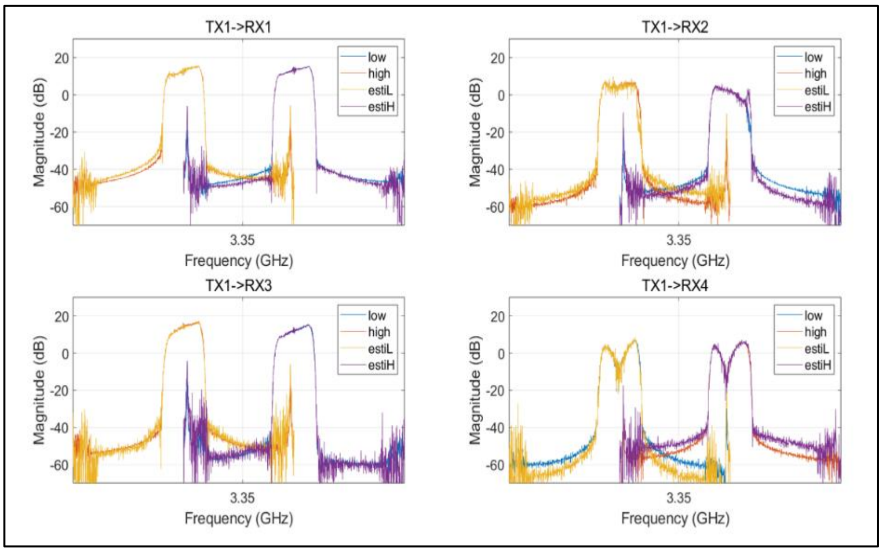
**Chapter 1. The Wireless Channel: Propagation and Fading**

The performance of wireless communication systems is mainly governed by the wireless channel environment.

- 무선 통신 시스템에서 **성능**은 주로 **무선 통신 채널 환경**에 영향을 받는다.

- 실제로 석사 과정에서 진행한 연구는 "하나의 전파 채널(**Propagation Channel**)을 주파수 영역에서 멀리 분리된 두 대역에서 동시에 사용할 때, 한 대역에서 송수신한 파일럿으로 다른 대역의 전파(**Radio Channel**)채널을 추정하는 방식"을 연구 및 실측을 한 것 이였다. 이를 위해 MIMO 송수신기를 FDD 방식으로 서로 다른 중심주파수를 가진 신호를 송수신하였고, 결과적으로 추정한 결과를 통해, Power Delay Profile(PDP), Frequency Response, Channel Magnitude Response 등을 활용했다. - 해당 연구 결과가 가능했던 이유는 결국, 연구 측정 환경이 포스텍의 LG연구동이라는 실내인 ergodic하며, stationary한 환경 이였기 때문이다. 즉, 무선 통신 시스템에서 성능은 무선 통신 채널에 많은 영향을 끼친다.

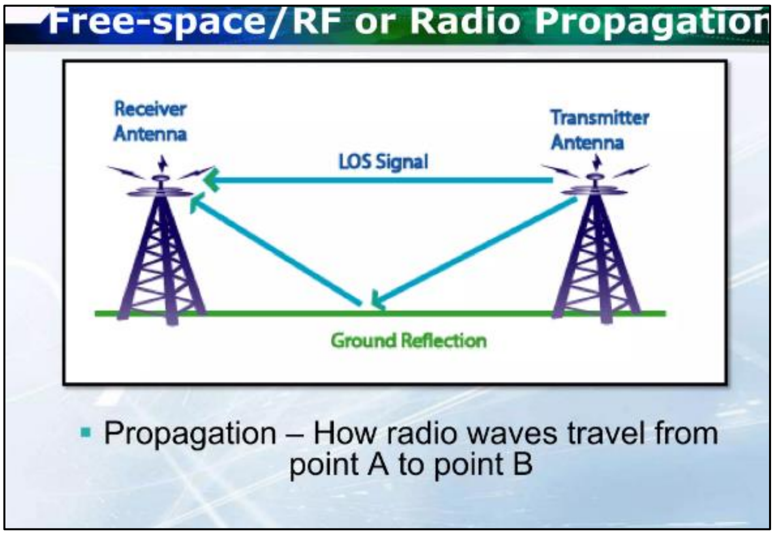



+) 2024.06.16부터 추가 내용

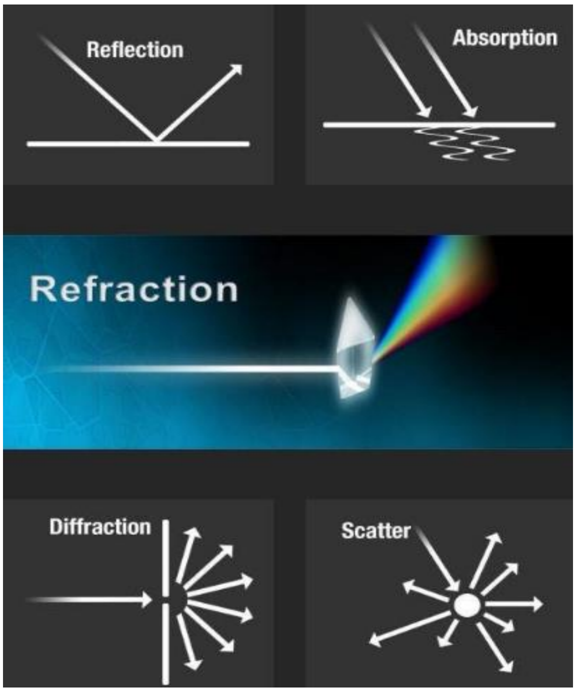
**Wired Channel(유선채널):** static and predictable characteristics

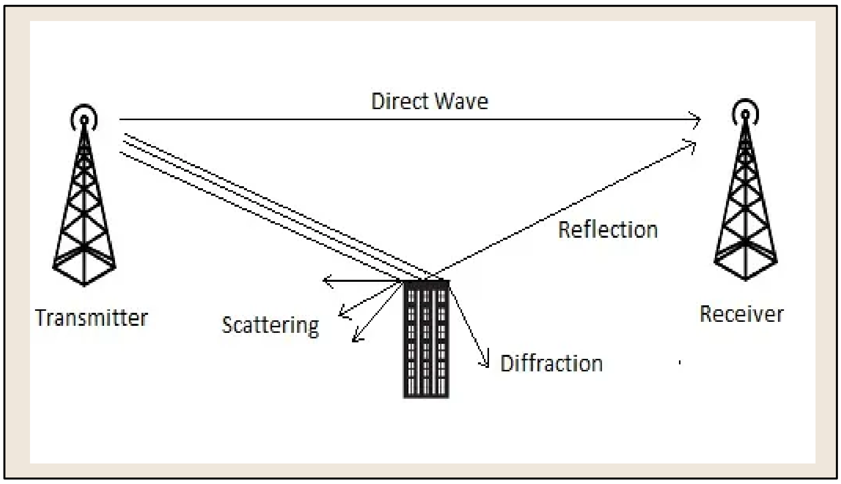
**Wireless Channel(무선채널)**: dynamic and unpredictable.

> In fact, the understanding of wireless channels will lay the foundation for the development of high performance and bandwidth-efficient wireless transmission technology.

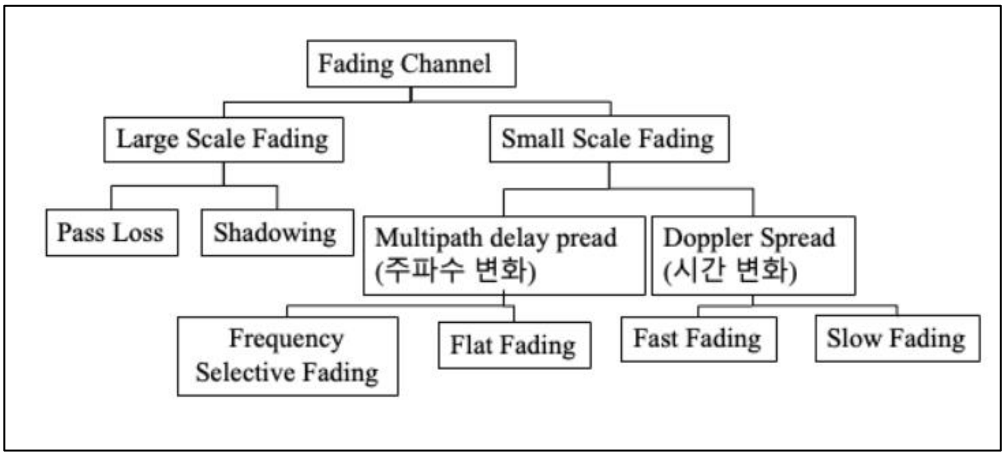


In wireless communication, radio propagation refers to the behavior of radio waves when they are propagated from transmitter to receiver. In the course of propagation, radio waves are mainly affected by three different modes of physical phenomena: - reflection, diffraction, and scattering.




회절: 파동이 진행 중 장애물을 만나면 장애물을 에워 돌아 나가고, 작은 구멍을 통과할 때 넓게 퍼지는 현상을 뜻한다.




출처: https://velog.io/@hsshin0602/%ED%86%B5%EC%8B%A0-%EC%9D%B4%EB%A1%A0-%ED%8E%98%EC%9D%B4%EB%94%A9fading%EC%9D%98-%EC%9C%A0%ED%98%95

**Fading**: variation of the signal amplitude over time and frequency.

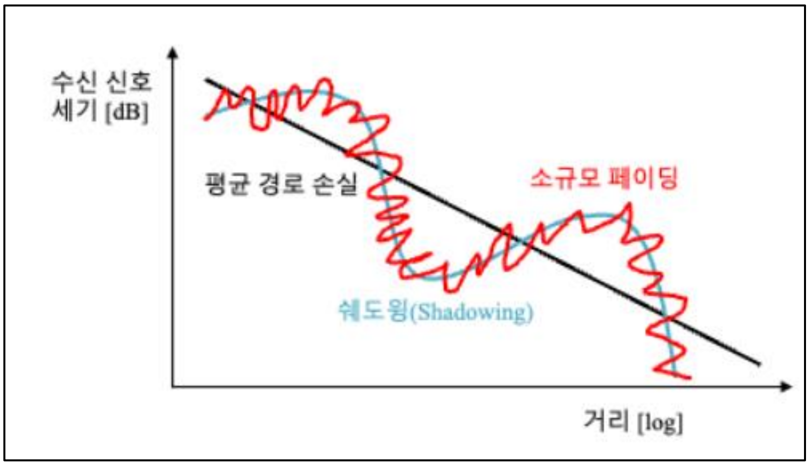
**<Classification of fading channels>**

The fading phenomenon can be broadly classified into two different types: large-scale fading and small-scale fading.

Doppler Spread: Time variance

- Depending on the time variation in a channel due to mobile speed (characterized by the Doppler spread), short-term fading can be classified as either fast fading or slow fading.

- **slow fading**: 기지국과 이동국이 멀어지는 경우, 도플러 효과에 의해 수신신호 주파수가 낮아지는 현상.




위의 그림은 소규모 페이딩과 대규모 페이딩의 차이를 보여주고 있다.

The relationship between large-scale fading and small-scale fading is illustrated in Figure.

Link budget is an important tool in the design of radio communication systems. Accounting for all the gains and losses through the wireless channel to the receiver, it allows for predicting the received signal strength along with the required power margin. -> **Path loss and fading are the two most important factors to consider in link budget.**

The mean path loss is a deterministic factor that can be predicted with the distance between the transmitter and receiver. On the contrary, shadowing and small-scale fading are random phenomena, which means that their effects can only be predicted by their probabilistic distribution.

**For example, shadowing is typically modeled by a log-normal distribution.**

Due to the random nature of fading, some power margin must be added to ensure the desired level of the received signal strength. In other words, we must determine the margin that warrants the received signal power beyond the given threshold within the target rate in the design.

1.1 **Large-Scale Fading**

### 1.1.1 General Path Loss Model

The **free-space propagation model** is used for **predicting the received signal strength** in the line-of-sight (LOS) environment where there is no obstacle between the transmitter and receiver.

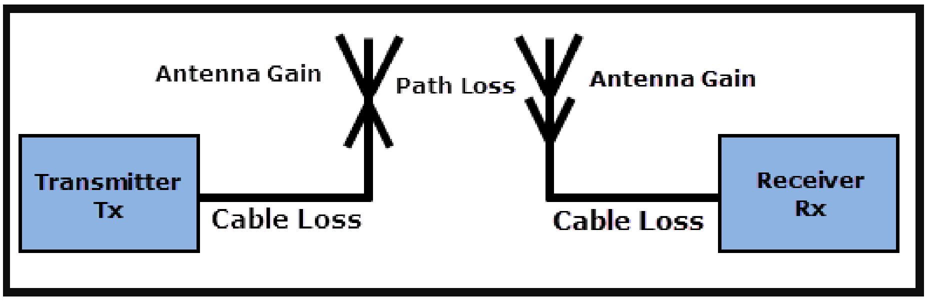
$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

d=distance in meters between the transmitter and receiver.

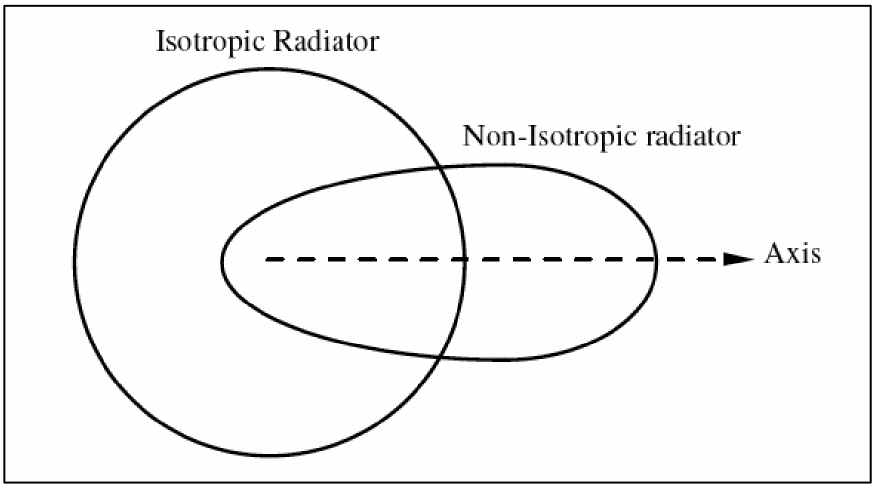
$P_t$=transmit power(watts), **L**=the **system loss factor** which is independent of propagation environment.

- The system loss factor represents overall attenuation or loss in the actual system hardware, including transmission line, filter, and antennas. In general, L>1, but L=1 if we assume that there is no loss in the system hardware.

When non-isotropic antennas are used with a transmit gain of $G_t$ and a receive gain of $G_r$, the received power at distance d, $P_r(d)$ is expressed by the well-known Friis equation.




$P_r(d)$: the free-space path loss, $PL_F(d)$,without any system loss can be directly derived from equation with L=1.




$$\frac{P_t}{P_r} = \frac{(4\pi)^2 d^2}{G_t G_r \lambda^2}(L=1) \rightarrow PL_F(d)[dB] = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right)$$

**Without antenna gain**($G_t = G_r = 1$), $PL_F(d)[dB] = 10\log\left(\frac{P_t}{P_r}\right) = 20\log\left(\frac{4\pi d}{\lambda}\right)$

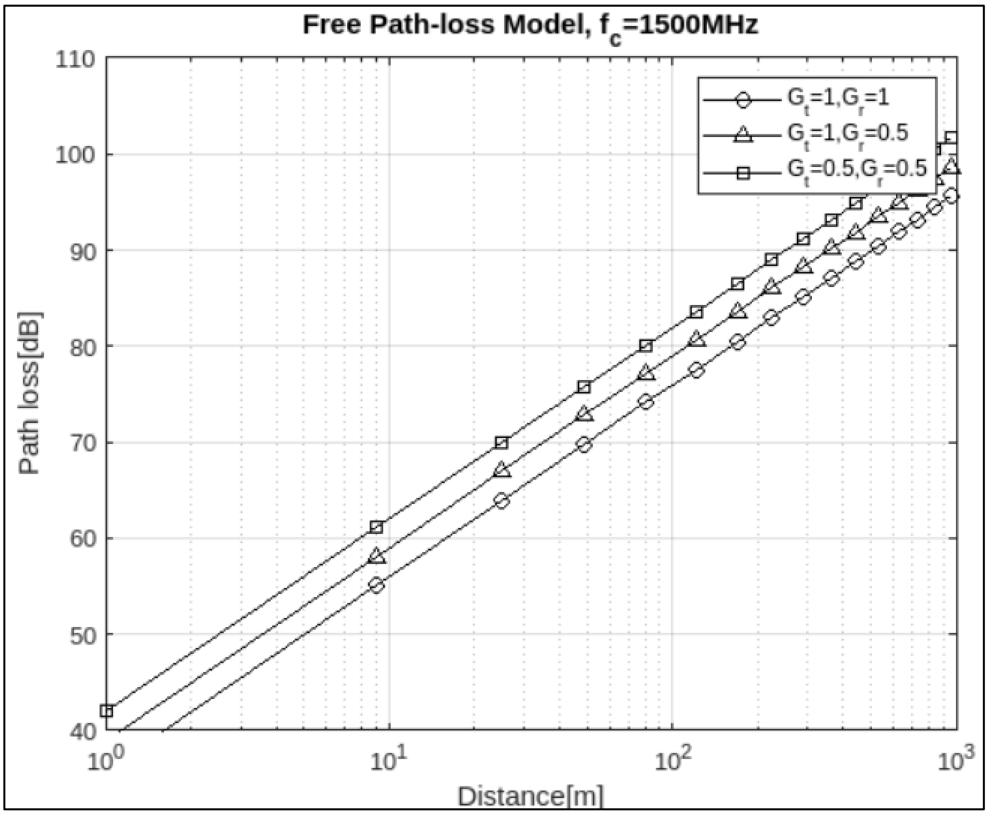
A log-normal shadowing model is useful when dealing with a more realistic situation.

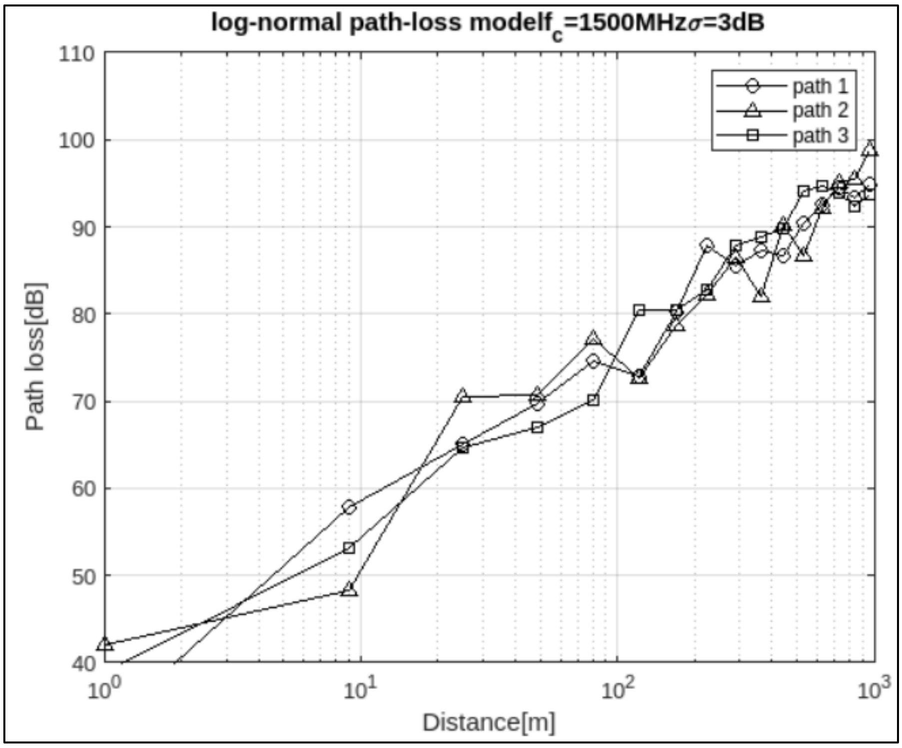
$X_\sigma$=Gaussian random variable with a zero mean and a standard deviation of $\sigma$.

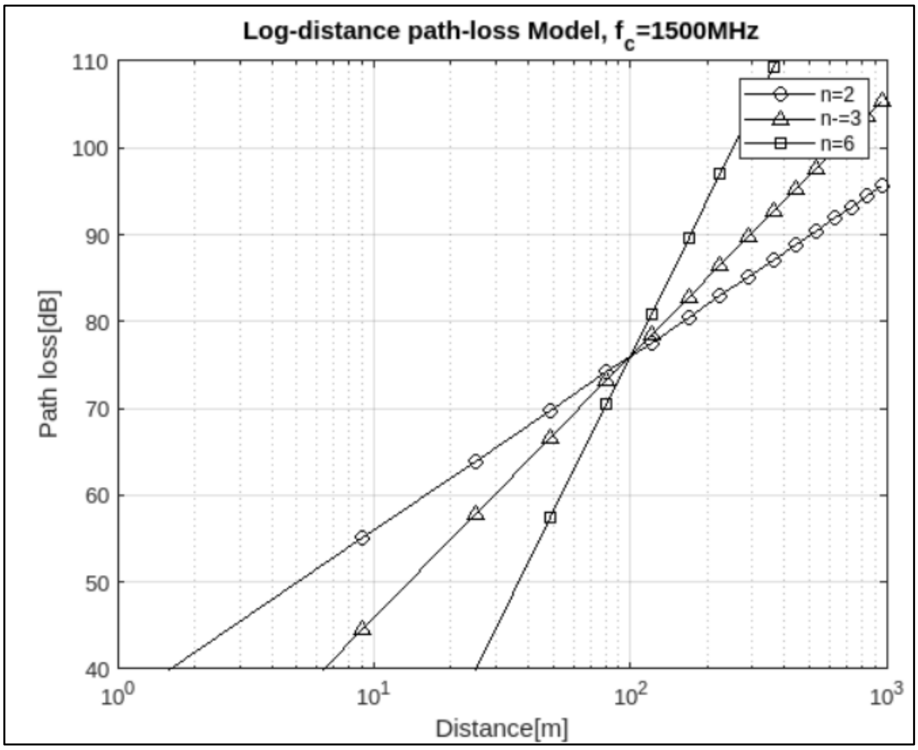
n: Path loss exponent -> **n tends to increase as there are more obstructions**.

Log-normal shadowing model

$PL(d)[dB] = \overline{PL}(d) + X_\sigma = PL_F(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$






### 1.1.2 Okumura/Hata Model

The Okumura model has been obtained **through extensive experiments** to compute the **antenna height** and **coverage area for mobile communication systems**. It is one of the most frequently adopted path loss models that can predict path loss in an urban area.

$$PL_{Ok}(d)[dB] = PL_F + A_{MU}(f,d) - G_{RX} - G_{TX} + G_{AREA}$$

$A_{MU}(f,d)$: the medium attenuation factor at frequency f

$G_{TX}, G_{RX}$: antenna gains of TX and RX antennas, $G_{AREA}$: the gain for the propagation environment in the specific area.

The Okumura model has been extended to cover the various propagation environments including urban, suburban and open area, which is now known as the Hata model.

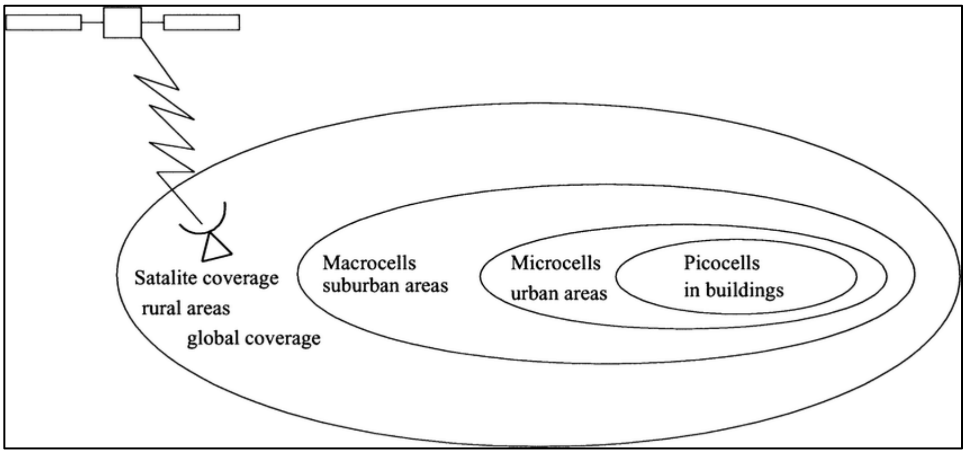
- Mainly covers the typical mobile communication system characteristics with a frequency band of 500 ~ 1500 MHz, cell radius of 1~100km, and an antenna height of 30~100m.

$PL_{Hata,O}(d)[dB] = PL_{Hata,U}(d) - 4.78(\log(f_c))^2 + 18.33(\log(f_c)) - 40.97$ : **Open Areas**

- it is clear that the urban area gives the most significant path loss as compared to the other areas, simply due to the dense obstructions observed in the urban area.

## Path loss: urban(도시) > suburban(교외) > open area

### 1.1.3 IEEE 802.16d model




IEEE 802.16d model is based on the **log-normal shadowing path loss model**.

$$P_{802.16}(d)[dB] = PL_F(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + C_f + C_{RX}, for\ d > d_0$$

Types of models (type A, B, C), depending on the **density of obstruction** between the transmitter and receiver in a macro-cell suburban area.

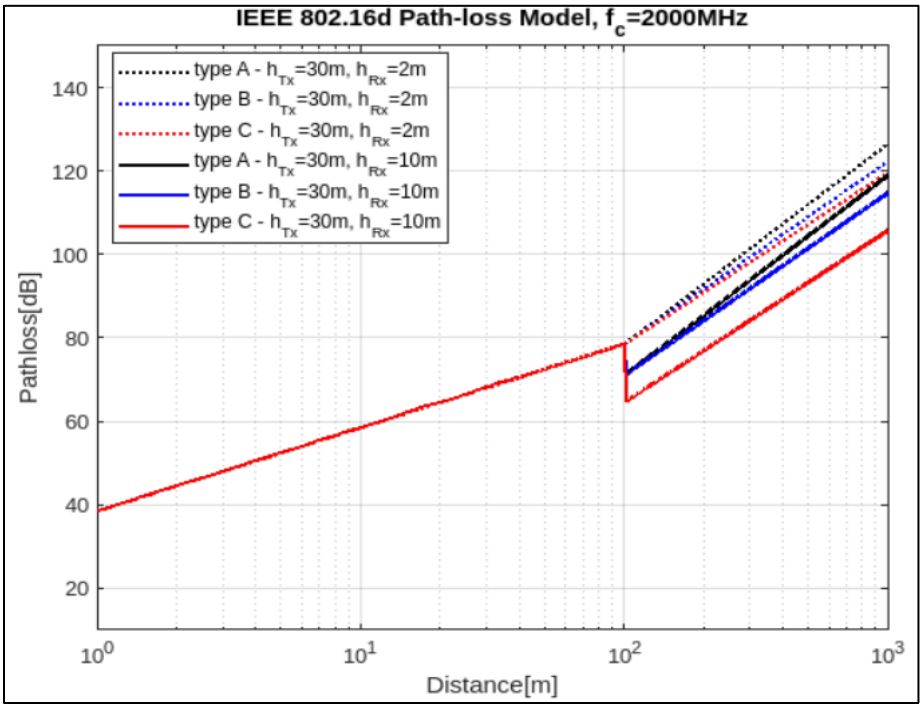
$C_{RX}$: correlation coefficient for the receive antenna

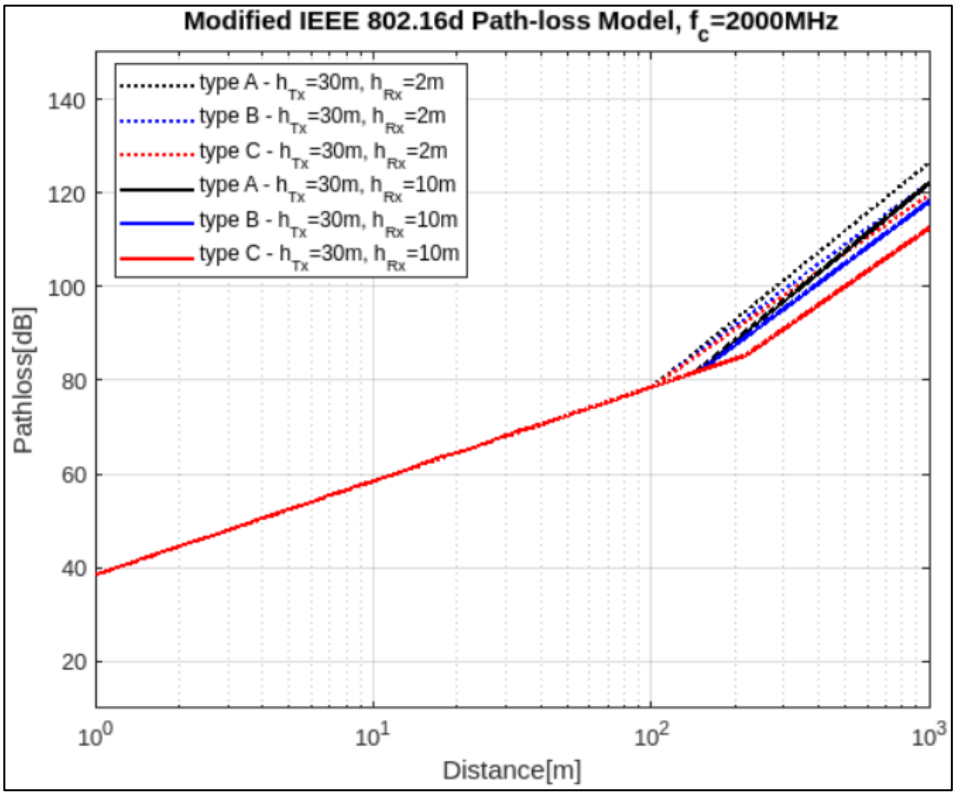
When the height of the transmit antenna is changed from 2m to 10m, there is a discontinuity at the distance of 100m, causing some inconsistency in the prediction of the path loss. -> $d_0$인 100m를 기준으로 송, 수신 안테나 간의 거리가 100m를 넘어가면 path loss가 연속적이지 않은 상태로 증가하기에, $d_0$를 개선한 $d'_0$를 만든다.

$$20\log_{10}\left(\frac{4\pi d'_0}{\lambda}\right) = 20\log_{10}\left(\frac{4\pi d'_0}{\lambda}\right) + 10\gamma\log\ \_10\left(\frac{d'_0}{d}\right) + C_f + C_{RX}$$

$20\log_{10}\left(\frac{4\pi d'_0}{\lambda}\right)$: $G_t = G_r = 1$일 때, free space path model: $PL_F(d) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$

$$d'_0 = d_0^{-\frac{C_f + C_{RX}}{10\gamma}}$$



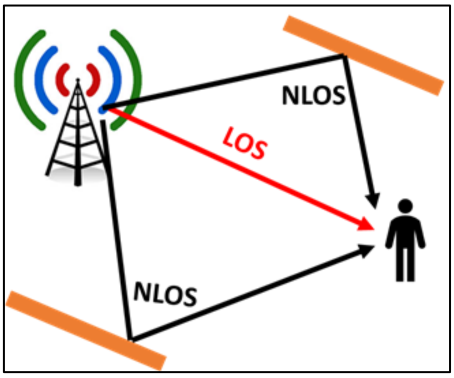



### 1.2 Small-Scale Fading

Unless confused with large-scale fading, small-scale fading is often referred to as fading in short.

- Small-Scale Fading: 다중 경로에 의해 생기는 fading의 총칭으로, 무선 이동 단말이 좁은 지역에서 이동할 때 수신 신호 세기의 급격한 변동을 의미한다.

- Fading (Small-Scale Fading) is the rapid variation of the received signal level in the short term as the user terminal moves a short distance. It is due to the effect of multiple signal paths, which cause interference when they arrive subsequently in the receive antenna with varying phases.




In other words, the variation of the received signal level depends on the relationships of the relative phases among the number of signals reflected from the local scatters.

- In summary, **small-scale fading is attributed to multi-path propagation, mobile speed, speed of surrounding objects, and transmission bandwidth of signal**.

#### 1.2.1 Parameters for Small-Scale Fading

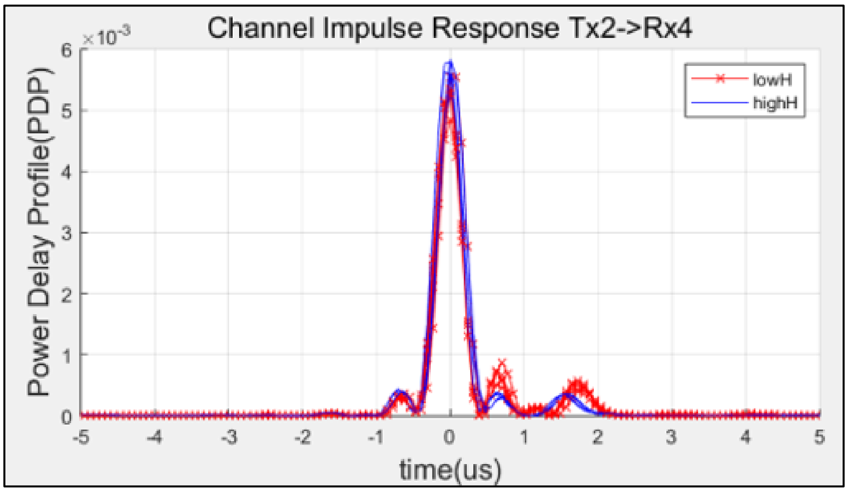
Characteristics of a multipaths fading channel are often specified by a **power delay profile** (PDP).

다중 경로 fading의 특징은 PDP에 의해 결정되어 지고, 이때 relative delay, average power 등의 파라미터로 채널의 특징을 분석한다.

The relative delay is an excess delay with respect to the reference time while average power for each path is normalized by that of the first path.

Mean excess delay and RMS delay spread are useful channel parameters that provide a reference of comparison among the different multipath fading channels, and furthermore, show a general guideline to design a wireless transmission system.

- 다중 경로에 의해 채널 특성은 다양하게 변화하는 데, 이 특징들을 파악하기 위해서 Mean excess delay, RMS delay spread 등을 통해 파악한다. 해당 값들은 석사 시절 채널 추정 연구를 진행할 때 서로 다른 주파수 대역 $f_1, f_2$가 있을 때, $f_1$의 채널 값으로 $f_2$의 채널을 예측한 다음 그 값과 실제 $f_2$의 채널 값을 비교할 때, 채널의 특성을 파악할 수 있는 파라미터인 Mean excess delay, RMS delay spread 등을 활용하였다.




$\tau_k$: channel delay of the kth, $a_k, P(\tau_k)$: amplitude and power.

**Mean excess delay: 수신된 신호의 평균 지연 시간.**

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2}$$

**RMS delay spread**

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$

**Coherence bandwidth**

$$B_c \approx \frac{1}{\sigma_\tau}$$

**1.2.2 Time-Dispersive vs Frequency-Dispersive Fading**

As mobile terminal moves, the specific type of fading for the corresponding receiver depends on both the transmission scheme and channel characteristics.

- 이동 단말기가 이동할 때, 전송 방식과 채널 특성에 따라 수신기에 대한 fading의 종류가 달라지는데, 전송 방식은 신호의 대역폭과 심볼 주기에 의해 구체화되고, 무선 채널은 multipath delay spread와 doppler spread에 의해 특징화 되어진다.

**1.2.2.1 Fading Due to Time Dispersion: Frequency-selective Fading channel**

Due to time dispersion, a transmit signal may undergo fading over a frequency domain either in a selective or non-selective manner, which is referred to as frequency-selective fading or frequency non-selective fading, respectively.

**1.2.2.2 Fading Due to Frequency Dispersion: Time-Selective Fading Channel**

- fast/slow fading: Doppler spread

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2024.03.13: 해당 내용을 대략적으로 알았지만, 정리를 하려고 정확하게 이해하는 데 어려움이 있었습니다.

그림과 수식으로 해석한 후 완벽하게 이해를 하였습니다.

Small-Scale Fading은 해당 책에서는 소분류로, multipath fading, time variance라고 분류를 하는데, 다른 자료에서는 time variance를 doppler effect로 분류합니다.

결국 Small-Scale Fading은 좁은 지역 및 짧은 시간동안 신호 강도 및 위상이 급격하게 바뀌는 현상을 말합니다.

이때, Multipath delay spread는 time dispersion과 관련된 개념이고, Doppler spread는 frequency dispersion과 관련된 개념입니다.

이때 Fading Due to Frequency Dispersion: Time-Selective Fading Channel의 경우, 결국 Frequency Dispersion이니까 Doppler spread와 관련된 개념으로 Fast/Slow Fading로 세부 분류를 할 수 있습니다.

Fast Fading의 경우, $T_s$: symbol period of the transmit signal(전송 신호의 심볼 주기), $\sigma_\tau$: RMS delay spread, $B_d$: Bandwidth of Doppler spectrum, $B_s$: bandwidth of the transmit signal로 정의할 수 있는데, $T_s > T_c, B_s < B_d$의 조건을 갖는다.

즉, Time domain에서 $T_s > T_c$을 통해, 전송신호의 주기보다 coherence time값이 길어서, 채널의 특성이 빠르게 변하고, 그로 인해 짧은 시간 간격으로 측정된 신호의 주파수 변화가 커진다는 것이며, $B_s < B_d$의 경우 Frequency Domain이니까 반대의 개념으로 생각했고, 그러기 때문에, $T_c \approx \frac{1}{f_m}$.

1.2.2의 마지막 문구에

It is important to note that fast or slow fading does not have anything to do with time dispersion-induced fading. In other words, the frequency selectivity of the wireless channel cannot be judged merely from the channel characteristics of fast or slow fading. This is simply because fast fading is attributed only to the rate of channel variation due to the terminal movement.

즉 앞서 언급했던 것처럼 fast/slow fading의 경우, frequency dispersion과 관련된 개념이기 때문에, time-dispersion-induced fading과 관련이 없고, fast fading은 단지 terminal의 움직임에 의한 채널의 변화속도만을 나타내기 때문이라고 설명하고 있다.

### 1.2.3 Statistical Characterization and Generation of Fading Channel

#### 1.2.3.1 Statistical Characterization of Fading Channel

In Clarke's proposed model, there are N planewaves with arbitrary carrier phases, each coming from an arbitrary direction under the assumption that each planewave has the same average power.

$x(t)$: baseband transmit signal. Passing through a scatter channel of different propagation paths with different I Doppler shift, the passband received signal can be represented as

$$\tilde{y}(t) = Re\left[\sum_{i=1}^{I} C_i\, e^{j2\pi(f_i+f_c)(t-\tau_i)} x(t-\tau_i)\right] = Re\left[y(t)e^{j2\pi f_c t}\right]$$

$C_i$: channel gain, $\tau_i$: delay, $f_i$: Doppler shift for the $i$th propagation path.

$v$: mobile speed, $\lambda$: wave length,

Doppler shift $f_i = f_m cos\theta_i = \frac{v}{\lambda}cos\theta_i, f_m$: maximum Doppler shift, $\theta_i$: angle of arrival (AOA) for the $i$th planewave.

The power spectrum density (PDS) of the fading process is found by the Fourier transform of the autocorrelation function of $\tilde{y}(t)$: **Classical Doppler Spectrum**

$$S_{\tilde{y}\tilde{y}}(f) = \begin{cases} \dfrac{\Omega_p}{4\pi f_m}\dfrac{1}{\sqrt{1-\left(\dfrac{f-f_c}{f_m}\right)^2}}, |f-f_c| \le f_m \\ 0, otherwise \end{cases}$$

$$\Omega_p = E\{h_I^2(t)\} + E\{h_Q^2(t)\} = \sum_{i=1}^{I} C_i^2$$

If some of the scattering components are much stronger than most of the components, the fading process no longer follows the Rayleigh distribution. -> Rician distribution.

자기상관함수(autocorrelation function)의 푸리에 변환 = power spectrum density: 파워 스펙트럼 밀도

- 와이너 힌친 정리(wiener-khinchin theorem)

시간 도메인에서의 신호의 자기상관 함수의 푸리에 변환은 주파수 도메인에서의 파워 스펙트럼 밀도와 같다.

### 하나의 경로일 때: 가우시안 분포

단일 경로에서 수신된 신호의 실수(real part)와 허수(imaginary part) 성분은 각각 평균이 0이고 분산이 $\sigma^2$인 독립적인 가우시안 분포를 따릅니다. 즉, 수신된 신호 $X$는 다음과 같이 표현될 수 있습니다:

$$X = X_{\text{real}} + jX_{\text{imag}}$$

여기서 $X_{\text{real}}$과 $X_{\text{imag}}$은 각각 독립적인 가우시안 분포를 따릅니다.

### 다중 경로 환경에서의 신호

다중 경로 환경에서는 여러 개의 신호가 서로 다른 경로를 통해 동시에 수신됩니다. 각 경로에서의 신호는 상호 간섭(interference)으로 인해 신호의 크기와 위상에서 랜덤한 변화를 겪습니다. 이 때, 각 경로의 신호 성분이 독립적인 가우시안 분포를 따를 경우, 전체 수신 신호의 실수와 허수 성분도 독립적인 가우시안 분포를 따르게 됩니다.

다중 경로 신호 $X(t)$를 다음과 같이 표현할 수 있습니다:

$$X(t) = X_{\text{real}}(t) + jX_{\text{imag}}(t)$$

여기서 $X_{\text{real}}(t)$과 $X_{\text{imag}}(t)$은 각각 독립적인 가우시안 분포를 따릅니다.

### 신호의 크기

다중 경로 환경에서의 신호 크기 $R(t)$는 다음과 같이 계산됩니다:

$$R(t) = \sqrt{X_{\text{real}}(t)^2 + X_{\text{imag}}(t)^2}$$

여기서 $X_{\text{real}}(t)$과 $X_{\text{imag}}(t)$이 각각 독립적인 가우시안 분포를 따를 때, 신호 크기 $R(t)$는 Rayleigh 분포를 따릅니다. 이는 가우시안 난수의 제곱합의 제곱근이 Rayleigh 분포를 따르기 때문입니다.

**AoA: Angle of Arrival** – AoA 를 사용하여 무선 송신기의 위치를 추적할 수 있습니다. 여러 수신기로부터 AoA 데이터를 수집하여, 삼각측량 기법을 사용하면 송신기의 정확한 위치를 계산할 수 있습니다.

#### 1.2.3.2 Generation of Fading Channels

In general, the propagation environment for any wireless channel in either indoor or outdoor may be subject to LOS or NLOS.

PDF of signal received in the LOS environment follows Rician distribution, while that in that in the NLOS environment follows the Rayleigth distribution.

- **LOS: Rician distribution**
- **NLOS: Rayleigh distribution**

By the central limit theorem, the received signal can be represented by a Gaussian random variable. In other words, a wireless channel subject to the fading environments can be represented by a complex Gaussian random variable, $W_1 + jW_2$, where $W_1$ and $W_2$ are the independent and identically-distributed (i.i.d) Gaussian random variable $W_1 + jW_2$, such that $X = \sqrt{W_1^2 + W_2^2}$. Then, note that X is a Rayleigh random variable with the following probability density function (PDF):

$$f_X(x) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}$$

where $2\sigma^2 = E\{X^2\}$. Furthermore, $X^2$ is known as a chi-square random variable.

Note that the Rayleigh random variable X with the PDF can be represented by $X = \sigma\sqrt{Z_1^2 + Z_2^2}$ where $Z_1 \sim N(0,1)$ and $Z_2 \sim N(0,1)$. Once $Z_1$ and $Z_2$ are generated by the built in-function “randn”, the Rayleigh random variable X with the average power of $E\{X^2\} = 2\sigma^2$ can be generated by $X = \sigma\sqrt{Z_1^2 + Z_2^2}$.