}{10}$): diffraction ⇒ 繞射.

★ most important issues of wireless propagation. (multipath propagation.)

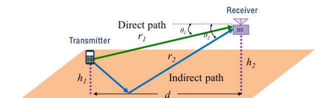
1. Multipath effects: fading, intersymbol interference, path loss.
2. Fading: amplitude of received signal fluctuate severely.
   衰弱 (Amplitude)

ex.



低於 threshold 造成無法辨認 noise、signal.

example of fading.



bouncing path ⇒ reflection coefficient "γ"

⇒ direct path ⇒ $r_1 = \sqrt{d^2 + (h_2 - h_1)^2} = \boxed{d + \frac{(h_2 - h_1)^2}{2d}}$ ← 二項式展開.

indirect path due reflection ⇒ $r_2 = \sqrt{d^2 + (h_2 + h_1)^2} = \boxed{d + \frac{(h_2 + h_1)^2}{2d}}$

assuming reflection coefficient $\boxed{R = |R| e^{j\phi}}$

⇒ received field, in phasor domain. ($\because E = \frac{E_0}{r} \cos(wt - kr + \phi)$.)

$\vec{E} = \frac{E_0}{r} \angle -kr + \phi = \frac{E_0}{r} e^{-jkr}$. $\therefore E_r = \underbrace{\frac{E_0 e^{-jkr_1}}{r_1}}_{\text{direct}} + \underbrace{\frac{E_0 R e^{-jkr_2}}{r_2}}_{\text{reflection.}}$

波數. $k = \frac{1}{\lambda}$ (1公尺有多少丁波).

or $\frac{2\pi}{\lambda}$ (1圈有多少丁波 ⇒ β)

ex. $r_1 = 100\lambda$, $\therefore e^{-jkr_1} = e^{-j\frac{2\pi}{\lambda}100\lambda} = e^{-j0}$.

$r_2 = 100.2\lambda$, $\therefore e^{-jkr_2} = e^{-j\frac{2\pi}{\lambda}100.2\lambda} = e^{-j0.4\pi} = e^{-j72^\circ}$. 二者相位差很多.

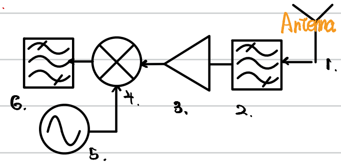
assuming $r_1 \approx r_2$. ⇒ 其長度對於波長相似. 但不可直接化成2倍.

$E_r = \frac{E_0 e^{-jkr_1}}{r_1} + \frac{E_0 R e^{-jkr_2}}{r_2} = \frac{E_0 e^{-jkr_1}}{r_1} (1 + R e^{-jk(r_2 - r_1)})$

將紫框代入. $= \frac{E_0 e^{-jkr_1}}{r_1} (1 + |R| e^{-j(k\frac{2h_1h_2}{d} - \phi)}) = \frac{E_0 e^{-jkr_1}}{r_1} \left(1 + |R| \left(\cos\left(\frac{k2h_1h_2}{d} - \phi\right) - j\sin\left(\frac{k2h_1h_2}{d} - \phi\right)\right)\right)$

$\therefore$ in time domain. $e_r(t) = \mathrm{Re}\{\vec{E_r}\} = \frac{E_0}{r_1}\cos(wt - kr_1)\left(1 + |R|\left(\cos\left(\frac{k2h_1h_2}{d} - \phi\right)\right)\right) + \frac{E_0}{r_1}\sin(wt - kr_1)\left(|R|\sin\left(\frac{k2h_1h_2}{d} - \phi\right)\right)$

·RX RF Band.



1. RX. Antenna: Receives EM Wave with. multipath propagation. on. very broad frequency range.
   本身具有些許濾波功能(低頻雜訊濾除)

2. Bandpass Filter.: Reject inteferning signals at undesired frequencies.
   ↳ Antenna會把部份諧波接收(但實際不需要.) ∴需 BPF 濾除.
   可以減少.高功率的干擾訊號被敏感的放大器.超載的机率.

3. Low-Noise Amplifier.: Magnifyng signal receved. which is weak. noisy. only for receiver.

4.5. Mixer and Oscillator: Local Carrier to down-convert the RF signal back to IF that processed by baseband module
   → RF. LO的頻率很相似. ⇒ $f_{RF}+f_{LO}=2f_{RF}$. $f_{RF}-f_{LO}$ ⇒ baseband.
   通常會串接多級來有更好的特性.
   若沒有使用 LNA.則 mixer 的 noise. loss 特性會占接收結果的一大部份

6. Filter: Remove any undesred harmonic. spurious products result from mixing process.

⚠ Conclusion.

· RF front ends requred low loss. low cost. light weight. high performance. power efficient
  ⇒ can be integrated in IC except Antenna.

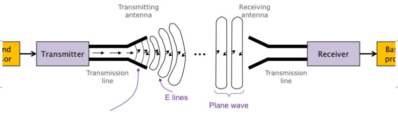
·RX Baseband

Demodulator: retreiving message from IF signal

Decoder: retreive original message from channel bits recieved.

1.2 How does an Antenna Work

· Basic Structure of Antenna.



An antenna is a transitional structure between free space and transmission line

Receiving input power comes from transmitter.

⇒ impedance matching, return loss, operational bandwidth.

Radiating input power toward desired direction

⇒ patterns, directivity, beamwidth, radiation efficiency.

Scenarios don't produce radiation.

⇒ Gauss's Law. charge not moving

Produce Static E-field.

⇒ Biot-Savart Law. charges moved constant velocity

Produce Static Magnetic field.

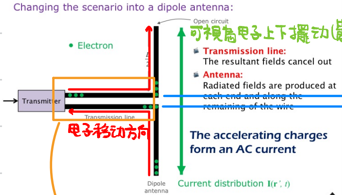
produce radiation.

Time-Varying current.

Acceleration and deceleration of charge

· Antenna Workflow.

Changing the scenario into a dipole antenna:



可視為电子上下擺动(簡諧運动)

电子移动方向

中間此處無輻射.

$F = -k\underset{\sim}{x} = m \cdot \frac{d^2x}{dt^2}$

position of electron (current)

$\therefore m \cdot \frac{d^2x}{dt^2} + kx = 0$. let $x = e^{\lambda t}$.

$\Rightarrow m\lambda^2 e^{\lambda t} + k e^{\lambda t} = 0$.

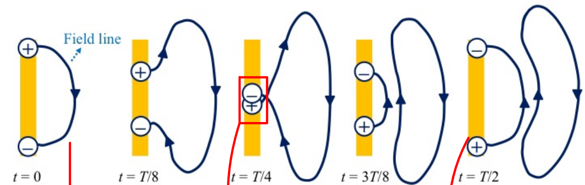
$\lambda = \pm j\sqrt{\frac{k}{m}}$

$\therefore x = c_1 \cos\sqrt{\frac{k}{m}}t \pm c_2 \sin\sqrt{\frac{k}{m}}t$

$= A\cos(\sqrt{\frac{k}{m}}t + \phi)$

→ 形成一類似 sinsoid wave.

A closer look to the radiation mechanism:



E filed line (wave front) at the ends of dipoles

Wave front moves out as charges go in

As charges pass the midpoint, the field line cuts loose

Wave fronts move out

Wave fronts move out

电力線.

正負电荷相切.

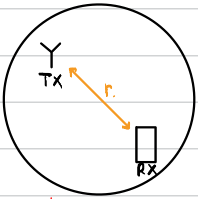
形成波導向外傳遞

neutralization.

亍半週期產生的波向外傳遞

1.3 Link Budget.

• Friis Transmission Formula.



direct path.

Transmitting Antenna

Transmitting Power : P_t.

Antenna Gain : G_t

→ propagation

Receiving Antenna.

Receiving Power : P_r

Antenna Gain : G_r.

· Free Space

· Distance : r

· Frequency : f_0.

def. Friis Formula $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2$

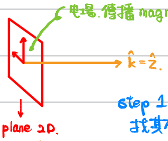
$\lambda_0 = \frac{c}{f_0}$ ⇒ common sense. $f_0 = 1\text{ GHz}$, $\lambda_0 = 30\text{cm}$.

∴ 2.4G Hz. $\lambda_0 = \frac{30}{2.4} = 12.5\text{ cm}$.

修正

→ if polarizations mismatch.

电場方向.



→ $P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2 |\hat{e}_t \cdot \hat{e}_r|^2$.

ex.

Transmitt.

$\vec{E} = (E_0 \hat{x} + E_0 \angle 90° \hat{y}) e^{-jkz}$.

Receive

$\vec{E} = (E_0 \angle 90° \hat{x} - E_0 \angle 180° \hat{y}) e^{-jkz}$

step 1.

找其方向 ⇒ $\vec{E} = \langle E_0, E_0 \angle 90° \rangle$.

$\vec{E} = \langle E_0 \angle 90°, -E_0 \angle 180° \rangle$.

step 2.

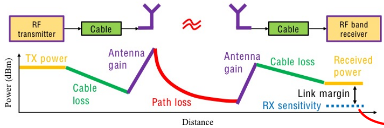
normalize $\langle 1, j \rangle = \langle \frac{1}{\sqrt{2}}, \frac{j}{\sqrt{2}} \rangle$

$\langle j, 1 \rangle = \langle \frac{j}{\sqrt{2}}, \frac{1}{\sqrt{2}} \rangle$

step 3.

求 polarization loss factor. $= |\hat{e}_t \cdot \hat{e}_r|^2 = |j| = 1$.

• Objective of Link Budget Caculation



→ 低於此範圍則無法辨識.

⇒ by Friis Equation. $P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2$.

we can have more precise estimation of path loss $= \left(\frac{\lambda_0}{4\pi r}\right)^2$.

by breakpoint model. :

1. for distance $r \leq r_{break}$

path loss $= \left(\frac{\lambda_0}{4\pi r}\right)^2$

2. for distance $r > r_{break}$

path loss $= \left(\frac{\lambda_0}{4\pi r_{break}}\right)^2 \left(\frac{r_{break}}{r}\right)^n$

Environment	Path loss exponent n
Free space	2
Urban	2.7–3.5
Shadowed urban	3–5
In-building LOS	1.6–1.8
In-building shadowed	4–6
Factory shadowed	2–3
Retail store	2.2
Office-soft partitions	2.4

Problem 1

Consider an outdoor small cell with f_c = 2.5 GHz, cells of radius 10 m, and gains of transmitting and receiving antennas G_t = 1 dBi and G_r = 1 dBi.

1. Using the free-space model, what is the path loss?
2. Based on (1), what transmit power is required at the base station in order for all terminals within the cell to receive a minimum power of 0.1 μW?
3. How does the transmit power change if the system frequency is 5 GHz?
4. How does the transmit power change if the transmitting distance is 40 m?
5. Propose methods to lower the transmit power yet maintaining the transmitting distance.

$f_c = 2.5\,GHz \qquad \lambda_0 = 12\,cm$

1. path loss $= \left(\frac{\lambda_0}{4\pi r}\right)^2 = \left(\frac{12\times10^{-2}}{40\pi}\right)^2$

取 $10\log \Rightarrow PL = 10\log\left(\frac{\lambda_0}{4\pi r}\right)^2 = 20\log\left(\frac{3\times10^{-3}}{\pi}\right) = -60.4\,dBi$

2. $P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2$

$10\log P_r = 10\log P_t + 1 + 1 - 60.4$

$-40 = 10\log P_t - 58.4 \Rightarrow \log P_t = 1.84. \quad \therefore P_t = 69\,mW.$

3. $f_c = 5\,GHz, \quad \lambda = 6\,cm. \therefore$ Path Loss 要再 $-6\,dBi$.

$-40 = 10\log P_t + 1 + 1 - 60.4 - 6 \Rightarrow \log P_t = 2.44 \qquad P_t = 275.4\,mW.$

4. $R = 40\,m. \therefore$ Path Loss 要再減 $-12.04\,dBi$.

$-40 = 10\log P_t + 1 + 1 - 60.4 - 12.04 \Rightarrow \log P_t = 3.44 = 2754\,mW.$

Problem 2

An engineer is designing a communication link at 3 GHz. The transmitting and receiving antennas are arranged face-to-face along the z axis. The separation between the two antennas is 1 km. The transmitter uses an antenna with gain of 10 dBi, transmitting power of 25 watts. The gain of the receiving antenna is 8 dBi. Consider each condition and find the receiving power.

1. The transmitting antenna transmits a time-domain E-field of $e(t, z) = E_0\cos(\omega t - \beta z)\hat{x} - E_0\cos(\omega t - \beta z)\hat{y}$, whereas the receiving antenna uses a time-domain E-field of $e(t, z) = E_0\cos(\omega t + \beta z)\hat{x} - E_0\cos(\omega t + \beta z)\hat{y}$.
2. The transmitting antenna transmits a time-domain E-field of $e(t, z) = E_0\cos(\omega t - \beta z)\hat{x} + E_0\cos(\omega t - \beta z)\hat{y}$, whereas the receiving antenna uses a time-domain E-field of $e(t, z) = E_0\cos(\omega t + \beta z)\hat{x} - E_0\cos(\omega t + \beta z)\hat{y}$.
3. The transmitting antenna transmits a time-domain E-field of $e(t, z) = E_0\cos(\omega t - \beta z)\hat{x} + E_0\cos(\omega t - \beta z)\hat{y}$, whereas the receiving antenna uses a time-domain E-field of $e(t, z) = E_0\cos(\omega t + \beta z)\hat{x} - E_0\cos(\omega t + \beta z + 90^\circ)\hat{y}$.
4. Based on (3), consider a doubled separation and do the problem one more time.
5. Propose methods to minimize the effect of polarization loss.

$f_c = 3\,GHz. \quad \lambda = 10\,cm.$

$PL = 20\log\frac{0.1}{4\pi 1000} = -101.98\,dBi.$

$10\log P_r = 10\log 25\times10^3 + 10 + 8 - 101.98 +$ polarization.

1. polarization: $\langle E_0\angle{-Bz}, -E_0\angle{-Bz}\rangle \quad \langle E_0\angle Bz, -E_0\angle Bz\rangle$

$\Rightarrow \langle -1, 1\rangle, \langle 1, -1\rangle$

$\Rightarrow \langle \frac{-1}{\sqrt2}, \frac{1}{\sqrt2}\rangle, \langle \frac{1}{\sqrt2}, \frac{-1}{\sqrt2}\rangle$

$e_t = \left|\langle \frac{-1}{\sqrt2}, \frac{1}{\sqrt2}\rangle \cdot \langle \frac{1}{\sqrt2}, \frac{-1}{\sqrt2}\rangle\right|^2 = 1. \Rightarrow 10\log e_t = 0$

$10\log P_r = 30 + 10\log 25 + 10 + 8 - 101.98 \qquad \log P_r = -4. \Rightarrow P_r = 0.1\,\mu W.$

2. polarization $\langle E_0\angle{-\beta z}, E_0\angle{-\beta z}\rangle \quad \langle E_0\angle\beta z, -E_0\angle\beta z\rangle$

$\Rightarrow \langle 1, 1\rangle, \langle -1, 1\rangle$

$e_t = \left|\langle \frac{1}{\sqrt2}, \frac{1}{\sqrt2}\rangle \cdot \langle \frac{-1}{\sqrt2}, \frac{1}{\sqrt2}\rangle\right| = 0. \qquad \therefore P_r = 0\,W.$

3. polarization $\Rightarrow \langle E_0\angle{-\beta z}, E_0\angle{-\beta z}\rangle, \langle E_0\angle\beta z, E_0\angle\beta z + 90^\circ\rangle.$

$\Rightarrow \langle 1, 1\rangle, \langle -1, -j\rangle \qquad (1+j)^2 = 1 + 2j - 1$

$e_t = \left|\langle \frac{1}{\sqrt2}, \frac{1}{\sqrt2}\rangle \cdot \langle \frac{-1}{\sqrt2}, \frac{-j}{\sqrt2}\rangle\right|^2 = \left|\frac{-1-j}{2}\right|^2 = \left|\frac{2j}{4}\right| = \frac{1}{2}. \Rightarrow 10\log e_t = -3\,dB.$

$10\log P_r = 30 + 10\log 25 + 10 + 8 - 101.98 - 3. \qquad \log P_r = -4.3\,dBm. \quad P_r = 0.05\,\mu W.$

4. $R = 2R.$ path loss 再減少 $6\,dB$.

$10\log P_r = 30 + 10\log 25 + 10 + 8 - 101.98 - 3 - 6. \qquad \log P_r = -4.9\,dBm. \quad P_r = 12.5\,nW$

Problem 3

In this problem, you will analyze the path loss in a UWB communication system (3.1–10.6 GHz) by considering different environments and carrier frequencies. The breakpoint model is used to differentiate the path loss behavior before and after a breakpoint distance d_{break}. There are two carrier frequencies used in this system: f_1 = 4.0 GHz and f_2 = 8.0 GHz. The environments considered are urban, with a path loss exponent of 2.7, and indoor line-of-sight, with a path loss exponent of 1.7. The breakpoint distance (d_{break}) for the two environments is 4 m.

1. Find the path loss at 10 m at the two frequencies in the environment of urban.
2. Find the path loss at 10 m at the two frequencies in the environment of indoor line-of-sight.
3. Find the path loss at 10 m at the two frequencies if the environment is free space.
4. How does the path loss exponent affect the path loss?
5. What role does the breakpoint distance play?

$f_{c1} = 4\,GHz.\quad \lambda_1 = 7.5\,cm.$

$f_{c2} = 8\,GHz\quad \lambda_2 = 3.75\,cm.$

1. $PLU_1 = \left(\frac{\lambda_0}{4\pi\, d_{break}}\right)^2 \left(\frac{d_{break}}{d}\right)^{2.7}$

$= \left(\frac{7.5\times10^{-2}}{4\pi 4}\right)^2 \left(\frac{4}{10}\right)^{2.7} = 1.88\times10^{-7}$

$PLU_2 = 4.69\times10^{-8}$

2. $PLI_1 = \left(\frac{\lambda_0}{4\pi\, d_{break}}\right)^2 \left(\frac{d_{break}}{d}\right)^{1.7} = 4.68\times10^{-7}$

$PLI_2 = 1.17\times10^{-7}$

3. $PL_1 = 3.56\times10^{-7}$

$PL_2 = 8.91\times10^{-8}$