HF Ionospheric Simulation

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Outline

- Overview of physical effects
- Results of the effects on an HF signal
- Most significant effects
- Simulation of the effects
- CCIR 520-1 Standard Test Conditions
- References

Overview of Physical Effects

- The ionosphere is very non-uniform:
  - It moves horizontally and vertically
  - It is non-homogeneous (the reflectivity varies)
  - Each layer can support two components: the *low-ray* and the *high-ray*
  - It is non-isotropic (the index of refraction depends on direction)
    - this causes *birefringence* which leads to the generation of:
      an *ordinary ray,* and an *extra-ordinary ray*
      (Watterson calls these the *magnetoionic components)*
- There are 3 different ionospheric regions generally capable of simultaneous reflection - called *modes 1E, 1F,* and *2F*

Non-Uniform Ionosphere

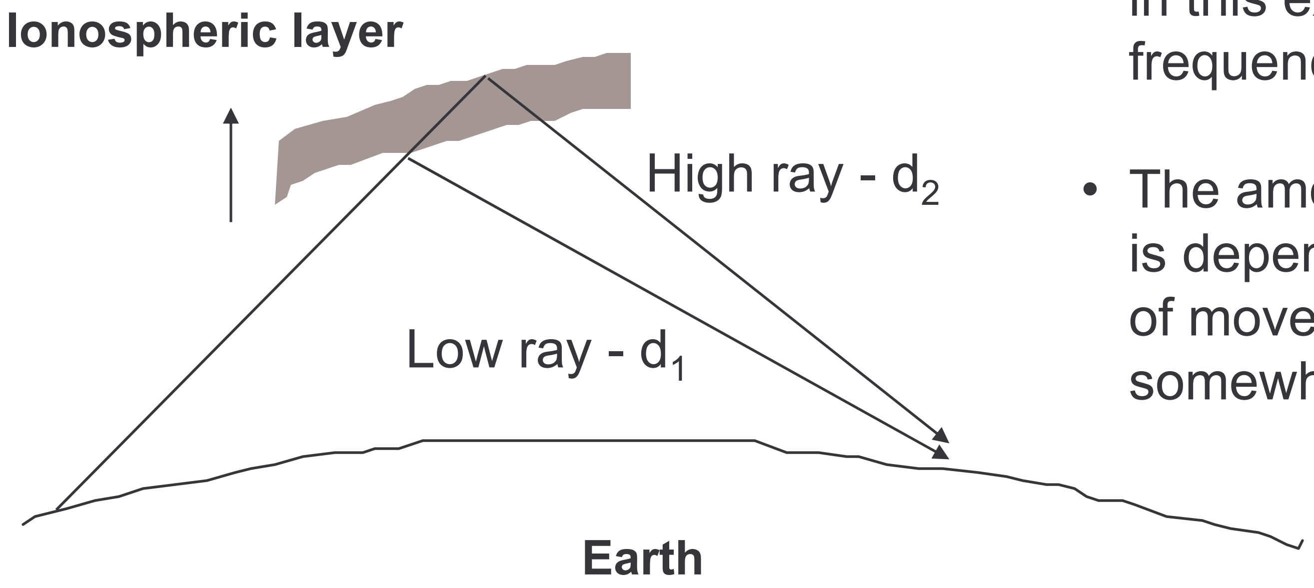
- **The reflectivity of the ionosphere is not uniform**
  - **Areas of higher and lower ionization**
  - **Therefore the strength of the reflected signal varies**
  - **This variation is independent of frequency:**
    - **known as *flat fading***

Moving Ionosphere

- **Each layer of the ionosphere moves with respect to the transmitter and the receiver.**
  - **The movement of each layer causes a *doppler shift* of it’s reflected signal.**
- **Each layer moves at a different rate with respect to the transmitter and receiver than the other layers.**
  - **The summation of different reflections from the different layers can ‘beat’ with each other**
    - **This causes constructive and destructive interference, which causes *frequency-selective fading*.**

Moving Ionospheric Layers

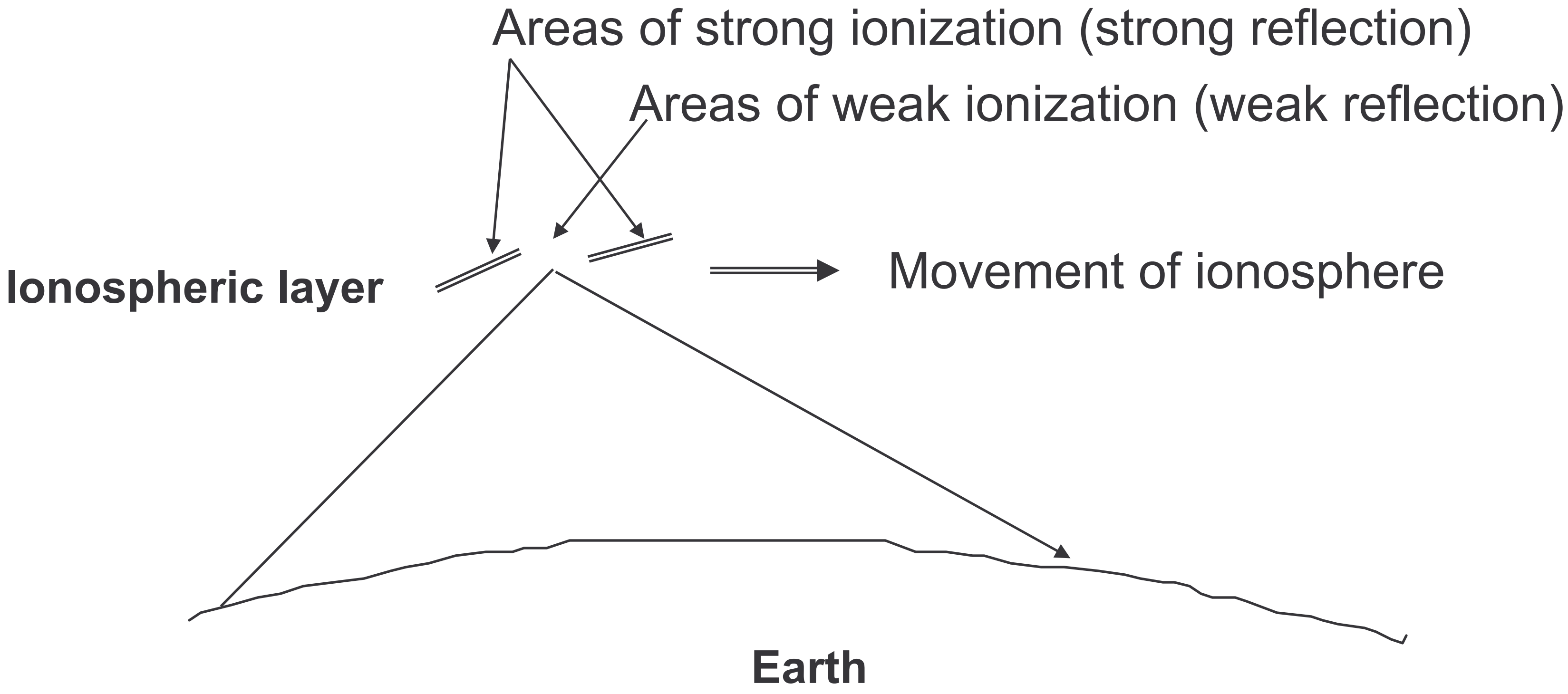
- Two rays are only resolvable when $(d_2 - d_1) > 1/(4\ F_{bw})$
  For F_{bw} = 2 kHz. then $1/(4\ F_{bw})$ = 125 microseconds
  For F_{bw} = 500 Hz. then $1/(4\ F_{bw})$ = 500 microseconds



- Movement of the ionospheric layer results in a *doppler shift* of the reflected wave - in this example, lower in frequency.
- The amount of doppler shift is dependent on the velocity of movement which is somewhat random.

Lateral Movement of Layer

- Fading is random, but with a characteristic upper period known as the *doppler spread*
- This fading is *flat* - not frequency dependent



Areas of strong ionization (strong reflection)

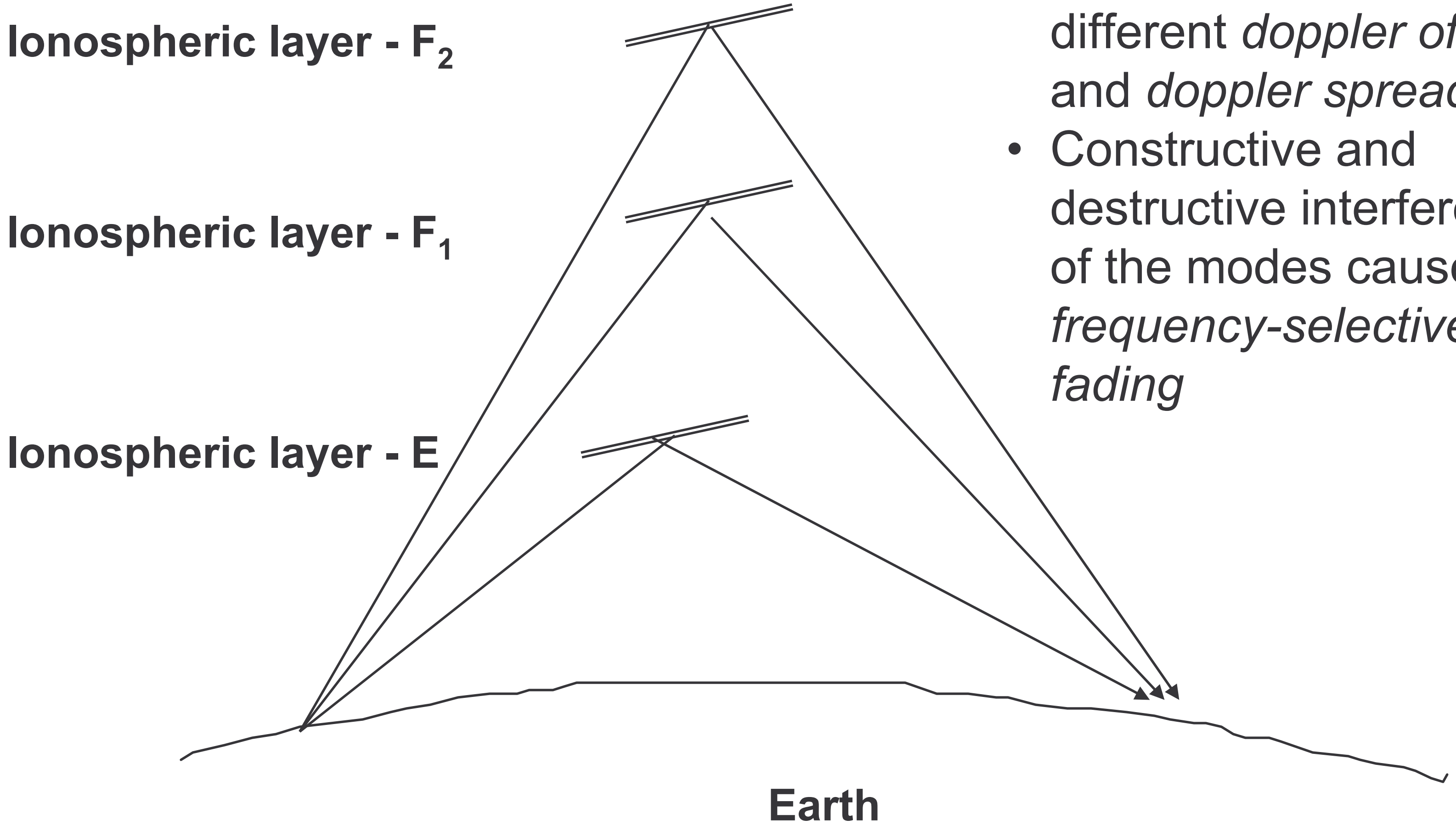
Areas of weak ionization (weak reflection)

Ionospheric layer

Movement of ionosphere

Earth

Multiple Reflective Layers (Modes)

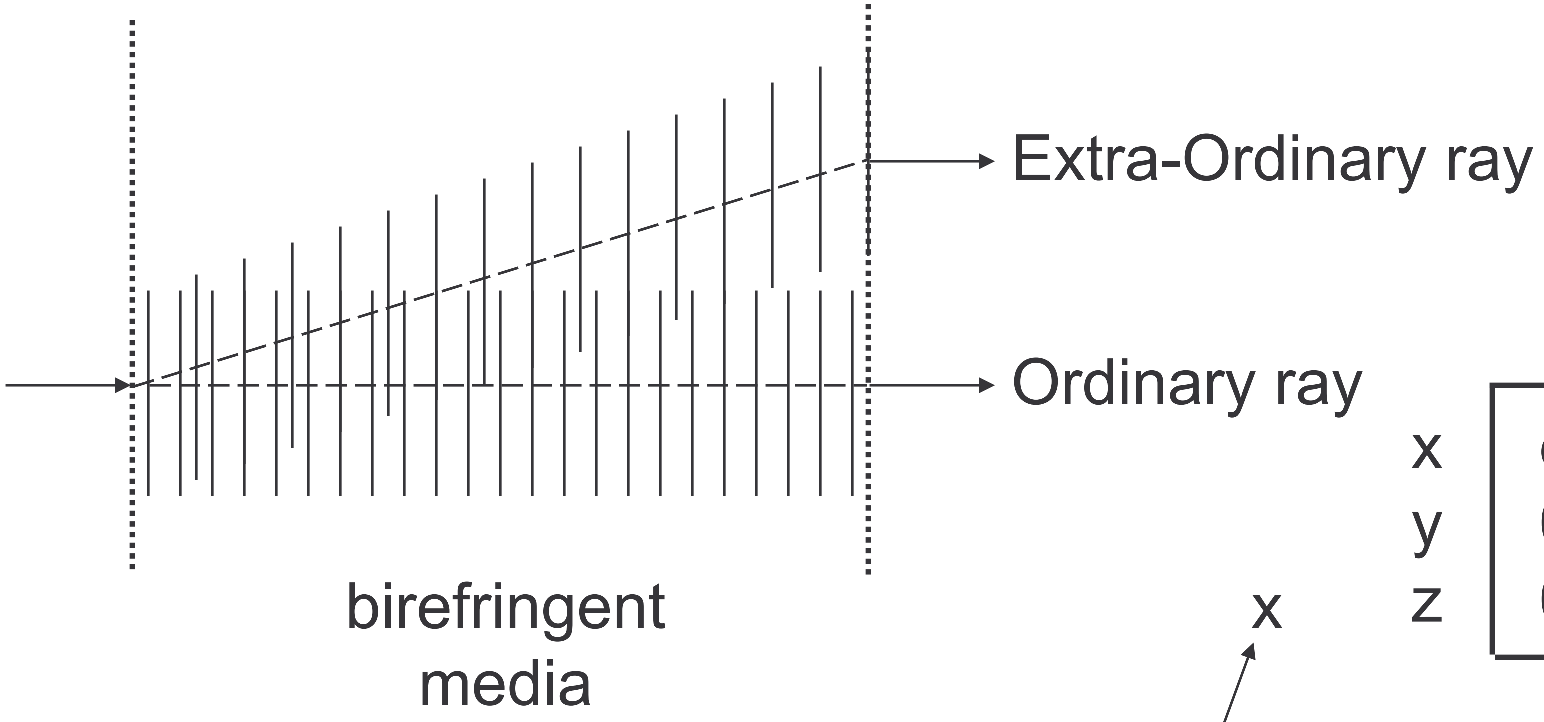


- Each layer has a different *doppler offset* and *doppler spread*
- Constructive and destructive interference of the modes causes *frequency-selective fading*

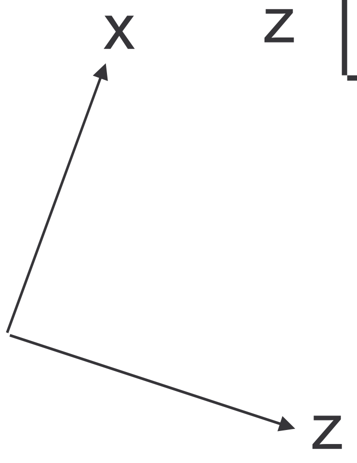
Birefringence

- The Index of refraction can vary with direction of propagation
- This leads to propagation of two EM waves in the medium
- One wave is normal to the direction of incidence - this is the *ordinary ray*
- The other wave propagates at an angle to the incidence - this is the *extra-ordinary ray*
- Thus two waves are generated which arrive at the receiver through different paths
- Watterson found that in the 5-12 Mhz region that:
  - DAYTIME: only the 1E mode has resolvable ordinary and extra-ordinary components
  - NIGHTIME: all 3 modes, 1E, 1F, 2F, have resolvable ordinary and extra-ordinary components

Birefringence



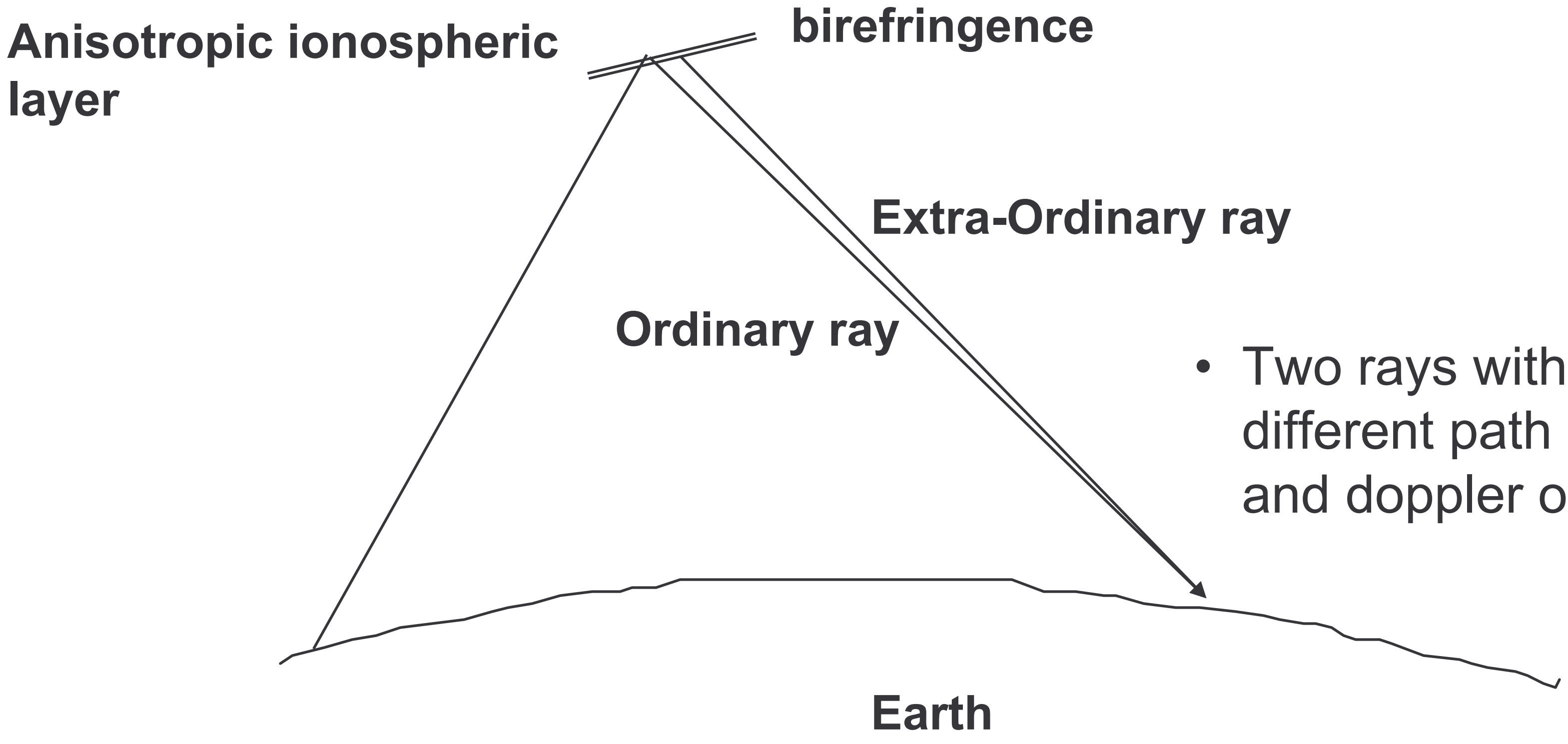
$$\begin{array}{c|ccc|} & x & y & z \\ x & e2 & 0 & 0 \\ y & 0 & e2 & 0 \\ z & 0 & 0 & e1 \end{array}$$



- **When e1 is not equal to e2, then z is called the ‘optical axis’**

Effect of Birefringence

“Magnetoionic Components”



Anisotropic ionospheric layer

birefringence

Extra-Ordinary ray

Ordinary ray

Earth

- Two rays with slightly different path geometries and doppler offsets

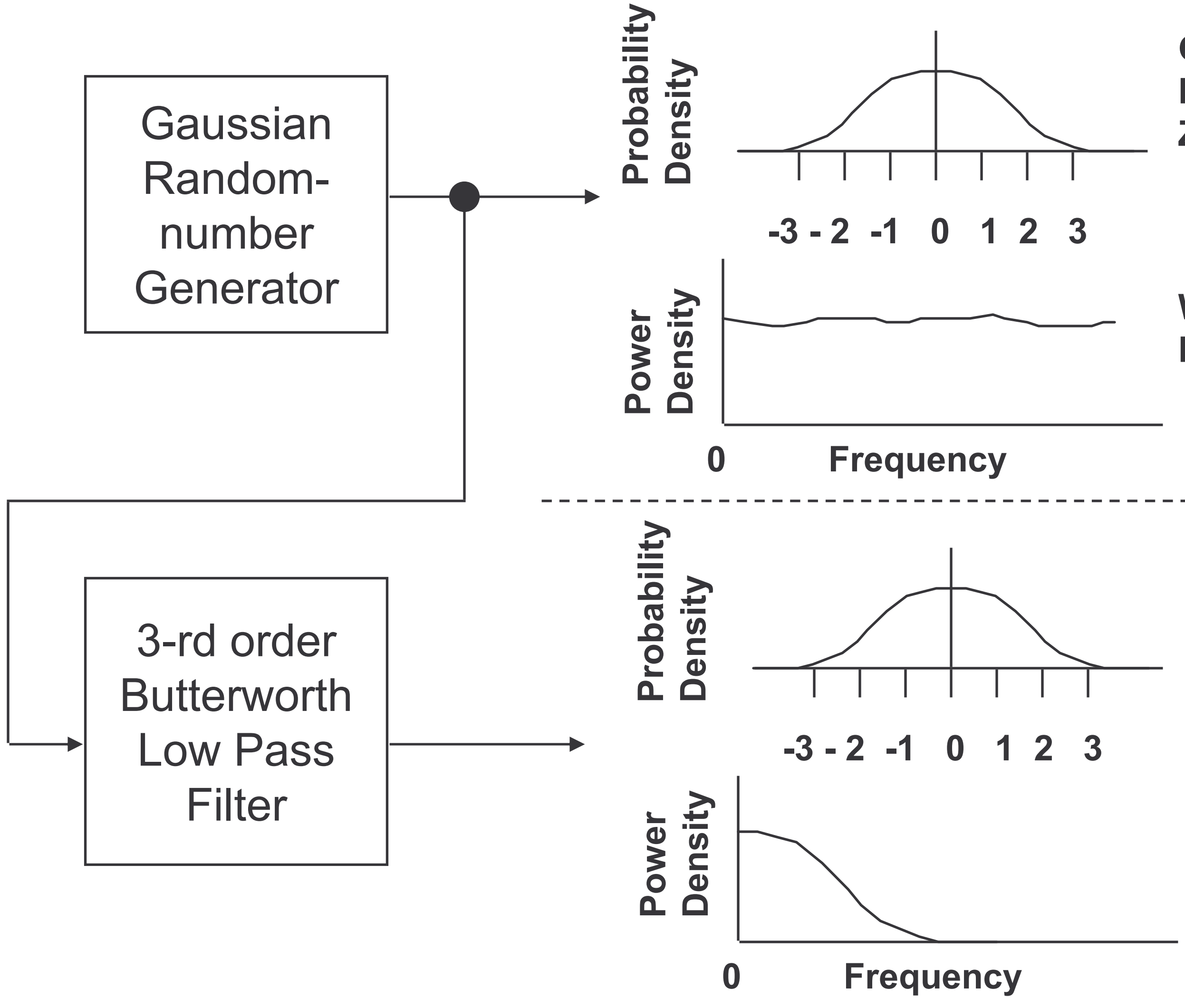
Total Number of Effective Paths

- Both the low-ray and the high-ray each have an ordinary ray and an extra-ordinary ray
- Thus there are 4 paths per mode
- There are usually 3 modes (i.e.: layers), thus a total of about 12 different paths are needed for an accurate simulation
- Most of the time, the 12 paths can only be resolved into 4 or 6 paths
- However, it is emperically derived that most HF modems are well compared against each other with about three paths
- Therefore most HF Simulators implement 3 or 4 paths

Path Characteristics, Simulation

- Each path has Rayleigh random fading, and uniform random phase. The fading rate is known as the *doppler spread*.
- Each path also has a *doppler offset*.
- Watterson, et al. shows that these can be adequately modeled by applying a Gaussian tap-gain spectrum (*doppler spread*) and a frequency offset (*doppler shift*) to each path.
- Rayleigh fading is accomplished by independent gaussian random number generators (amplitude PDF) of the in-phase and the quadrature phase components. The spectrum of which is *white*.
- The Gaussian tap-gain spectrum (PSD) is accomplished by low-pass filtering this Rayleigh fading tap-gain white complex spectrum with a 3-rd order Butterworth filter.
- The low-pass tap-gain spectrum is applied via a complex mixer.
- The frequency offset is applied via another complex mixer.

Generating a Gaussian Tap-Gain Spectrum



Gaussian Random-number Generator

3-rd order Butterworth Low Pass Filter

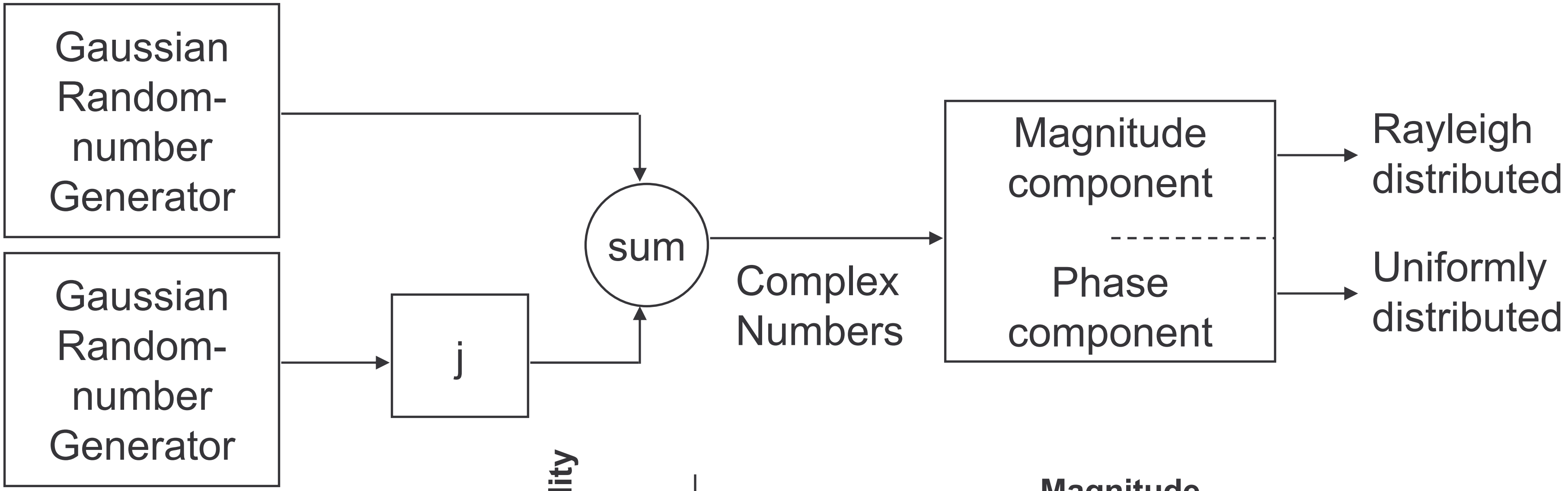
Gaussian Probability
Density Function (PDF)
Zero mean, Unit standard deviation

White Power Spectral
Density (PSD)

Gaussian Probability
Density Function (PDF)
Zero mean, Unit standard deviation

Approximate Half-Gaussian
Power Spectral Density (PSD)

Generating Rayleigh Fading



Gaussian Random-number Generator

Gaussian Random-number Generator

j

sum

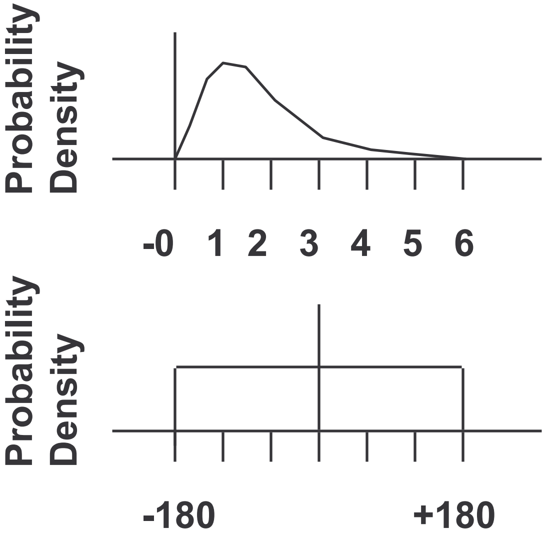
Complex Numbers

Magnitude component

Phase component

Rayleigh distributed

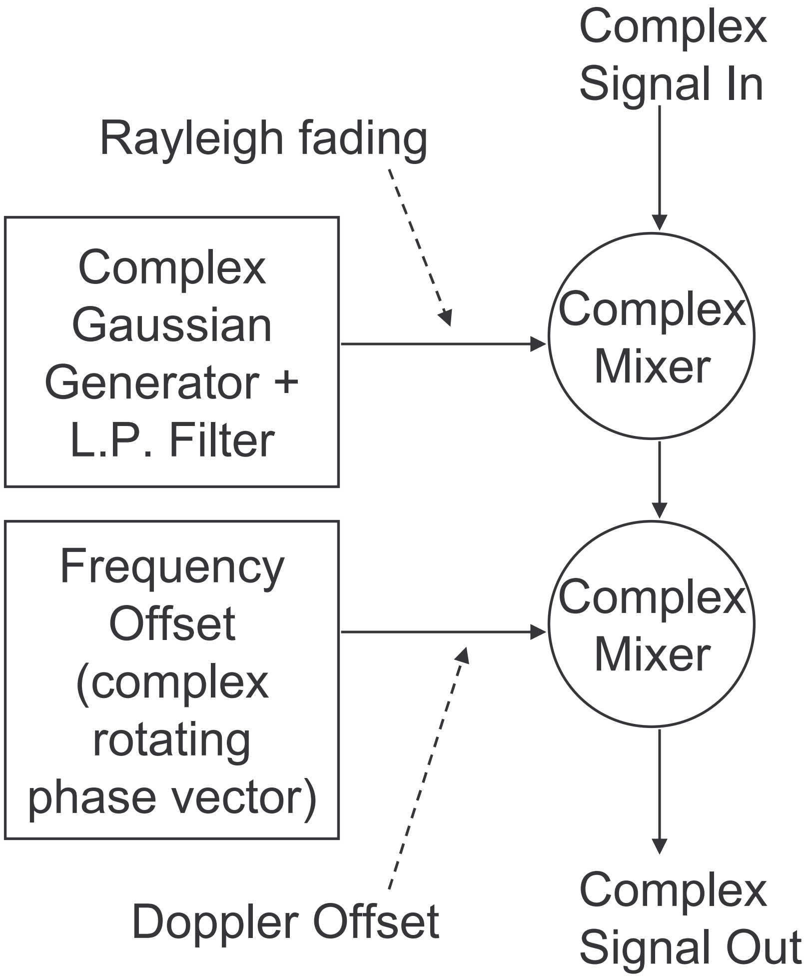
Uniformly distributed



Magnitude - Rayleigh Probability Density Function (PDF)

Phase - Uniform Probability Density Function (PDF)

Tap-Gain Spectrum



Complex
Signal In

Rayleigh fading

Complex
Gaussian
Generator +
L.P. Filter

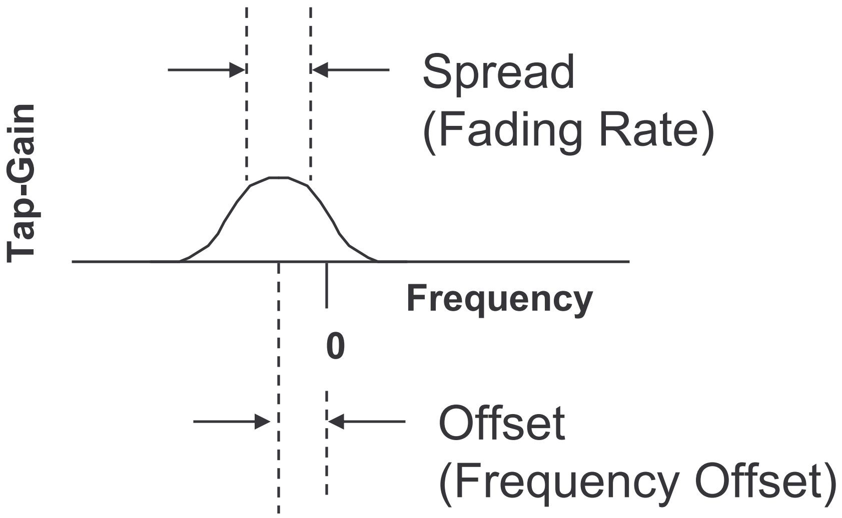
Complex
Mixer

Frequency
Offset
(complex
rotating
phase vector)

Complex
Mixer

Doppler Offset

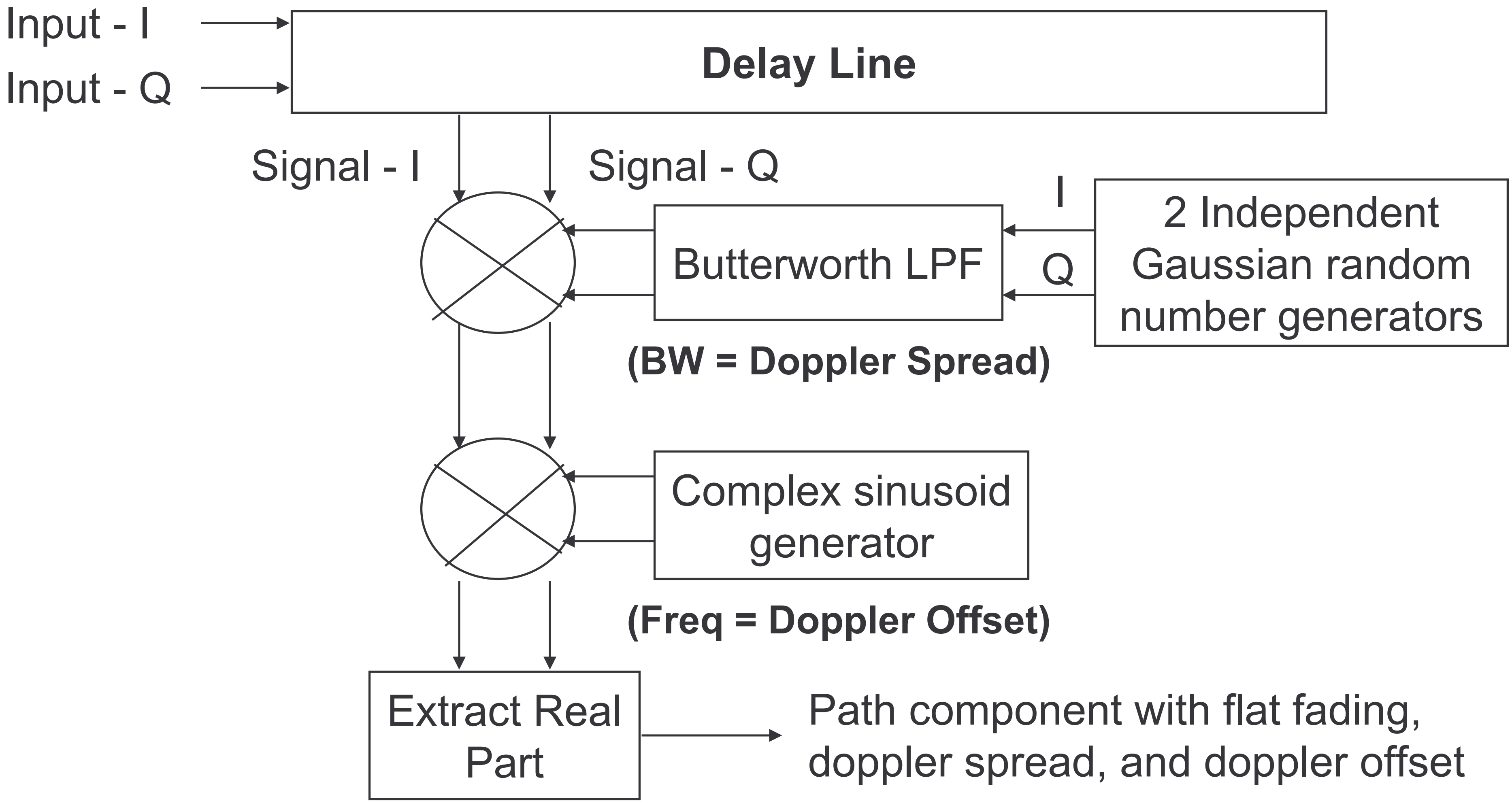
Complex
Signal Out



Spread
(Fading Rate)

Offset
(Frequency Offset)

Modeling One Path



Input - I

Input - Q

Delay Line

Signal - I

Signal - Q

I

Q

2 Independent Gaussian random number generators

Butterworth LPF

(BW = Doppler Spread)

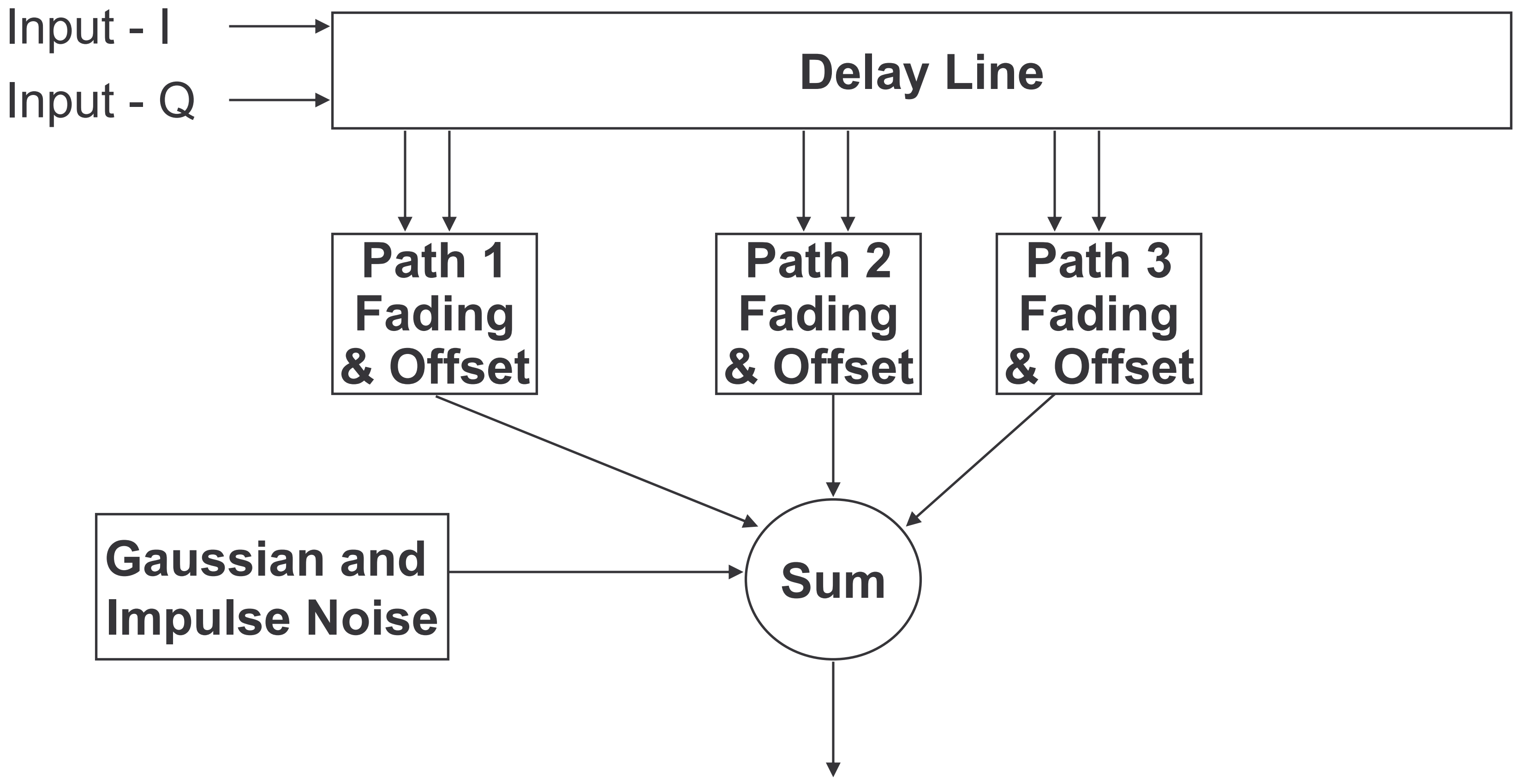
Complex sinusoid generator

(Freq = Doppler Offset)

Extract Real Part

Path component with flat fading, doppler spread, and doppler offset

Modeling Multiple Paths



Input - I

Input - Q

Delay Line

Path 1 Fading & Offset

Path 2 Fading & Offset

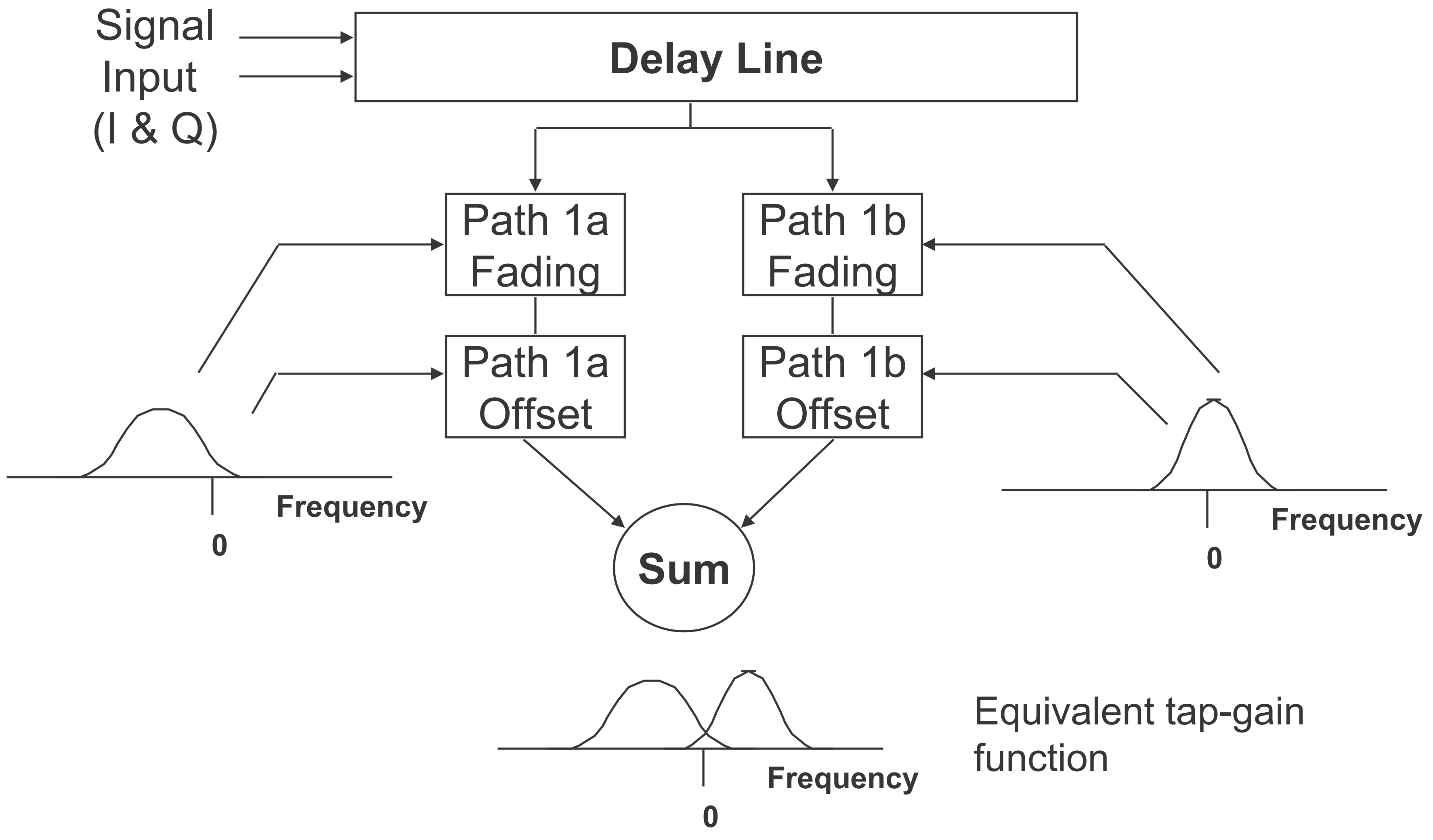
Path 3 Fading & Offset

Gaussian and Impulse Noise

Sum

Output with multipath, flat fading,
selective fading, and noise

Modeling the Magnetoionic Components



Signal
Input
(I & Q)

Delay Line

Path 1a
Fading

Path 1a
Offset

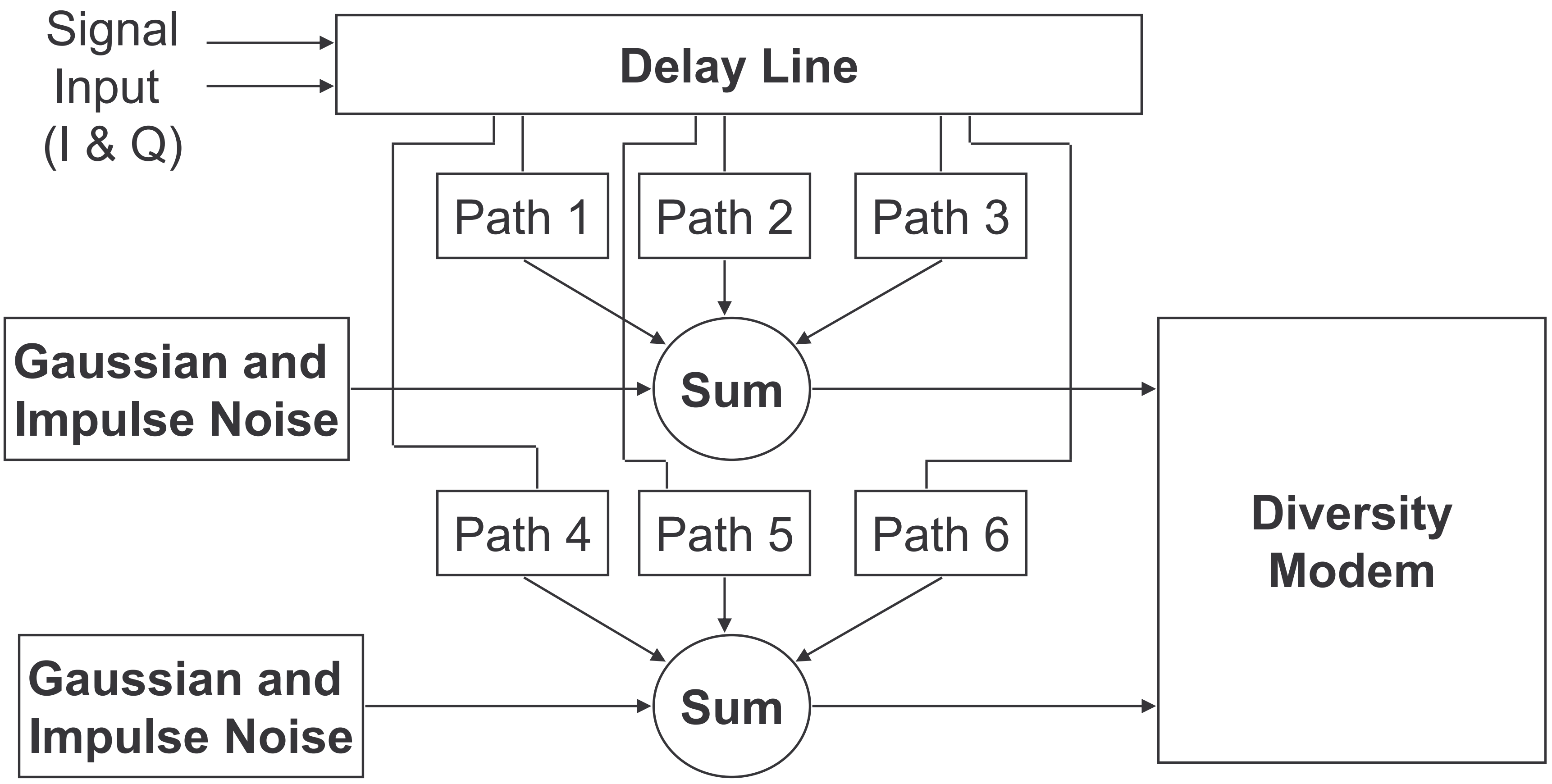
Path 1b
Fading

Path 1b
Offset

Sum

Equivalent tap-gain
function

Testing A Diversity Modem



Signal Input (I & Q)

Delay Line

Path 1

Path 2

Path 3

Gaussian and Impulse Noise

Sum

Path 4

Path 5

Path 6

Diversity Modem

Gaussian and Impulse Noise

Sum

CCIR 520-1 Standard Test Conditions

- **Test 2.1: Single path, flat fading 0.2 Hz and 1.0 Hz. : plot BER vs. Eb/No (Gaussian noise)**
- **Test 2.2: Two paths, equal mean attenuation, equal doppler spreads : plot BER vs. Eb/No (Gaussian noise)**
  - **Good Conditions:**
    - **0.5 millisecond differential delay**
    - **0.1 Hz. frequency spread**
  - **Moderate Conditions:**
    - **1.0 millisecond differential delay**
    - **0.5 Hz. frequency spread**
  - **Poor Conditions:**
    - **2.0 millisecond differential delay**
    - **1.0 Hz. frequency spread**
  - **Flutter fading:**
    - **0.5 millisecond differential delay**
    - **10.0 Hz. frequency spread**

CCIR 520-1 Standard Test Conditions

- **Test 2.3: Two paths, equal mean attenuation, equal doppler spreads : plot BER vs. Eb/No (Gaussian noise)**
  - **0.5 millisecond differential delay**
  - **0.2 Hz. frequency spread**
  - **0 to 10 Hz. frequency offset**

References

- Watterson, C. et al., “Experimental Confirmation of an HF Channel Model”, IEEE Transactions on Communications Technology, Vol. COM-18, No. 6, December 1970
- Ehrman, L. et al., “Real-Time Software Simulation of the HF Radio Channel”, IEEE Transactions on Communications, Vol. COM-30, No. 8, August 1982
- CCIR Recommendation 520-1, “Use of High Frequency Ionospheric Channel Simulators”, 1982
- CCIR Report 549-3, “HF Ionospheric Channel Simulators”, 1990