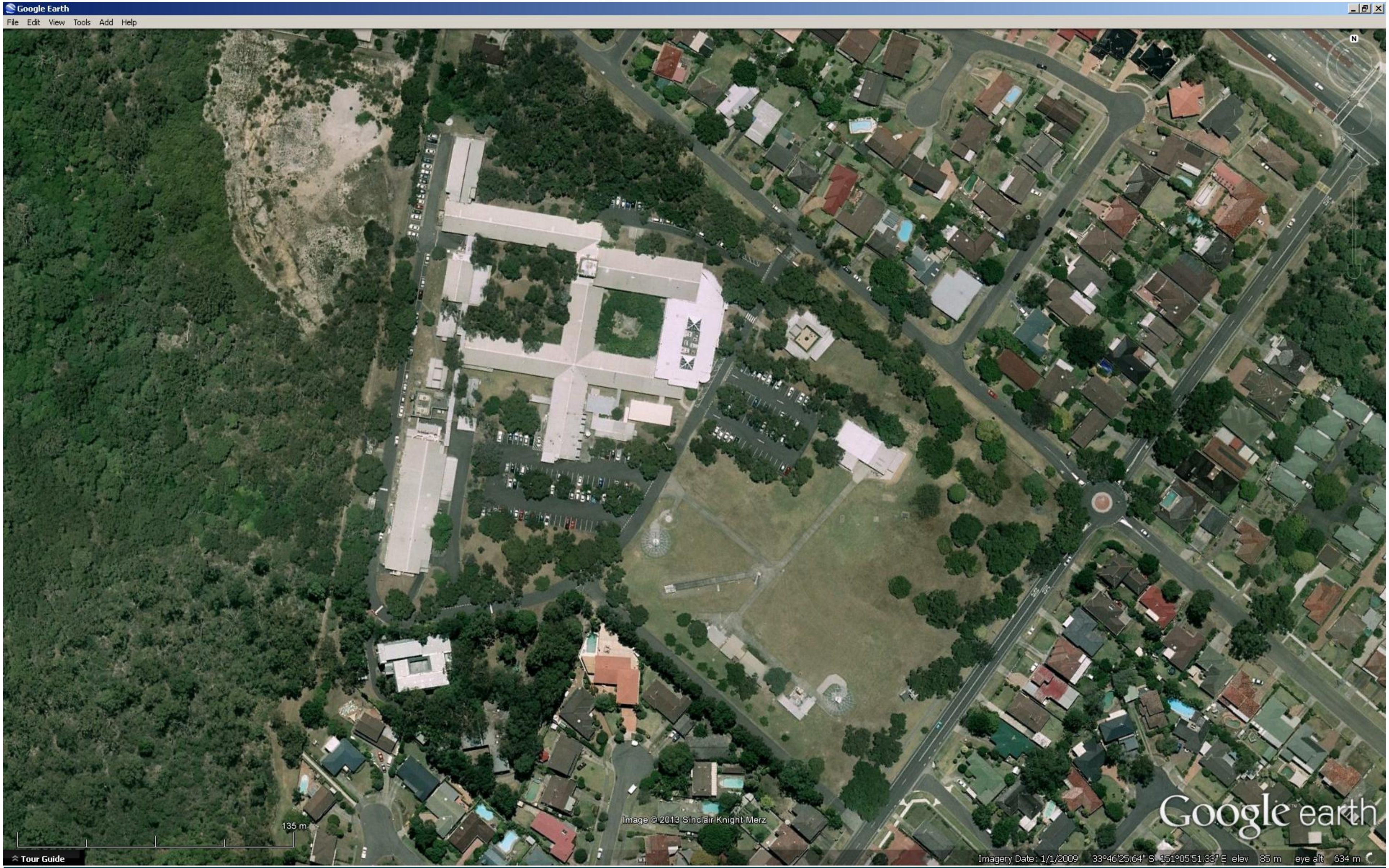
Mm-Wave Propagation: Fundamentals and Models

Hajime Suzuki

7 April 2014

CSIRO Radio Physics Laboratory



Coded OFDM Wireless LAN

US005487069A

United States Patent [19]

O'Sullivan et al.

[11] **Patent Number: 5,487,069**

[45] **Date of Patent: Jan. 23, 1996**

[54] **WIRELESS LAN**

[75] Inventors: **John D. O'Sullivan**, Ermington; **Graham R. Daniels**, Willoughby; **Terence M. P. Percival**, Lane Cove; **Diethelm I. Ostry**, Petersham; **John F. Deane**, Eastwood, all of Australia

[73] Assignee: **Commonwealth Scientific and Industrial Research Organisation**, Australia

[21] Appl. No.: **157,375**

[22] Filed: **Nov. 23, 1993**

[30] **Foreign Application Priority Data**

Nov. 27, 1992 [AU] Australia PL6069

[51] **Int. Cl.**^{6} **H04B 7/01**

[52] **U.S. Cl.** **370/94.3**; 375/284; 375/348; 455/52.3; 455/65

[58] **Field of Search** 375/34, 39, 51, 375/57, 58, 99, 101, 254, 261, 279, 284, 285, 346, 348; 370/95.3; 455/56.1, 54.1, 63, 65, 52.3

26–line 35.

IEEE Transactions on Communications, vol. 39, No. 5, May 1991, New York US pp. 783–793 E. F. Casas et al. 'OFDM for Data Communication over Mobile Radio FM Channels—Part I: Analysis and Experimental Results' p. 784, left col., line 1—right col., line 2; FIG. 1 p. 790, right col., line 18–line 22.

42nd VTS Conference vol. 2, May 1992, Denver US pp. 819–822 T. Le–Ngoc 'A CSMA/CD Portable Data System Using Adaptive Reed–Solomon Coding' p. 820, left col., line 2–line 9.

IEEE Transactions on Communications, vol. 33, No. 7, Jul. 1985, New York US pp. 665–675 L. J. Cimini Jr. 'Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing' par. I–par. II. Par IV.

Primary Examiner—Benedict V. Safourek
Attorney, Agent, or Firm—William S. Frommer

[57] **ABSTRACT**

The present invention discloses a wireless LAN, a peer-to-peer wireless LAN, a wireless transceiver and a method of transmitting data, all of which are capable of operating at


40 GHz TRANSMITTER
PLL ALARMS
960 MHz
UNLOCKED
2 GHz
UNLOCKED
40 GHz
UNLOCKED
REFERENCE FREQUENCY
INTERNAL
EXTERNAL
INPUT
OUTPUT
REF FREQUENCY ADJUSTMENT
MANUAL ADJUST
EXTERNAL
IF MIXER BIAS ADJUSTMENT
I
Q
EXTERNAL I
EXTERNAL Q
RF OUTPUT
TRANSMIT POWER CONTROL
RF LEVEL
EXT POWER CONTROL
RF LEVEL OUTPUT
IF MONITOR
OUTPUT
IF LINK
IF OUTPUT
MIXER INPUT
BASEBAND INPUTS
I
Q
DAC
PC INTERFACE
ACTIVE
STATE CONTROL
RUN
STOP
MODE CONTROL
SINGLE
CONT
CLOCK SELECTION
INT
EXT
CLOCK INPUT
ECL
50 OHM
NO CLK
CLOCK OUTPUTS
ECL
50 OHM
CLOCK
CLOCK
SEQUENCE TRIGGER
TTL
50 OHM
INPUT
OUTPUT
AUXILIARY DAC OUTPUTS
0 – +10 V
1 k OHM
AUX 0
AUX 1
AUX 2
AUX 3
MAIN DAC OUTPUTS
+/– 0.25 V
50 OHM
I
Q


40 GHz RECEIVER
PLL ALARMS
960 MHz
UNLOCKED
2 GHz
UNLOCKED
40 GHz
UNLOCKED
REFERENCE FREQUENCY
INTERNAL
EXTERNAL
INPUT
OUTPUT
REF FREQUENCY ADJUSTMENT
MANUAL ADJUST
EXTERNAL
IF MIXER BIAS ADJUSTMENT
I
Q
EXTERNAL I
EXTERNAL Q
RF INPUT
AUTOMATIC GAIN CONTROL
ATTENUATOR LEVEL
MAN/EXT
EXT ATTN CONTROL
ATTN LEVEL OUTPUT
IF MONITOR
OUTPUT
IF LINK
MIXER OUTPUT
IF INPUT
BASEBAND OUTPUTS
I
Q
ADC
PC INTERFACE
ACTIVE
START ACQUISITION
RUNNING
TRIGGER ENABLE
ARMED
STORED
CLOCK SELECTION
INT
EXT
CLOCK INPUT
ECL
50 OHM
NO CLK
CLOCK OUTPUTS
ECL
50 OHM
CLOCK
CLOCK
SEQUENCE TRIGGER
TTL
50 OHM
INPUT
OUTPUT
AUXILIARY DAC OUTPUTS
0 – +10 V
1 k OHM
AUX 0
AUX 1
AUX 2
AUX 3
ADC INPUTS
+/–1.0V
50 OHM
I
Q

Multigigabit mm-Wave PtoP System

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 55, NO. 12, DECEMBER 2007 2813

A Multigigabit Millimeter-Wave Communication System With Improved Spectral Efficiency

Val Dyadyuk, *Member, IEEE*, John D. Bunton, *Senior Member, IEEE*, Joseph Pathikulangara, Rodney Kendall, Oya Sevimli, *Senior Member, IEEE*, Leigh Stokes, and David A. Abbott

***Abstract*—This paper describes the details of a new method for improved spectral efficiency in a multigigabit millimeter-wave communication system, and the outdoor and indoor test results of a 6-Gbit/s concept demonstrator in the 81–86-GHz frequency band. Achieved aggregate data with a 2.4-bit/s/Hz spectral efficiency was the fastest wireless transmission published thus far with a carrier-grade bit error rate over a millimeter-wave link.**

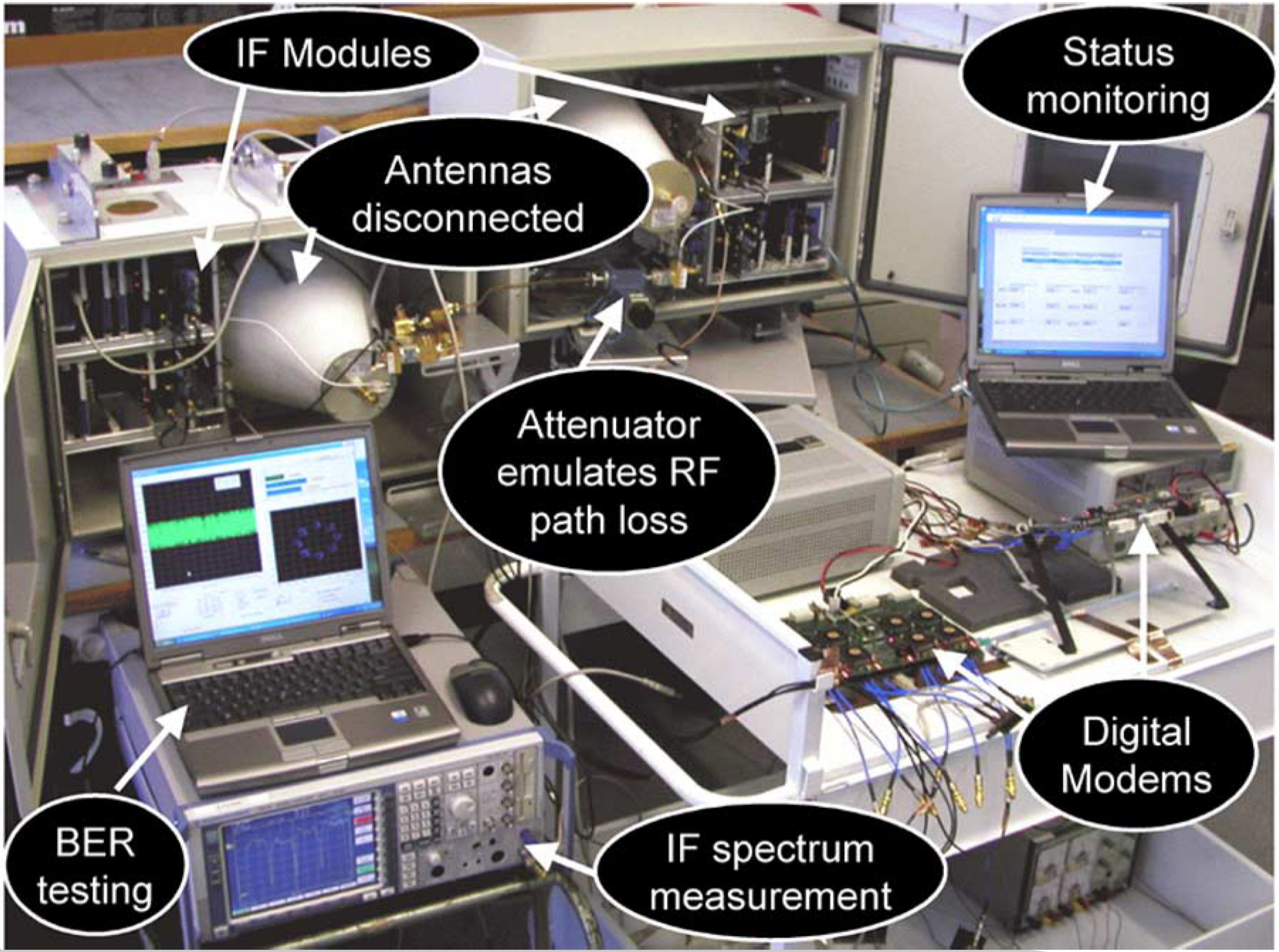
***Index Terms*—Communication systems, millimeter-wave radio communication, monolithic microwave integrated circuits (MIMICs), modems, phase-shift keying, transceivers.**

I. Introduction

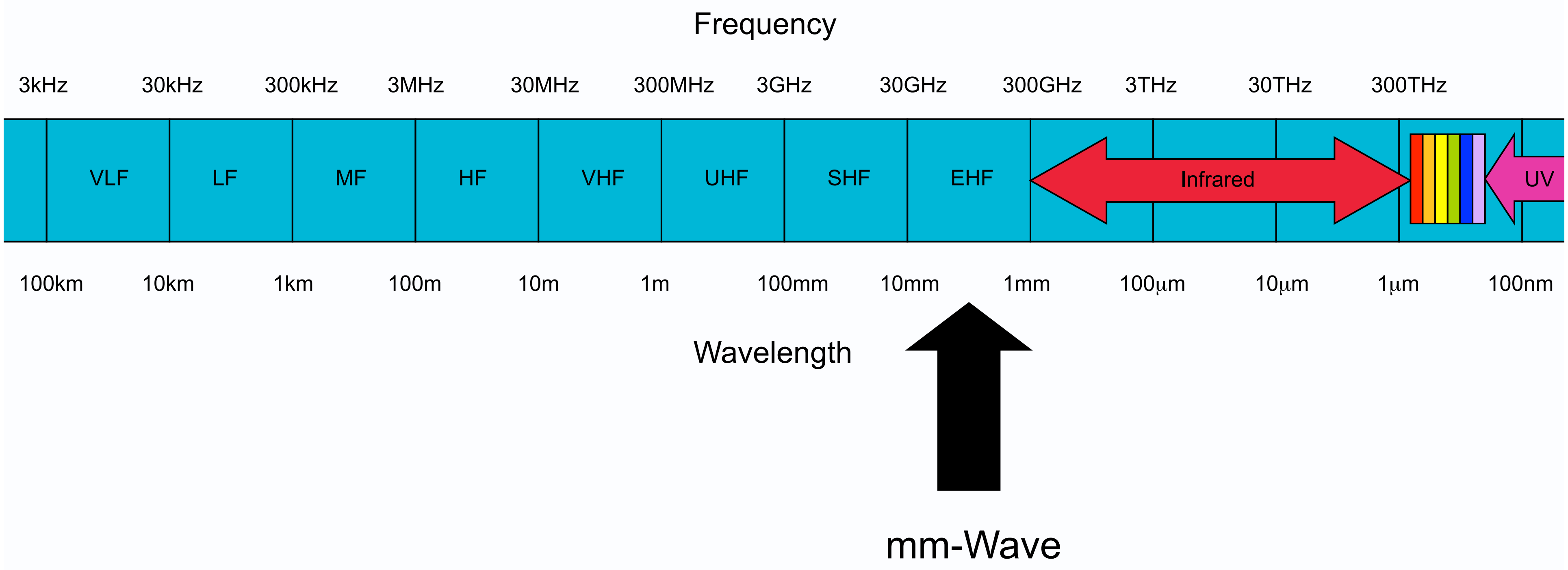
DEMAND FOR very high-speed wireless communication is increasing due to the increasing computer and fiber speeds. Gigabit Ethernet standard (GbE) is now widespread and 10 Gigabit Ethernet (10 GbE) standard has been available since 2002. While known fiber-optic data-transfer devices can

Current commercial point-to-point wireless links[1,2,3,4,5] in the millimeter-wave spectrum are limited to speeds up to 1.25 Gbit/s and use simple modulation techniques like amplitude shift keying (ASK) or binary phase-shift keying (BPSK) with spectral efficiency below 1 bit/s/Hz. As an alternative, a 120-GHz band photonic wireless link with 10-Gbit/s data rate has been reported achieving error-free transmission of 10-GbE signals over a distance of 200 m [3]. In this case, the millimeter-wave signal was optically modulated by intensity modulation and demodulated by envelope detection. The signal occupied 17-GHz bandwidth (BW) with a 0.6-bit/s/Hz spectral efficiency. Another group [4] have reported 5.2-Gbit/s combined data rate over a 60-m outdoor path using four quadrature amplitude modulation (4QAM) over three separate RF bands (2–7 GHz) with 1.6-bit/s/Hz spectral efficiency, and suggested that 10.4 Gbit/s could be achieved if combined with polarization-based frequency reuse.

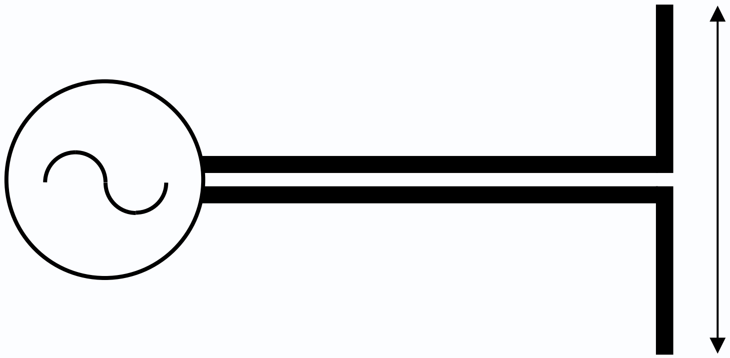
Although over 19 GHz of millimeter-wave spectrum is available for fixed communication services with allocated continuous BW up to 5 GHz, practical realization of efficient


IF Modules
Status monitoring
Antennas disconnected
Attenuator emulates RF path loss
Digital Modems
BER testing
IF spectrum measurement

mm-Wave

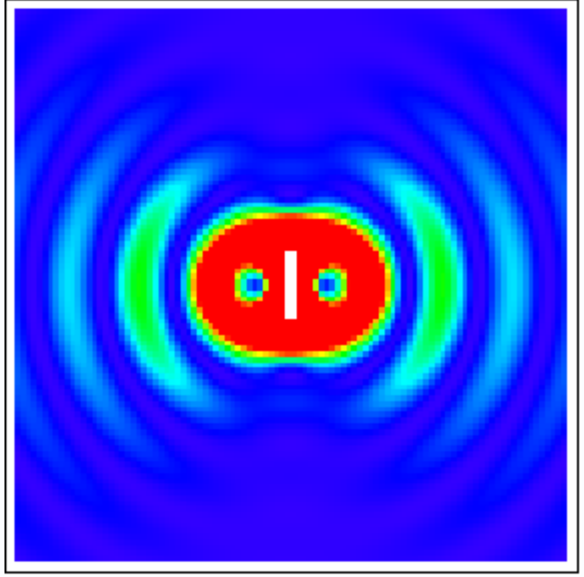

Frequency
3kHz
30kHz
300kHz
3MHz
30MHz
300MHz
3GHz
30GHz
300GHz
3THz
30THz
300THz
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
Infrared
UV
100km
10km
1km
100m
10m
1m
100mm
10mm
1mm
100μm
10μm
1μm
100nm
Wavelength
mm-Wave

How to Generate Electromagnetic Wave



Half wavelength, e.g. 5 mm at 30 GHz

Half-Wave Dipole Radiation



http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/halfdip/halfdip-j.html

Friis Transmission Formula

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

P_r : Received power (W)

P_t : Transmitted power (W)

G_t : Transmitter antenna gain

G_r : Receiver antenna gain

λ : Wavelength (m)

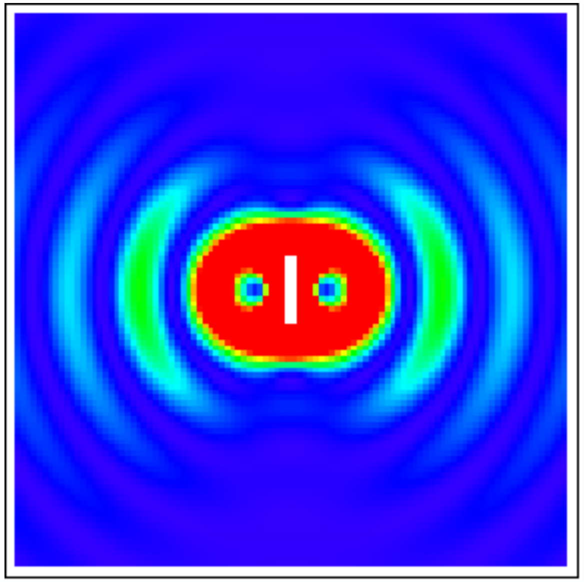
d : Distance (m)

Friis Transmission Formula

$$P_r[\mathrm{dBm}] = P_t[\mathrm{dBm}] + G_t[\mathrm{dBi}] + G_r[\mathrm{dBi}] - \left(32.4 + 20\log_{10} f[\mathrm{MHz}] + 20\log_{10} d[\mathrm{km}]\right)$$

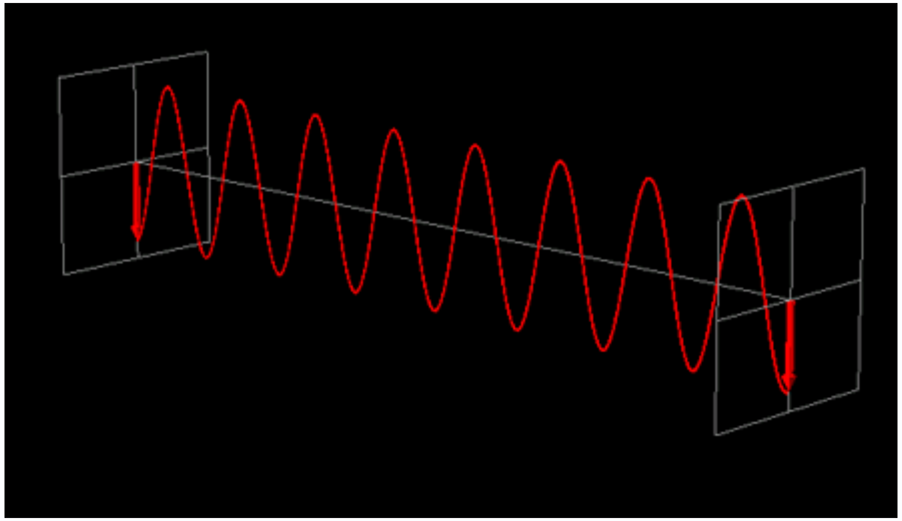
$$P_r[\mathrm{dBm}] = P_t[\mathrm{dBm}] + G_t[\mathrm{dBi}] + G_r[\mathrm{dBi}] - \left(32.4 + 20\log_{10} f[\mathrm{GHz}] + 20\log_{10} d[\mathrm{m}]\right)$$

Half-Wave Dipole Radiation



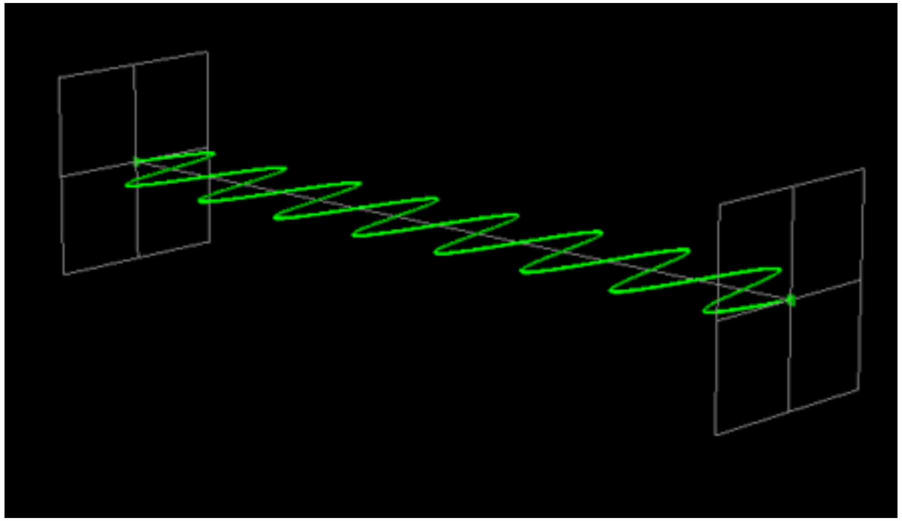
http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/halfdip/halfdip-j.html

Vertically Polarized Wave



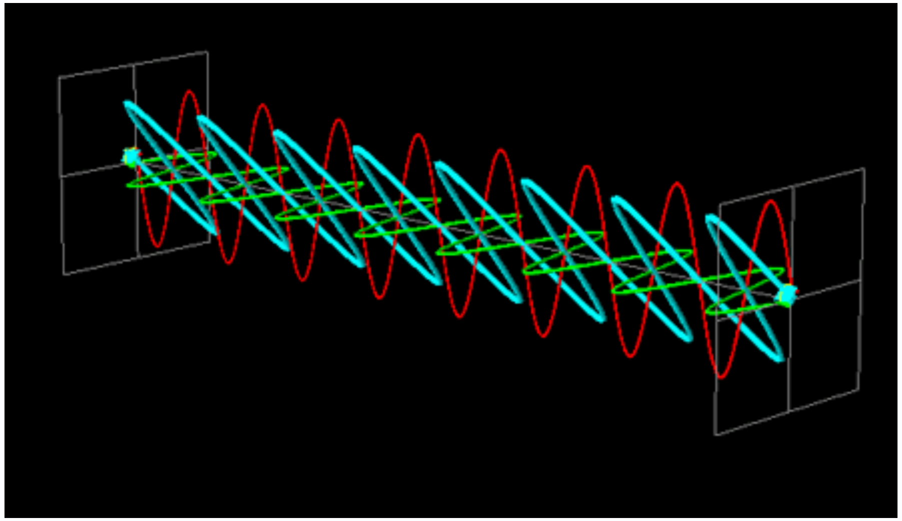
http://www.photophysics.com/tutorials/circular-dichroism-cd-spectroscopy/1-understanding-circular-dichroism

Horizontally Polarized Wave



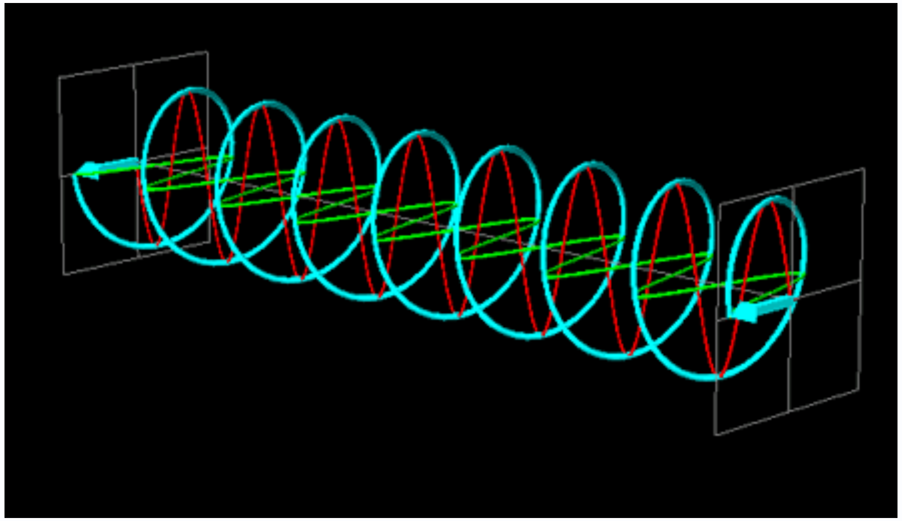
http://www.photophysics.com/tutorials/circular-dichroism-cd-spectroscopy/1-understanding-circular-dichroism

Linearly Polarized Wave



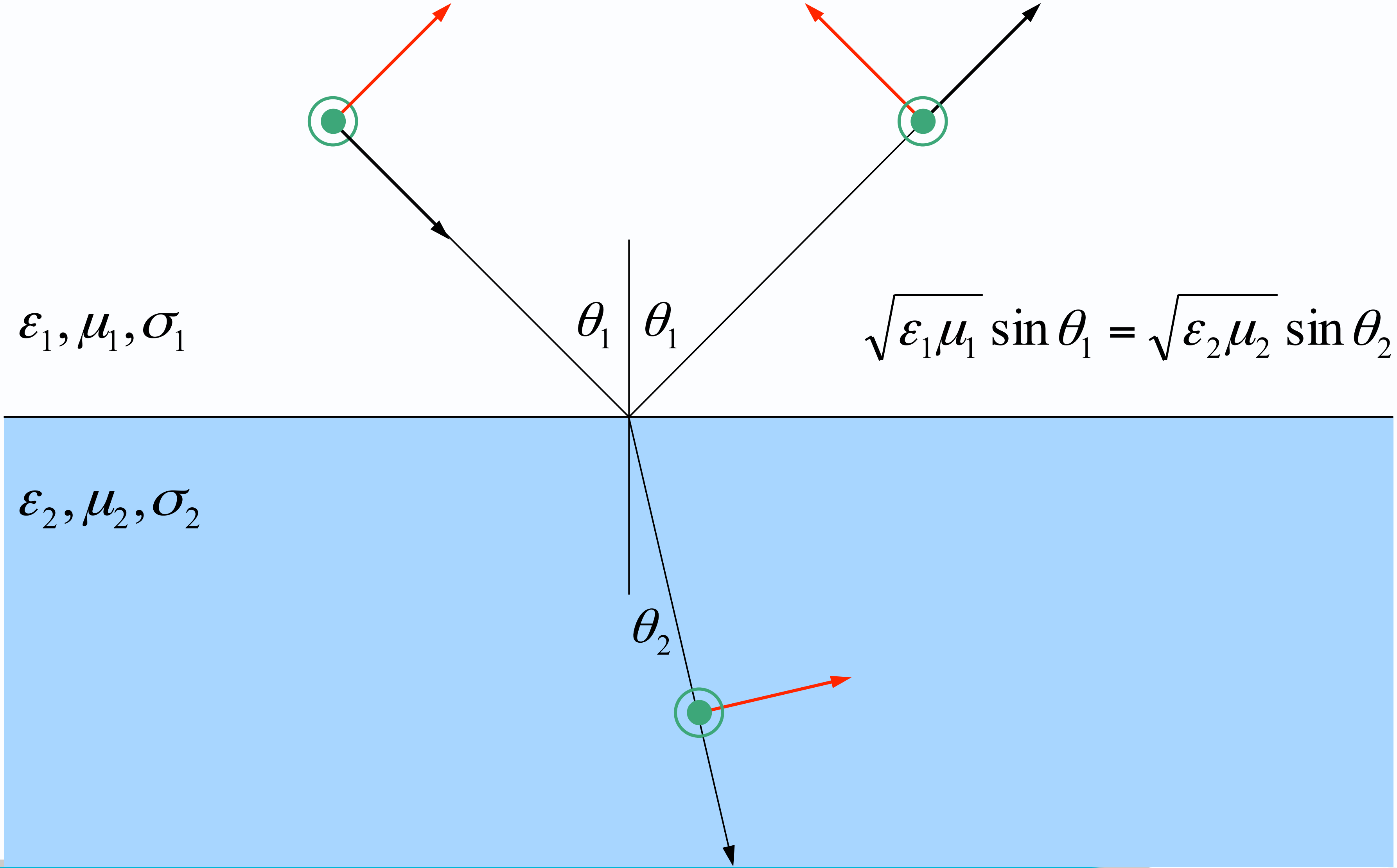
http://www.photophysics.com/tutorials/circular-dichroism-cd-spectroscopy/1-understanding-circular-dichroism

Circularly Polarized Wave



http://www.photophysics.com/tutorials/circular-dichroism-cd-spectroscopy/1-understanding-circular-dichroism

Reflection and Refraction



$$\sqrt{\varepsilon_1 \mu_1} \sin \theta_1 = \sqrt{\varepsilon_2 \mu_2} \sin \theta_2$$

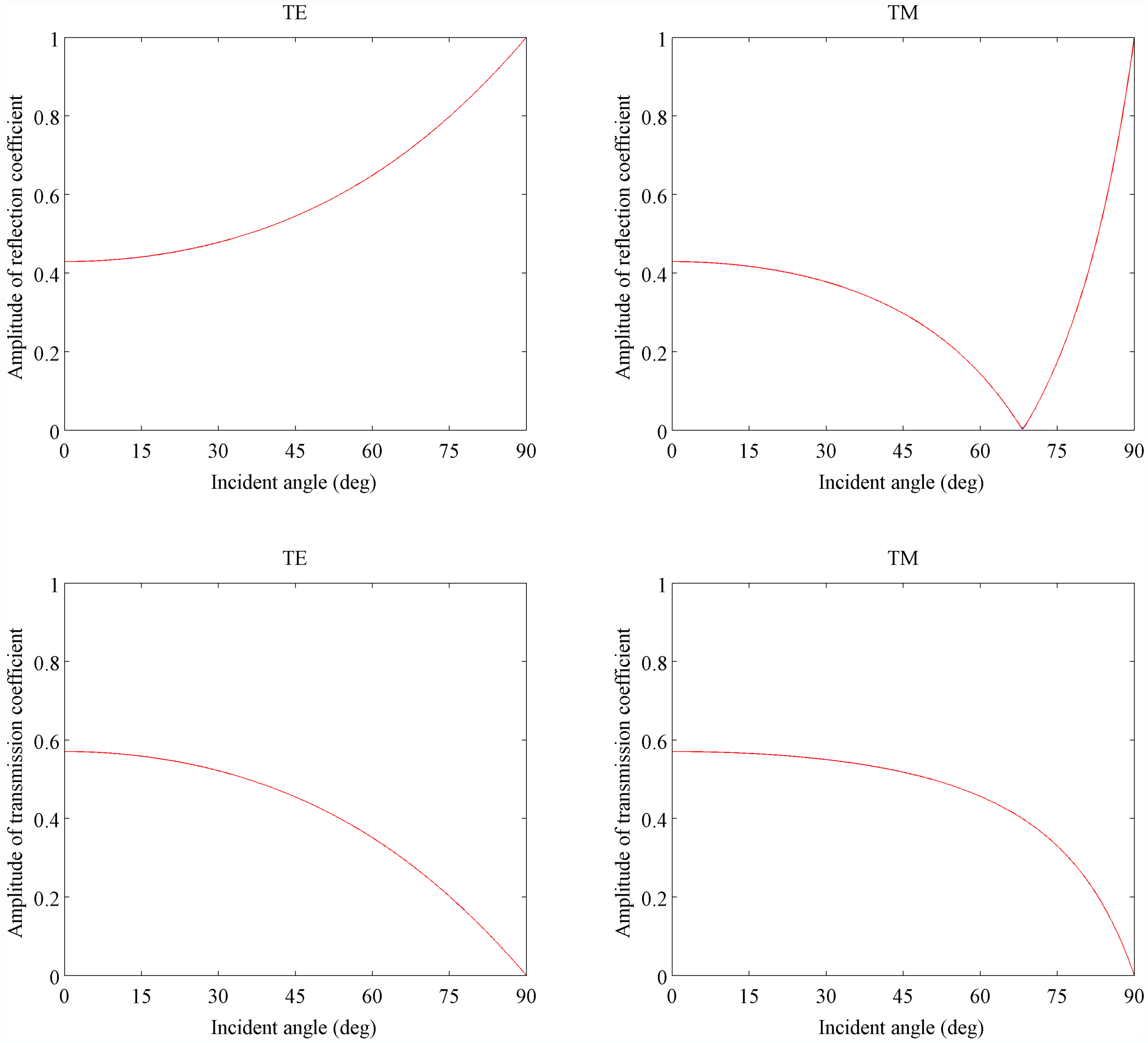
Electrical Properties of Material

$$\varepsilon_r' = a\left(f[\mathrm{GHz}]\right)^b \qquad \sigma = c\left(f[\mathrm{GHz}]\right)^d \ [\mathrm{S/m}]$$

Material class	Relative permittivity		Conductivity		Frequency range
	a	b	c	d	GHz
Concrete	5.31	0	0.0326	0.8095	1-100
Brick	3.75	0	0.038	0	1-10
Plasterboard	2.94	0	0.0116	0.7076	1-100
Wood	1.99	0	0.0047	1.0718	0.001-100
Glass	6.27	0	0.0043	1.1925	0.1-100
Ceiling board	1.50	0	0.0005	1.1634	1-100
Chipboard	2.58	0	0.0217	0.7800	1-100
Floorboard	3.66	0	0.0044	1.3515	50-100
Metal	1	0	10^7	0	1-100
Very dry ground	3	0	0.00015	2.52	1-10 only
Medium dry ground	15	−0.1	0.035	1.63	1-10 only
Wet ground	30	−0.4	0.15	1.30	1-10 only

ITU-R P.2040 Effects of building materials and structures on radiowave propagation above about 100 MHz

Reflection and Transmission Coefficients

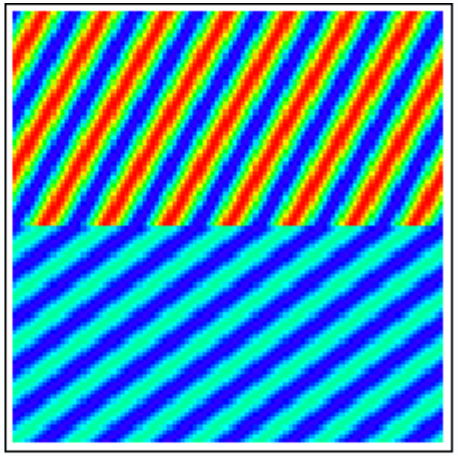


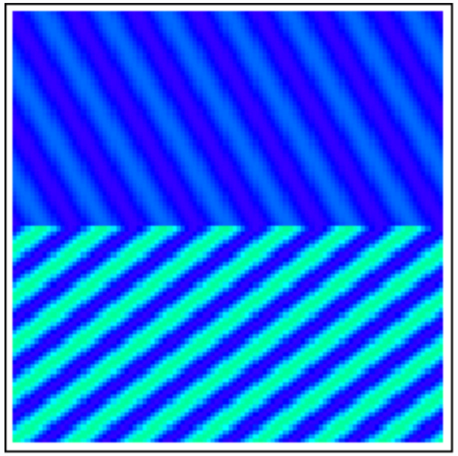
ITU-R P.2040

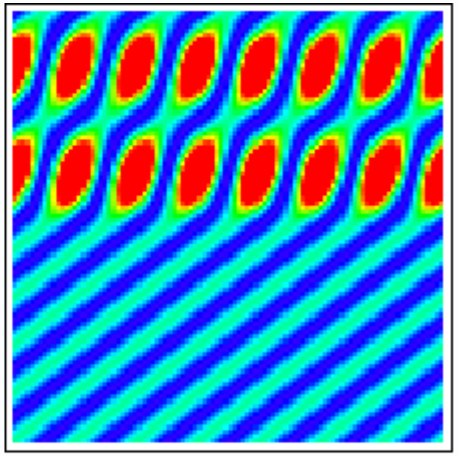
Glass

30 GHz

Reflection and Refraction





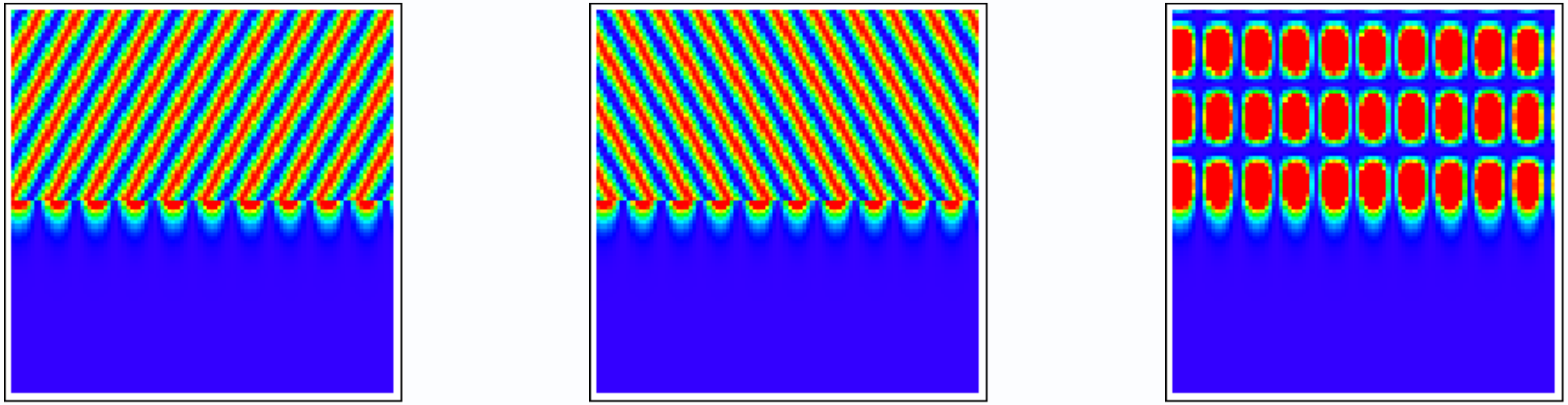


http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/fresnel/index.html

Standing Wave

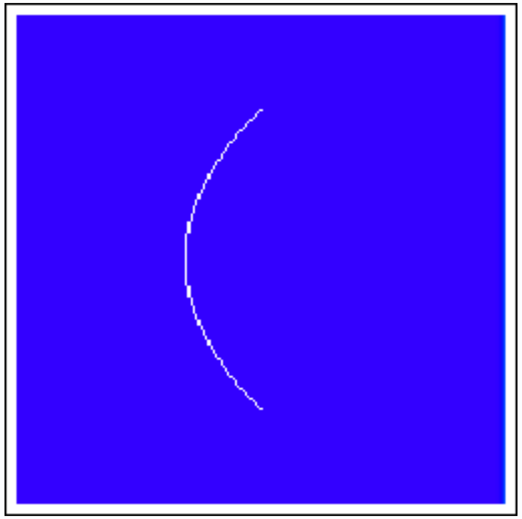
http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/fresnel/index.html

Total Reflection



http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/fresnel/index.html

Reflection of Parabola Antenna



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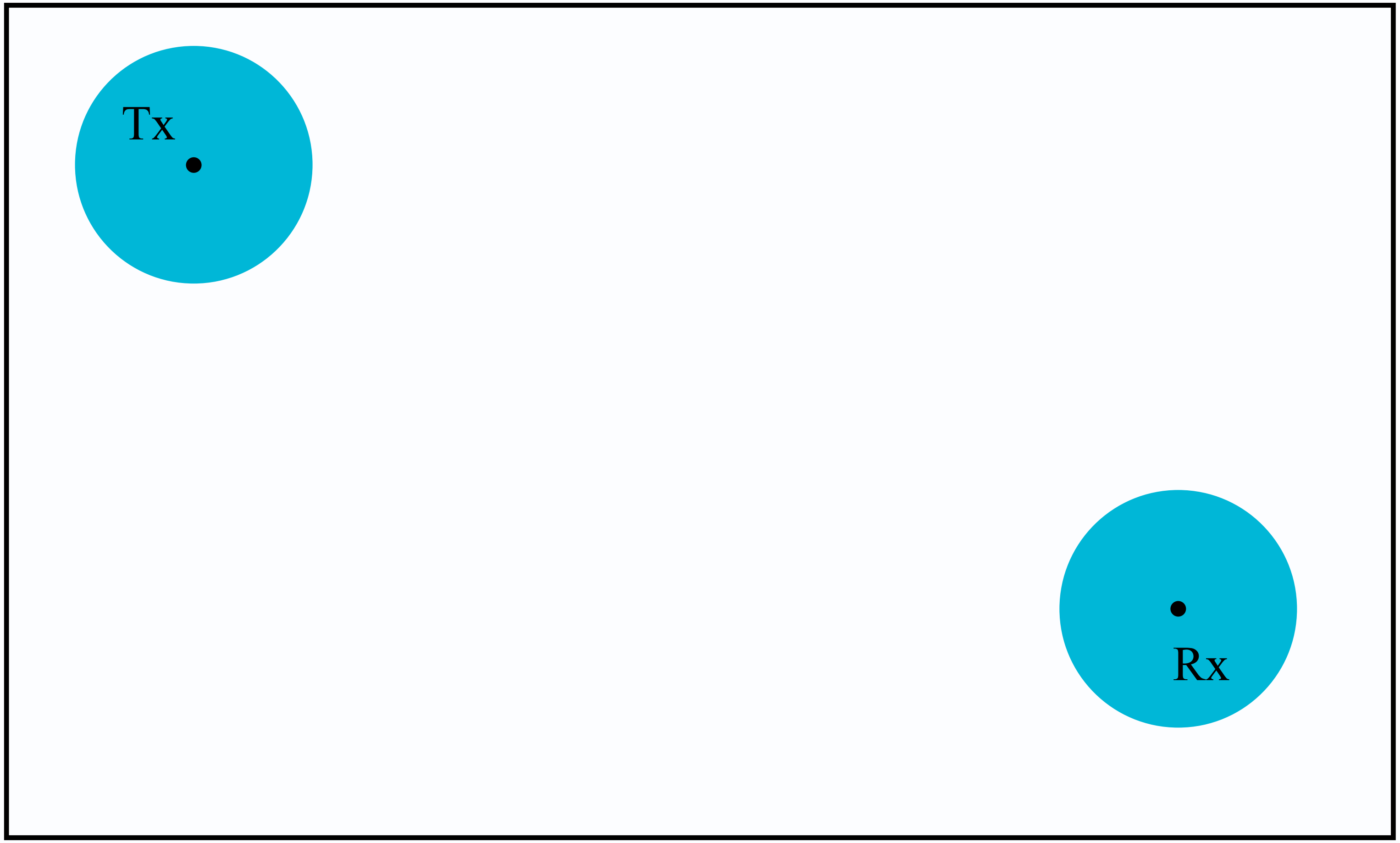
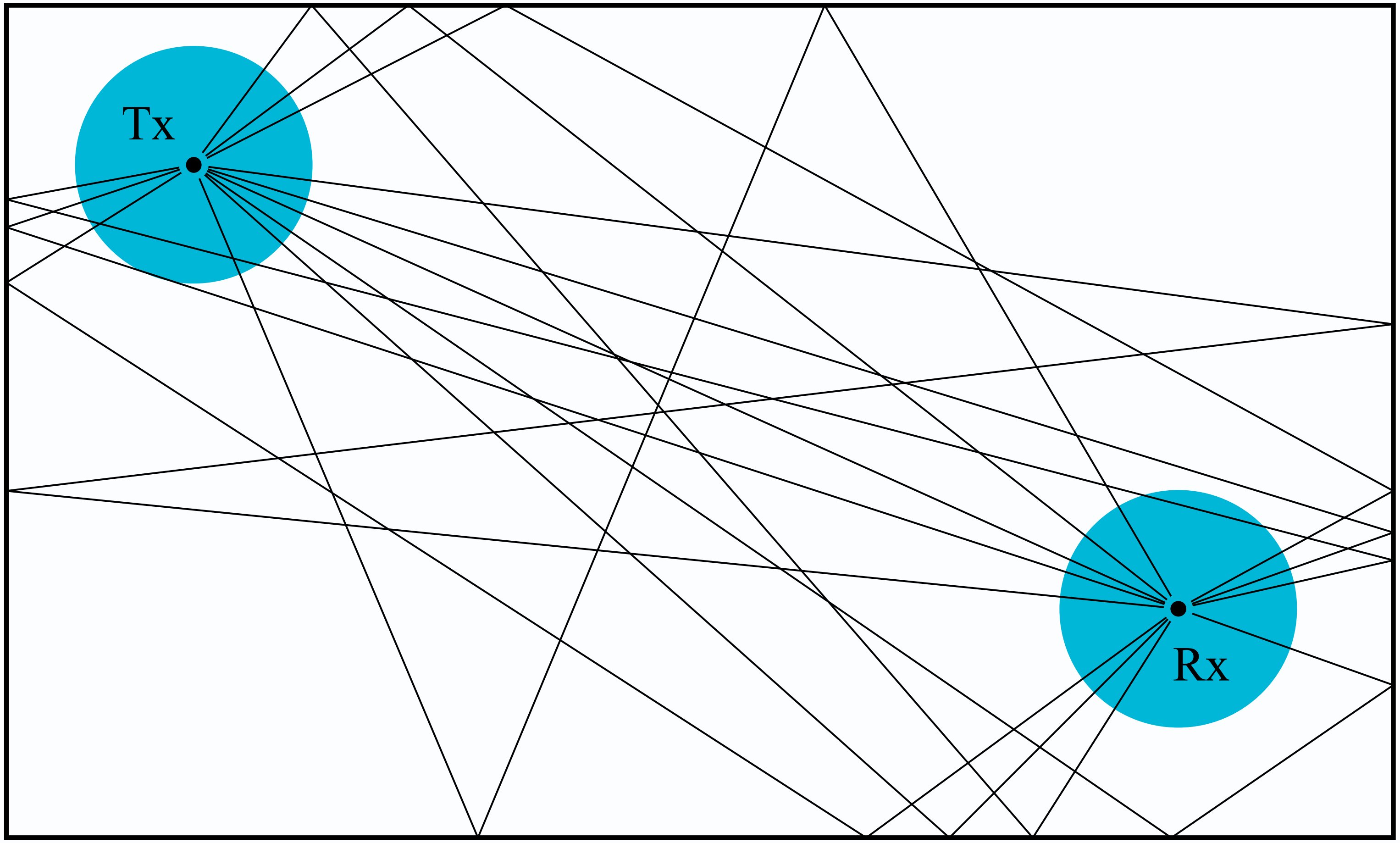
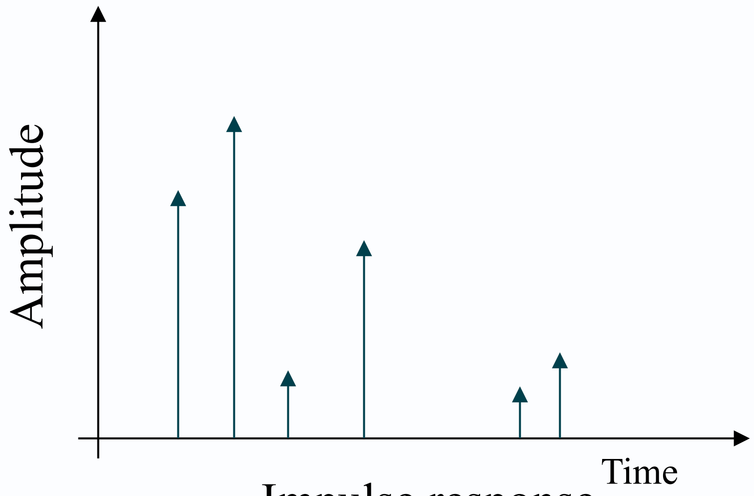
Multipath



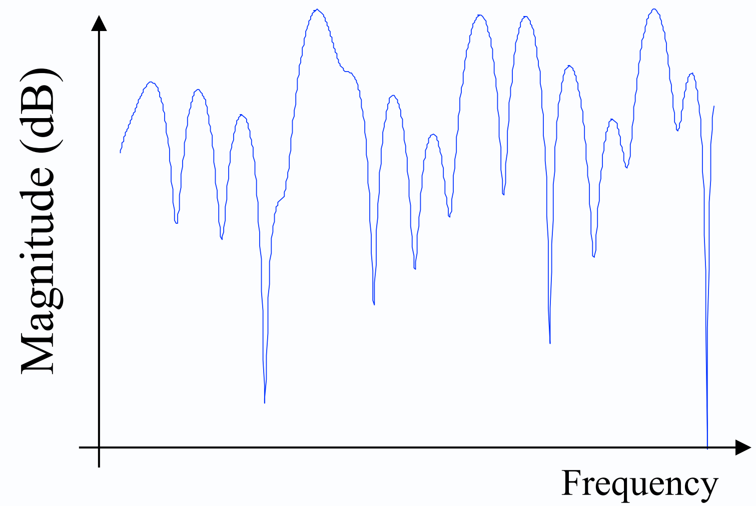
Multipath



Multipath



Impulse response



Frequency Response

$$h(\tau) = \sum_{k=1}^{N} \alpha_k e^{j\phi_k} \delta(\tau - \tau_k)$$

α_k : Amplitude of kth component

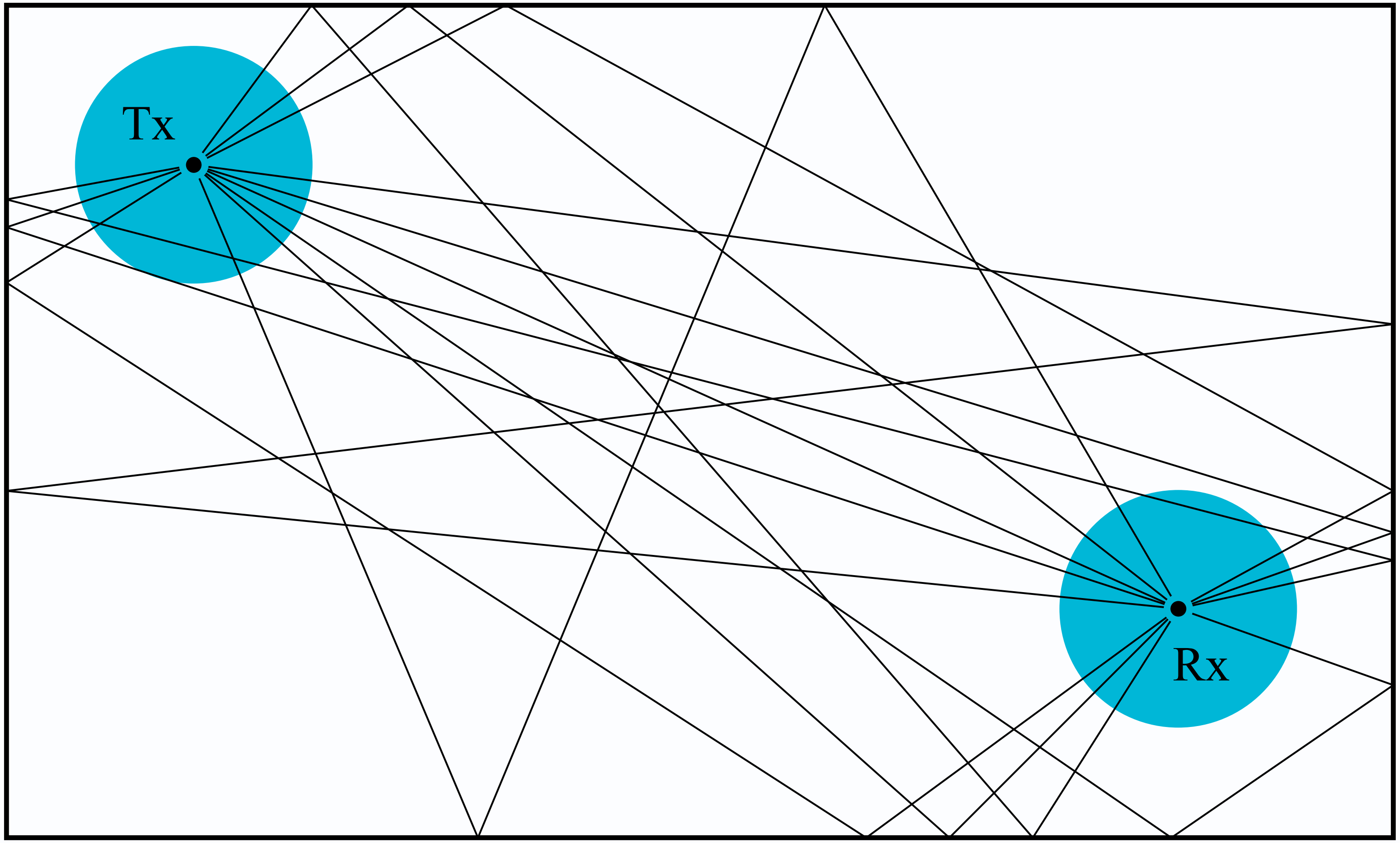
ϕ_k : Phase shift of kth component

τ_k : Time delay of kth component

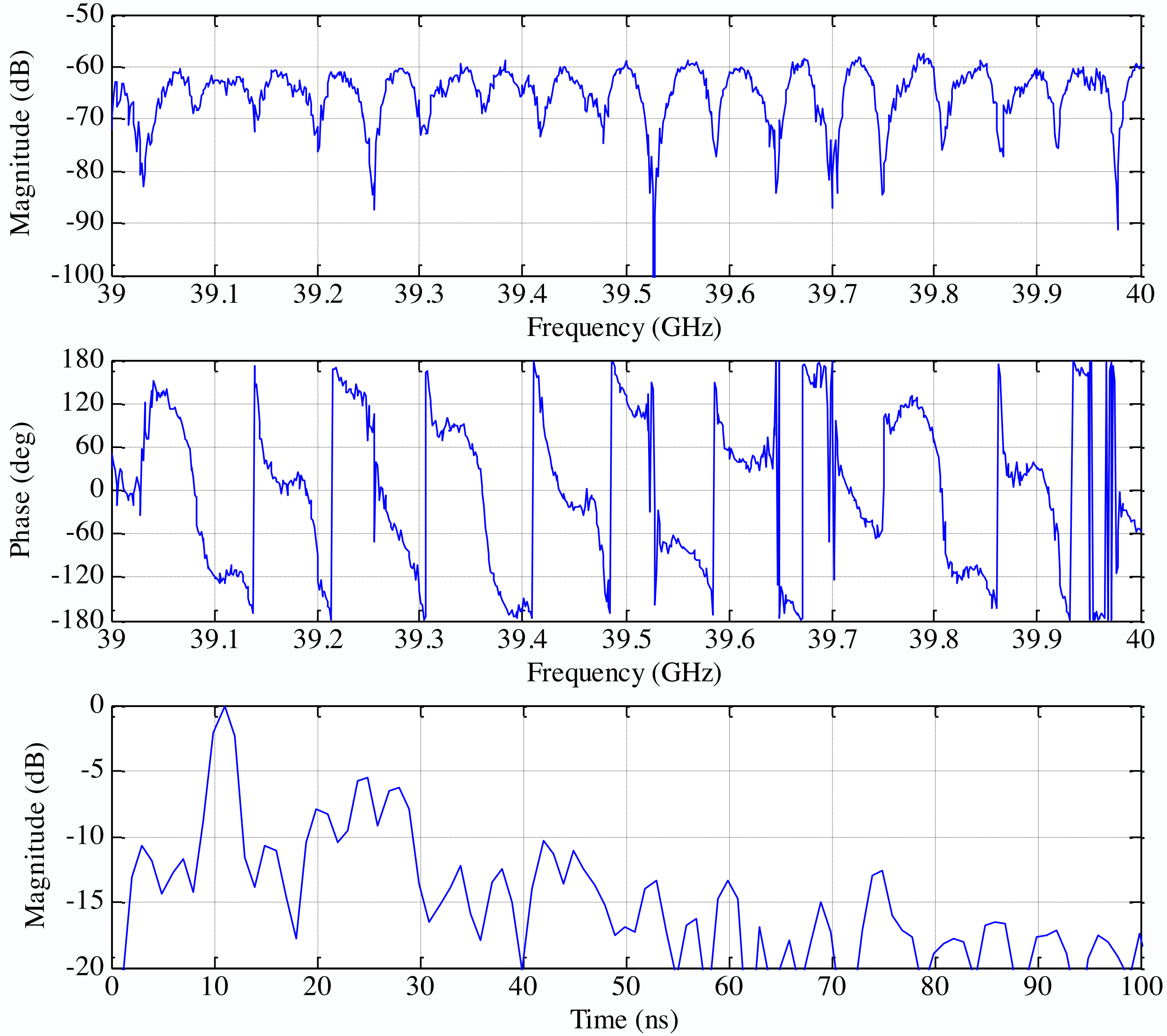
N : Number of signal components

$$H(f) = \sum_{k=1}^{N} \alpha_k e^{j\phi_k} e^{-j2\pi f \tau_k}$$

Multipath

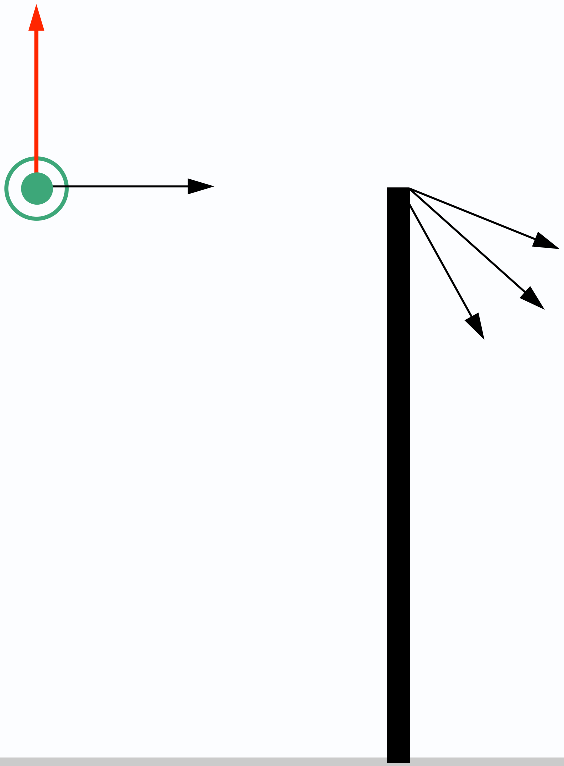


Multipath

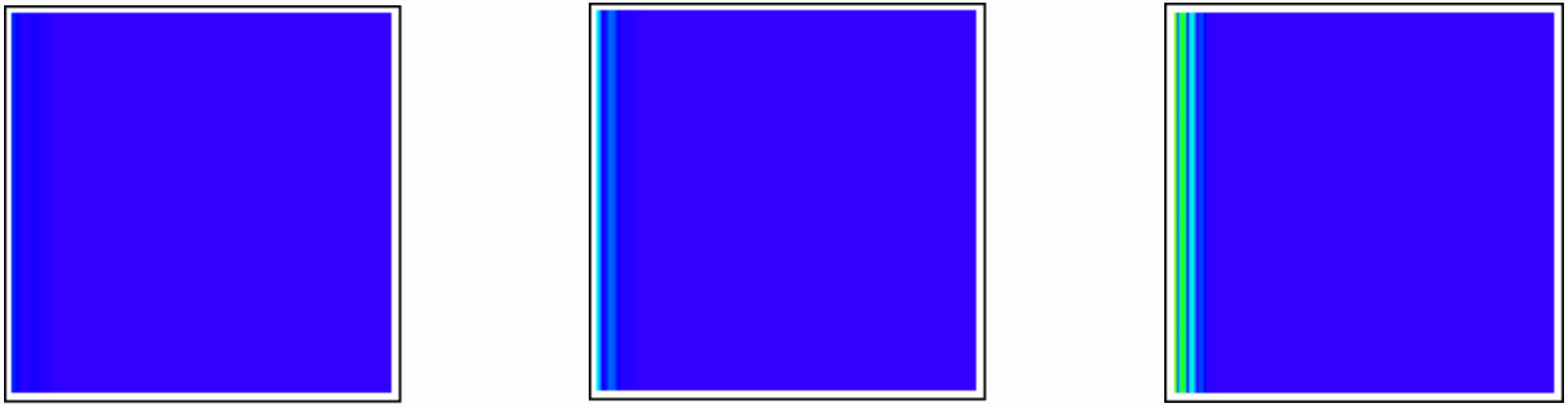


Magnitude (dB)
-50
-60
-70
-80
-90
-100
39
39.1
39.2
39.3
39.4
39.5
39.6
39.7
39.8
39.9
40
Frequency (GHz)
Phase (deg)
180
120
60
0
-60
-120
-180
39
39.1
39.2
39.3
39.4
39.5
39.6
39.7
39.8
39.9
40
Frequency (GHz)
Magnitude (dB)
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100
Time (ns)

Diffraction

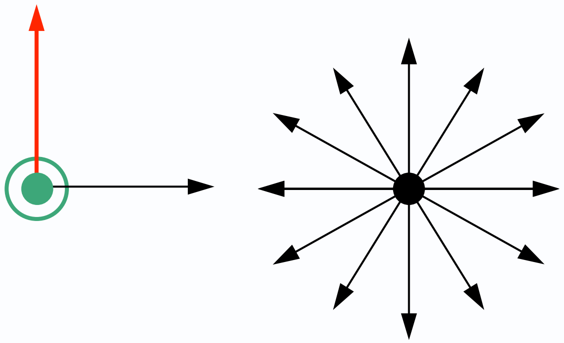


Diffraction

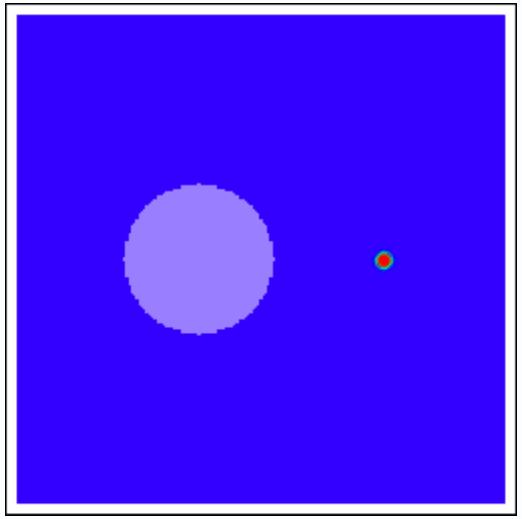


http://www-antenna.ee.titech.ac.jp/~hira/hobby/edu/em/diffraction/te/lf_hf.html

Scattering



Scattering



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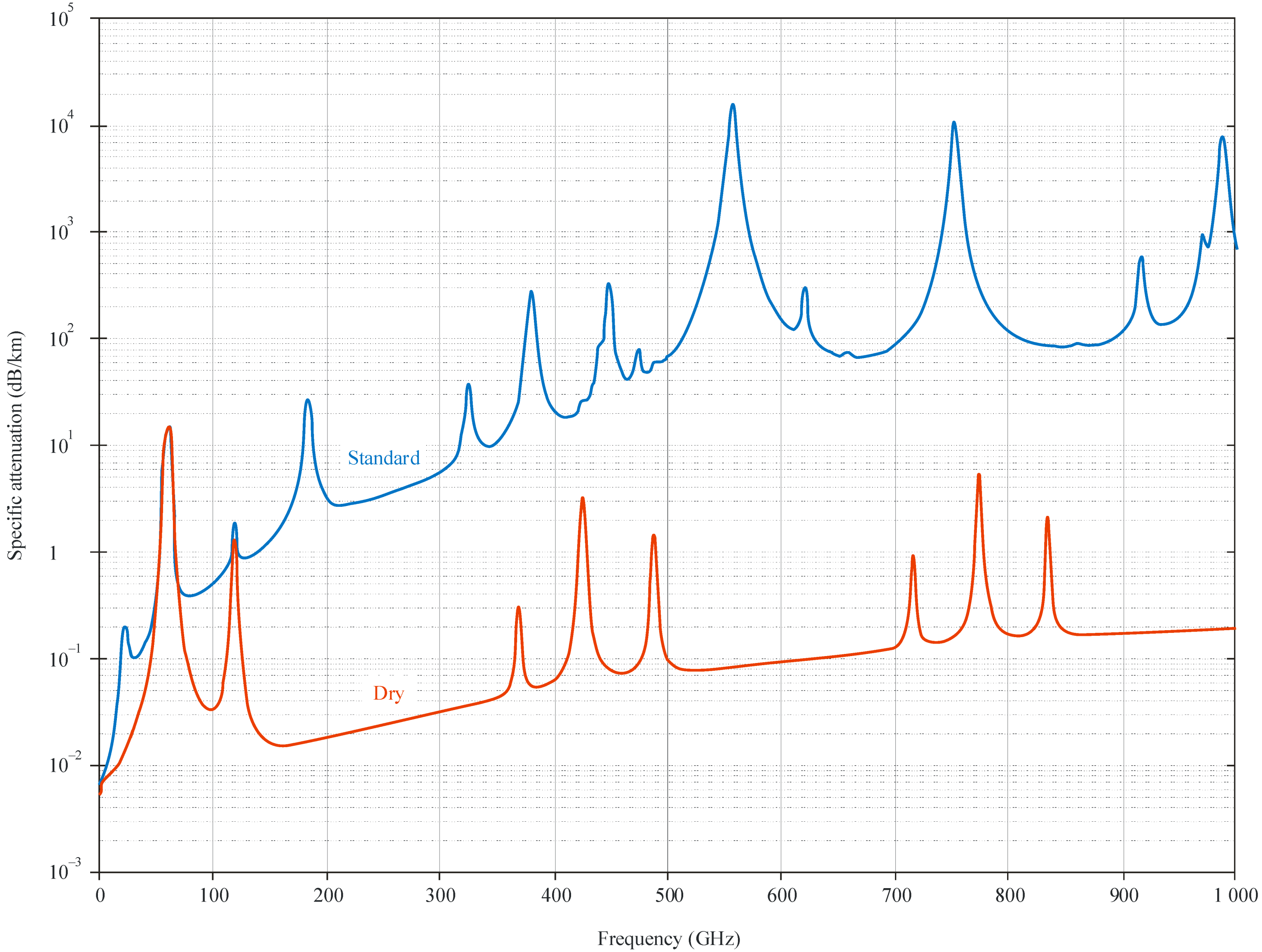
Attenuation Due to Atmospheric Gases



ITU-R P.676-10

Line-by-line calculation

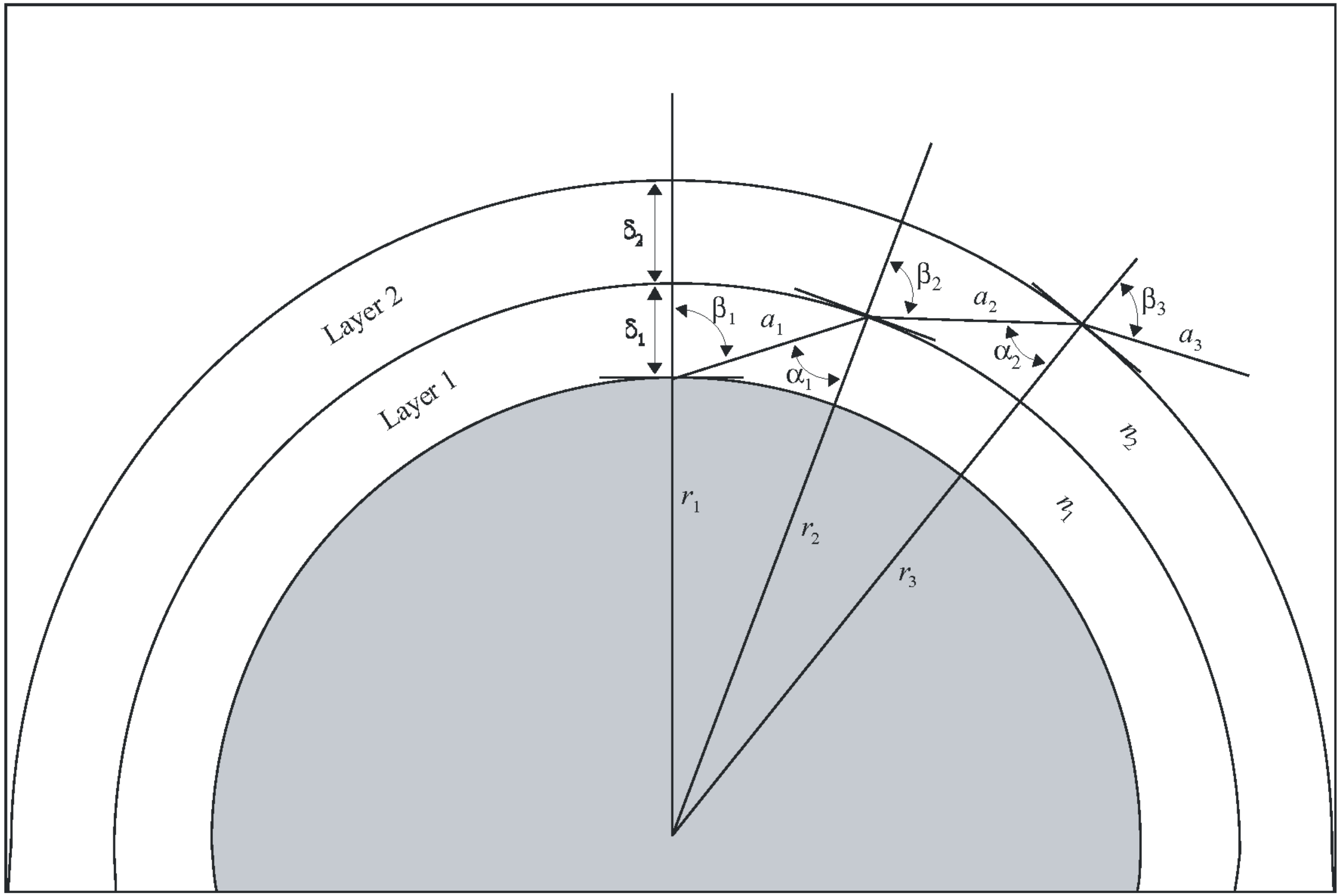
Pressure: 1013 hPa

Temperature: 15°C

Water-vapor density:

7.5g/m^3

Attenuation Due to Atmospheric Gases



ITU-R P.676-10 Path Attenuation Calculation Method

Conclusions

- mmW propagation fundamentals and models covered (especially for terrestrial and indoor communications).
- mmW propagation issues related to radio astronomy and space communications?