



جامعة الفرات الأوسط التقنية
كلية البوليتكنك / النجف
قسم تقنيات الإلكترونيات والاتصالات



— **حقيبة محاضرات**

الموجات الدقيقة

MICROWAVE ENGINEERING

المرحلة الثانية

إعداد
أ.م.د. محمد عبدالعباس توفيق

2025 – 2026

العام الدراسي

أهداف المادة الدراسية

1 يتعلم الطالب طبيعة الموجات الدقيقة.

2 يتعرف الطالب على كيفية توليد وإرسال واستقبال الموجات الدقيقة.

3 يكتسب الطالب مهارة في التعامل مع الأجهزة والمعدات المستعملة في تقنية الموجات الدقيقة.

استراتيجيات



مشاركة الطلبة المستمرة أثناء الدرس.



شرح الدرس الجديد على شاشة العرض مع الرسومات للتوضيح، مع استخدام السبورة.



تقييم الطلبة نهاية الدرس بالأسئلة والامتحان اليومي.



عرض فيديوها توضحية للدرس.

Course Syllabus

Week	Details
1	Introduction to Microwave , Spectral of Electromagnetic wave , Microwave bands, and Applications of Microwaves .
2	Maxwells Equations.
3-4	<ul style="list-style-type: none"> - Fields in media and boundary conditions includes: - Fields in general material interface - Fields at a dielectric interface, - Fields at the interface with a perfect conductor(Electrical wall) -the magnetic wall boundary condition , -the radiation condition.
5-7	Transmission Lines:Coaxial cable , Flexible coaxial cable , Semirigid cable Stripline ,Microstrip, Waveguide – Rectangular Waveguide – Circular Waveguide
8	Transmission modes (TEM ,TE _{mn} and TM _{mn})
9-10	Smith chart , matching , mismatching , stand wave ratio
11-12	Microwave components, directional components, attenuators, - Mixers ,and duplexers, Resonators, cavities, Hybrids,Terminals.
13-14	Microwave sources : - Solid state source:- varactor diode , Tuned diode and gun oscillator. - Microwave tubes:- Klystron , Magnetron.

15-16	Microwave Path loss :- - Line of sight microwave propagation, - wave propagation equation ,(Friis equation)
17	Principles of antennas and Radiation pattern directivity and antenna gain
18-19	Horn antenna , Helix antenna , Parabolic antenna , Micro strip antenna
20	Doppler effect.
21-22	Microwave filters
23-24	Satellite communication systems ,
25-27	Modulation and multiplexing -ASK , FSK and PSK -Space Division Multiple access (SDMA) -Frequency Division Multiple access (FDMA) -Time Division Multiple access (TDMA) -CDMA code division Multiple access
28-29	Basic principles of Radar systems
30	Biological effects of microwaves

Grading

Student achievement in the course objectives will be assessed using a combination of homework and exams as well as class attendance and participation. Your course grade will be determined by your weighted performance in the following categories:

Homework	5%
Participation	5%
Midterm Exam #1	20%
Midterm Exam #2	20%
Final Exam	50%

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿وَإِنَّ يَوْمًا عِنْدَ رَبِّكَ كَأَلْفِ سَنَةٍ مِّمَّا تَعُدُّونَ﴾

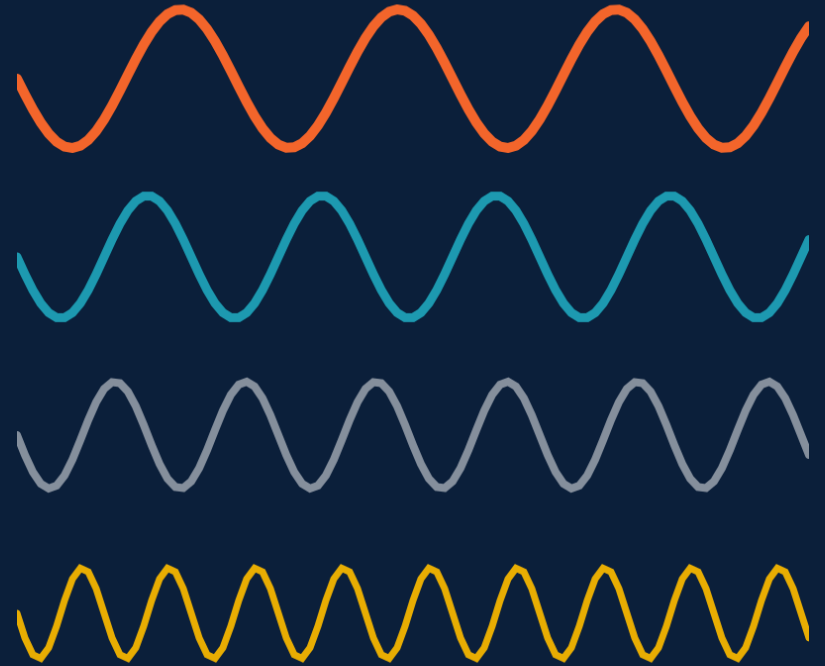
LECTURE 1 & 2

Microwave Engineering

Introduction to Microwaves

المحاضرة الأولى والثانية: مقدمة في الموجات الدقيقة

Communication Dept · Al-Najaf Technical Institute
Al-Furat Al-Awsat Technical University
By: D. Mohammed Abdalabbas



الاختبار القبلي (Pre-test)

- 1. Which type of wave can travel through a vacuum? (a) Sound wave (b) Water wave (c) Electromagnetic wave (d) Seismic wave**
- 2. The microwave frequency range is: (a) 3–300 kHz (b) 30–300 MHz (c) 300 MHz–300 GHz (d) 300 GHz–3 THz**
- 3. When the frequency of a wave increases, its wavelength: (a) increases (b) decreases (c) stays the same (d) becomes infinite**
- 4. Which radiation is ionizing? (a) Microwaves (b) Radio waves (c) X-rays (d) Visible light**
- 5. A microwave link needs: (a) a clear line of sight between antennas (b) a metal wire between stations (c) a water medium (d) no antennas**

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What is a wave?

A disturbance that travels through matter or space and transfers energy

اضطراب ينتقل عبر المادة أو الفراغ وينقل الطاقة.



Mechanical waves

- Need a medium to travel
- Sound, water, seismic waves



Electromagnetic waves

- Travel even in vacuum
- Radio · Microwaves · Infrared · Visible · UV

ملاحظة: الموجة تنقل الطاقة وليس المادة. الموجات الميكانيكية تحتاج وسطاً، أما الكهرومغناطيسية (ومنها الميكروويف) فلا تحتاج.

What are microwaves?



Frequency

300 MHz – 300 GHz



Wavelength in air

1 m – 1 mm



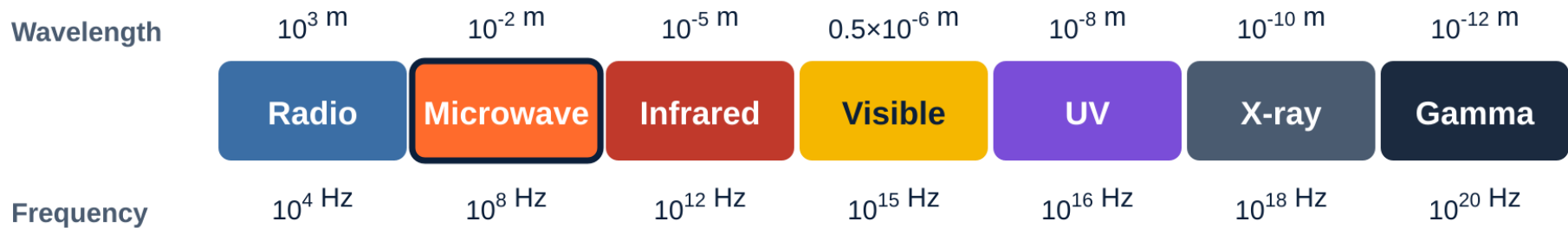
Key formula

$$\lambda = c / f$$

“Micro” = very short wave. Microwaves are the shortest-wavelength region of the radio spectrum, where $c = 3 \times 10^8$ m/s is the speed of light.

ملاحظة: كلما زاد التردد قصر الطول الموجي. الميكروويف = موجات كهرومغناطيسية قصيرة جداً بين 300 ميغاهرتز و 300 غيغاهرتز.

Where do microwaves live?



Phones, Wi-Fi, radar, satellites
& ovens



Between radio waves and
infrared



Higher frequency = shorter
wavelength

ملاحظة: اقرأ الشكل من اليسار لليمين: يقصر الطول الموجي ويزداد التردد، وتزداد طاقة الموجة.

الطيف الكهرومغناطيسي

كل الموجات الكهرومغناطيسية تسير بسرعة الضوء، وتختلف في التردد والطول الموجي

طول موجي أقصر · تردد وطاقة أعلى → طول موجي أطول · تردد وطاقة أقل

النوع	أشعة غاما	الأشعة السينية	الأشعة فوق البنفسجية	الضوء المرئي	الأشعة تحت الحمراء	الميكروويف	موجات الراديو
الطول الموجي بالمتري	10^{-12}	10^{-10}	10^{-8}	0.5×10^{-6}	10^{-5}	10^{-2}	10^3
التردد بالهرتز	10^{20}	10^{18}	10^{16}	10^{15}	10^{12}	10^8	10^4
مثال							
التطبيقات	علاج الأورام	التصوير الطبي	الشمس والتعقيم	ما تراه العين	ريموت وكاميرا حرارية	هاتف وواي فاي وراдар وفرن	إذاعة وتلفاز

إشعاع غير مؤين: لا يكسر الروابط الكيميائية

إشعاع مؤين: يضر بالحمض النووي

نطاق الميكروويف: من 300 ميغاهرتز إلى 300 غيغاهرتز

الطول الموجي من 1 متر إلى 1 ملم · السرعة = التردد × الطول الموجي

Microwave links: advantages and disadvantages

Advantages



High frequency → high bandwidth, higher speeds



Short wavelength → small antennas, focused beams



Repeaters carry signals over very long distances

Disadvantages



Needs a clear line of sight (no obstacles)



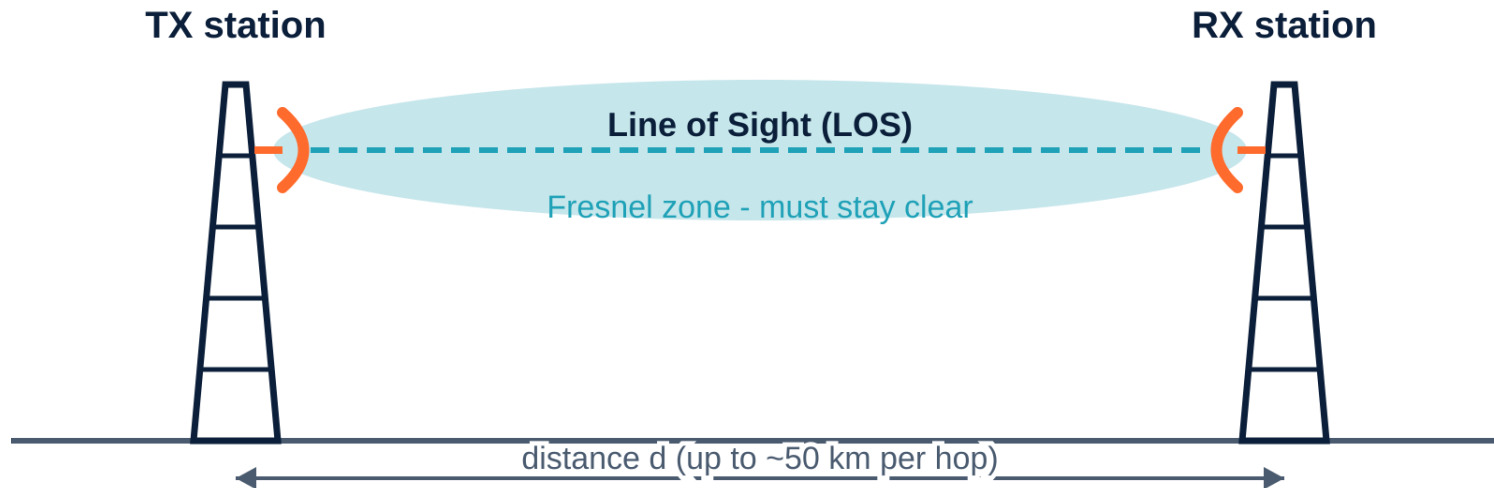
Infrastructure cost is high



Rain, snow & interference weaken the signal

ملاحظة: الميزة الأهم: سعة بيانات عالية بهوائيات صغيرة. العيب الأهم: تحتاج مسارًا مكشوفًا وتتأثر بالطقس.

How a microwave link works



Terminal stations originate and receive the information

تقوم المحطات الطرفية بإنشاء المعلومات واستقبالها.

Repeaters relay the signal to the next station

تقوم أجهزة إعادة إرسال بنقل الإشارة إلى المحطة التالية.

Terrain, buildings & lakes must not block the path

يجب ألا تعيق التضاريس والمباني والبحيرات المسار.

ملاحظة: يجب اختيار مواقع المحطات بعناية لتجنب الجبال والمباني، وإبقاء منطقة فرنل خالية من العوائق.

Types of links by distance (haul)



Short haul

≤ 15 km

Urban cells, campus & factory links



Medium haul

15–40 km

Town links, mobile backhaul



Long haul

40–80 km

City-to-city backbone, rural areas



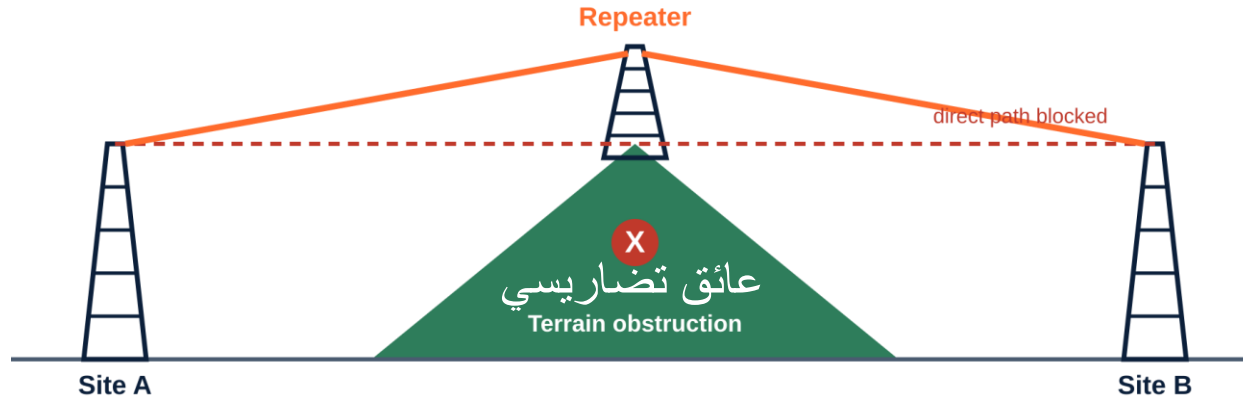
Ultra-long

> 100 km

Deserts & borders via repeaters

ملاحظة: كلما زادت المسافة احتجنا أبراجاً أعلى وقدرة أكبر وهوائيات قطرها أكبر، أو محطات تكرار.

Microwave repeaters



Passive repeater

Re-radiates the beam with no extra electronic power; just redirects it.

Active repeater

Receiver + transmitter back-to-back: receives, amplifies, reshapes, retransmits.

ملاحظة: السلبي = عاكس بلا طاقة كهربائية. الفعال = يستقبل ويضخم ويعيد الإرسال .

Why signals get weaker: attenuation

لماذا تضعف الإشارات: التوهين

Attenuation = the reduction of signal power as it travels through a medium or space



Free-space loss

Wave spreads as distance grows



Rain

Strong above 10 GHz



Fog & humidity

Noticeable above 30 GHz



Snow & ice

Mainly 20–40 GHz



Gas absorption

Peaks: 22 GHz (H₂O), 60 GHz (O₂)



Obstacles & hardware

Multipath, fading, cable & antenna loss

ملاحظة: المطر أخطر عدو للترددات العالية (فوق 10 GHz) لذلك تُصمَّم الوصلات مع هامش أمان للتضاؤل.

Key properties of microwaves



Line-of-sight

Travel in straight lines



Wide bandwidth

Carry large amounts of data



Metals reflect

Pass through plastic, wood, glass



Heating effect

Water molecules absorb → heat (ovens)



Polarization

Vertical, horizontal or circular

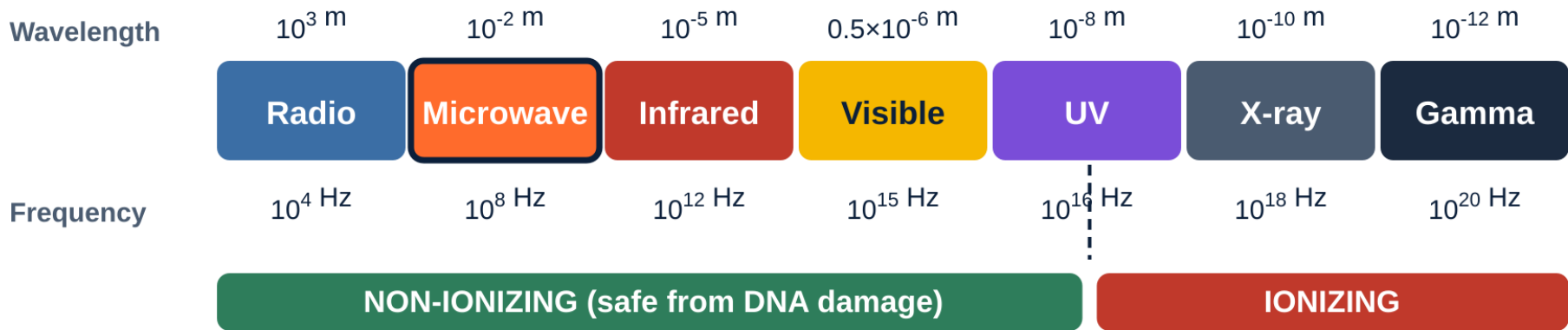


Narrow beams

Dish or horn antennas → point-to-point

ملاحظة: تخيل شعاعاً ضيقاً يسير بخط مستقيم: لهذا نحتاج رؤية مباشرة بين الهوائيين.

Ionizing vs non-ionizing radiation



Ionizing: X-rays & gamma

Strips electrons from atoms → can damage DNA and tissue.

ينتزع الإلكترونات من الذرات ← يمكن أن يلحق الضرر بالحمض النووي والأنسجة.

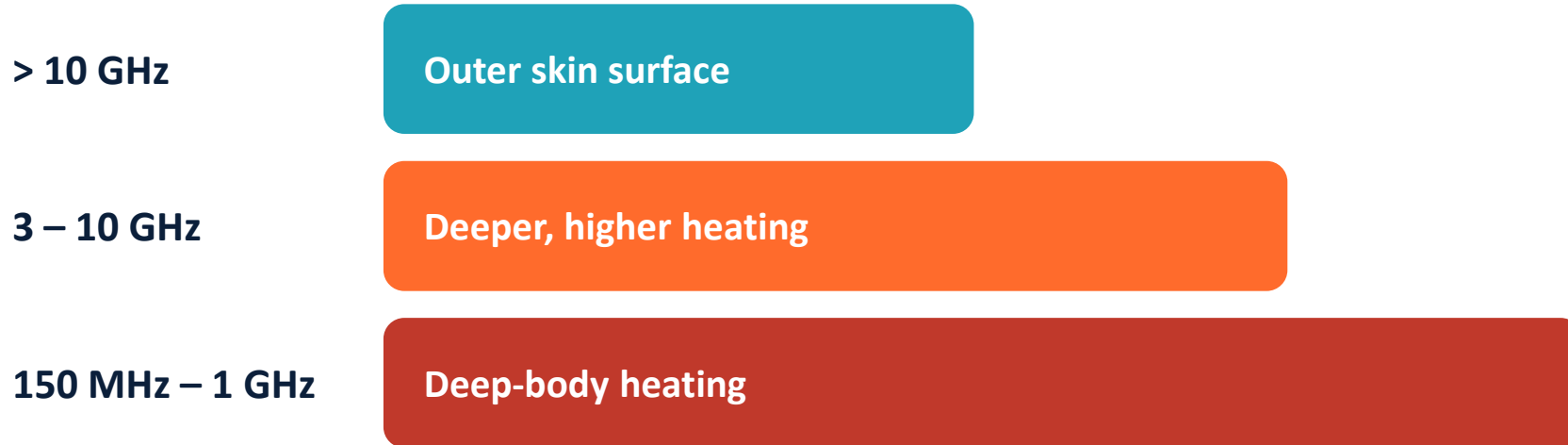
Non-ionizing: microwaves & RF

Not enough energy to ionize; the only proven harm is heating.

الطاقة غير كافية لإحداث التأين؛ والضرر الوحيد المثبت هو التسخين.

ملاحظة: الميكروويف لا يؤين الذرات لأن طاقته منخفضة، أما الأشعة السينية وجاما فتؤين وتضر الـ DNA.

How deep does microwave heating go?



0.4 W/kg

SAR limit – workers

0.08 W/kg

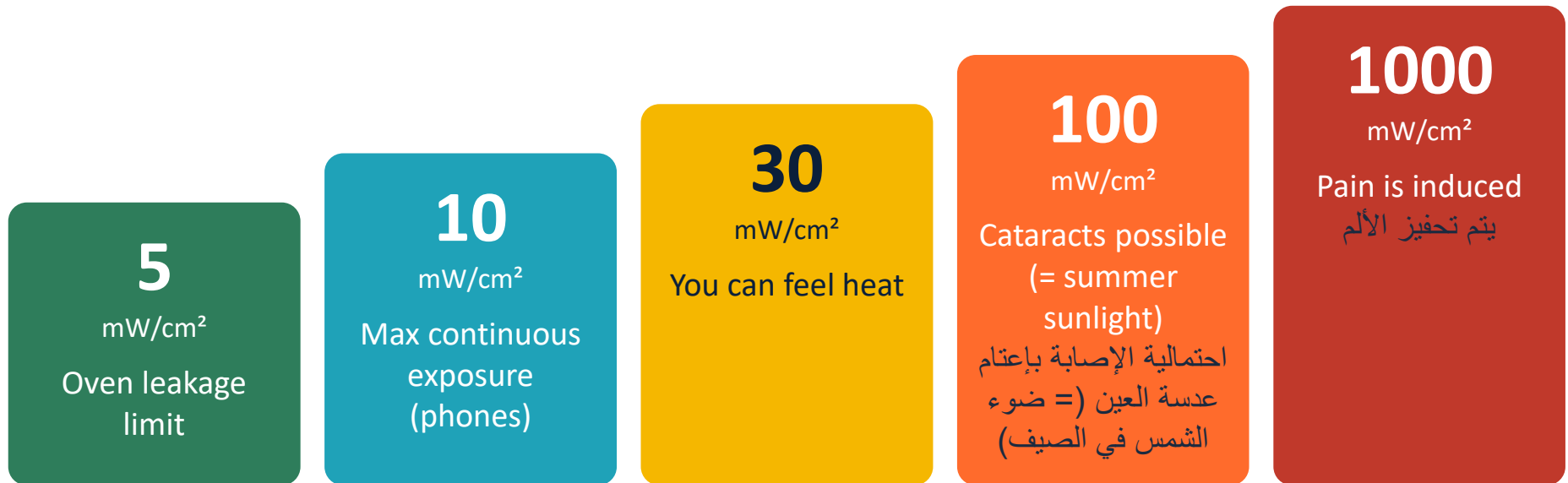
SAR limit – public

6 min

Averaging time

معدل الامتصاص النوعي: الطاقة الممتصة لكل كيلوغرام من الجسم. التردد الأقل يتغلغل أعمق. ملاحظة = SAR:

Power density and its effects



ملاحظة: كثافة القدرة تُقاس بـ mW/cm^2 . تحت 10 لا يوجد تأثير معروف طويل الأمد على الجسم.

Critical thinking: do phones “fry” the brain?

التفكير النقدي: هل "تُحرق" الهواتف الدماغ؟



Heating is real but tiny

الاحترار حقيقي ولكنه ضئيل.

Phone microwaves warm tissue by only a fraction of a degree.

«تُسبب الموجات الميكروية الصادرة من الهاتف ارتفاعاً طفيفاً جداً في درجة حرارة الأنسجة، بمقدار جزء من درجة مئوية فقط».



Limits sit far below heating

SAR safety limits are set well under levels that cause harm.

تم تحديد حدود السلامة لمعدل عند (SAR) الامتصاص النوعي) مستويات تقل بكثير عن تلك التي تسبب الضرر.



Thermal photos mislead

الصور الحرارية مضللة

Warm ear = the phone & skin contact, not “fried” brain tissue.

سخونة الأذن ناتجة عن تلامس الهاتف مع الجلد، وليس عن احتراق أنسجة الدماغ.

Sensible habit: keep calls short, use speaker or headset. Research continues.

ملاحظة: لا تأخذ العناوين المثيرة كحقيقة: التفكير النقدي يعني التحقق من المصدر ومن مقدار الجرعة.

Key takeaways

- Microwaves: 300 MHz – 300 GHz, $\lambda = 1 \text{ m} - 1 \text{ mm}$
- High bandwidth + small, focused antennas
- Need line of sight; repeaters extend range
- Rain, fog & obstacles cause attenuation
- Non-ionizing: the proven effect is heating

Quick questions

1. Why do microwave links need line of sight?
2. Passive vs active repeater: what is the difference?
3. Why is microwave radiation non-ionizing?

أسئلة سريعة للنقاش داخل القاعة

الاختبار البعدي (Post-test)

1. Calculate the wavelength in air of a 3 GHz microwave signal ($c = 3 \times 10^8$ m/s).
2. Rain becomes the strongest attenuator at frequencies: (a) below 1 GHz (b) 1–3 GHz (c) above 10 GHz (d) it has no effect
3. A microwave link of 60 km is classified as: (a) short haul (b) medium haul (c) long haul (d) ultra-long
4. Explain the difference between a passive repeater and an active repeater.
5. Why is microwave radiation called non-ionizing, and what is its only proven harmful effect?
6. Give two advantages and two disadvantages of microwave links.

Lecture-3-

TRANSMISSION IMPAIRMENT (PROBLEMS)

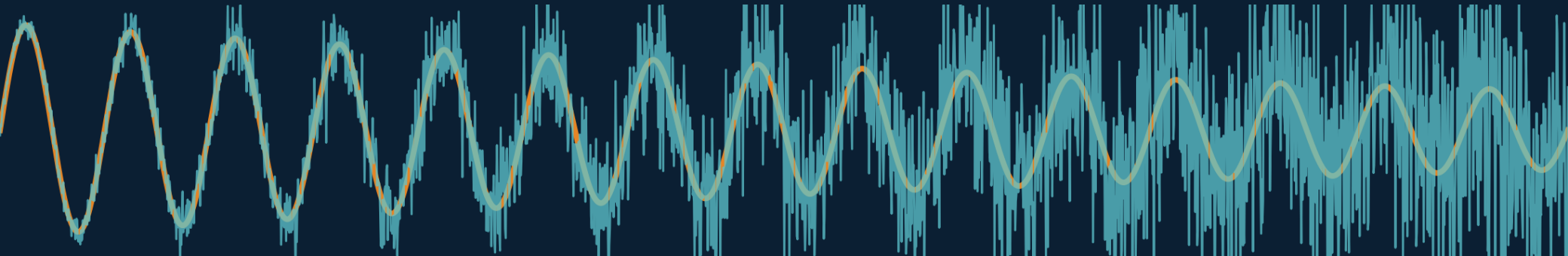
﴿الَّذِي خَلَقَ سَبْعَ سَمَاوَاتٍ طِبَاقًا مَّا تَرَىٰ فِي خَلْقِ الرَّحْمَنِ مِن تَفَوتٍ ۚ فَارْجِعِ الْبَصَرَ هَلْ تَرَىٰ مِن فُطُورٍ * ثُمَّ ارْجِعِ الْبَصَرَ
كَرَّتَيْنِ يَنقَلِبْ إِلَيْكَ الْبَصَرُ خَاسِئًا وَهُوَ حَسِيرٌ﴾

Transmission Impairments

Why the received signal is not the sent signal

Attenuation · Fading · Distortion · Noise

مشاكل الإرسال: لماذا لا تصل الإشارة كما أرسلت؟



الاختبار القبلي (Pre-test)

1. Attenuation means: (a) an increase in signal frequency (b) loss of signal power as it travels (c) addition of unwanted signals (d) a change in signal phase
2. A power ratio of 0.5 (power halves) corresponds to about: (a) +3 dB (b) -3 dB (c) +10 dB (d) -10 dB
3. Unwanted signals that add to the useful signal are called: (a) fading (b) distortion (c) noise (d) gain
4. Multipath propagation mainly causes: (a) fading (b) amplification (c) modulation (d) coding
5. A high signal-to-noise ratio (SNR) means: (a) more bit errors (b) a signal buried in noise (c) a cleaner signal and fewer errors (d) lower channel capacity

Lecture Objectives



Describe the wireless channel and its problems



Explain attenuation: causes and measurement in dB



Understand fading and signal distortion



Understand noise and the signal-to-noise ratio (SNR)

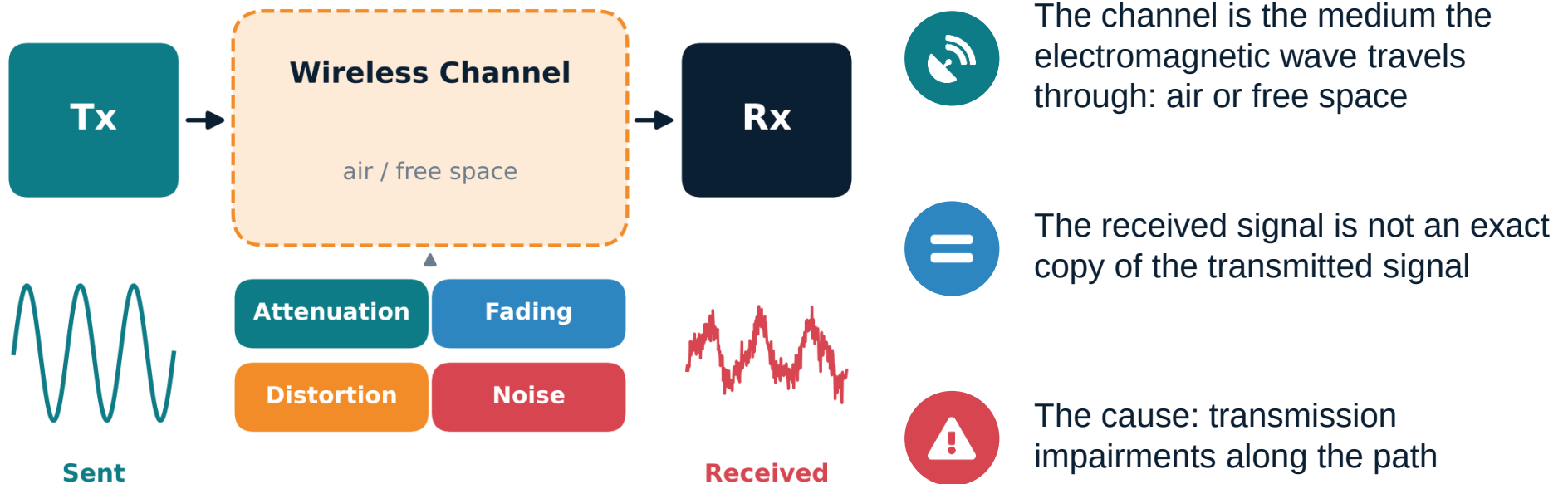


Solve numerical problems on dB and SNR

الهدف: فهم كل مشكلة من مشاكل الإرسال ثم حل مسائل dB و SNR.

ملاحظة:

The Wireless Communication Channel



القناة اللاسلكية هي الهواء أو الفضاء بين هوائي الإرسال وهوائي الاستقبال.

ملاحظة:

The Four Transmission Problems



Attenuation

التوهين

Signal power weakens as it travels away from the transmitter



Fading

الخفوت

Received level fluctuates because of multipath and obstacles



Distortion

التشويه

Signal shape changes because frequencies arrive at different times



Noise

الضوضاء

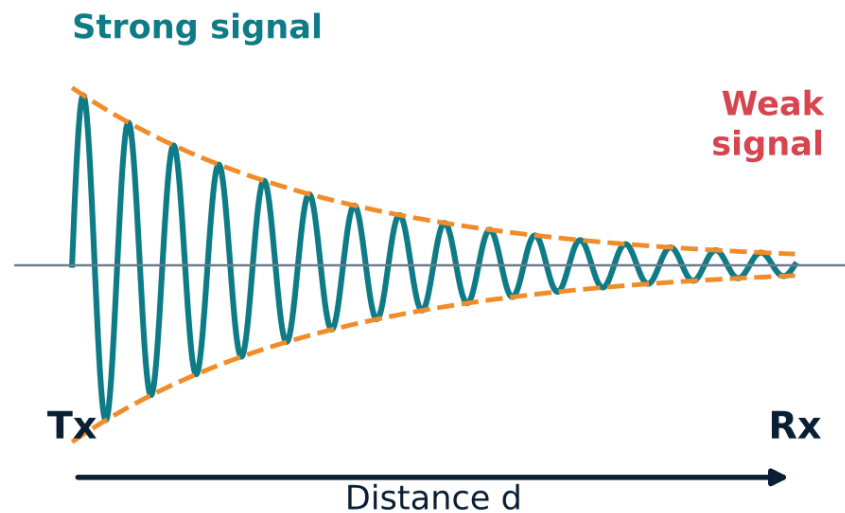
Unwanted signals add to the useful signal

Result: poorer reception and more bit errors

النتيجة النهائية لكل المشاكل: زيادة أخطاء البيانات (Bit Errors).

ملاحظة:

What Is Attenuation?



- 1 Attenuation: the loss of signal power as it travels through the medium
- 2 The longer the distance or the higher the frequency, the larger the attenuation
- 3 If the signal drops close to the noise level, the receiver cannot recover it

التوهين = ضعف الإشارة مع المسافة. لاحظ أن التردد لا يتغير، فقط السعة.

ملاحظة:

Causes of Attenuation



Distance (Spreading)

The wave spreads in all directions, so its energy covers a larger area



Absorption

Rain, water vapor and oxygen absorb energy, mostly at higher microwave frequencies



Obstacles

Walls, buildings, hills and trees block or absorb the signal



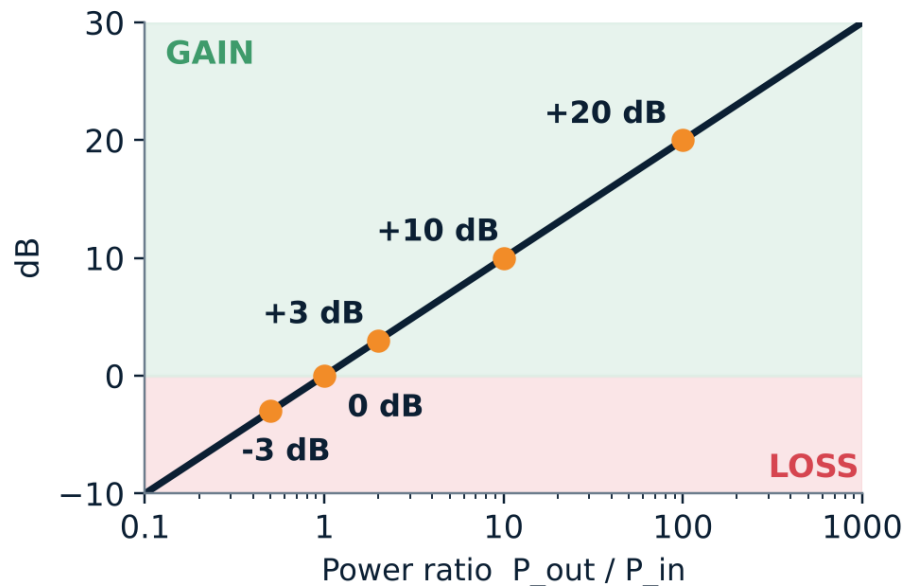
Reflection & Scattering

Reflection, scattering and diffraction send part of the energy in other directions

المسافة هي السبب الذي لا يمكن تجنبه حتى في الفراغ التام.

ملاحظة:

Measuring Attenuation: the Decibel (dB)



$$G (dB) = 10 \cdot \log_{10} (P_{out} / P_{in})$$

Negative = loss · Positive = gain

+3 dB Power doubles

-3 dB Power halves

+10 dB Power becomes 10 times larger

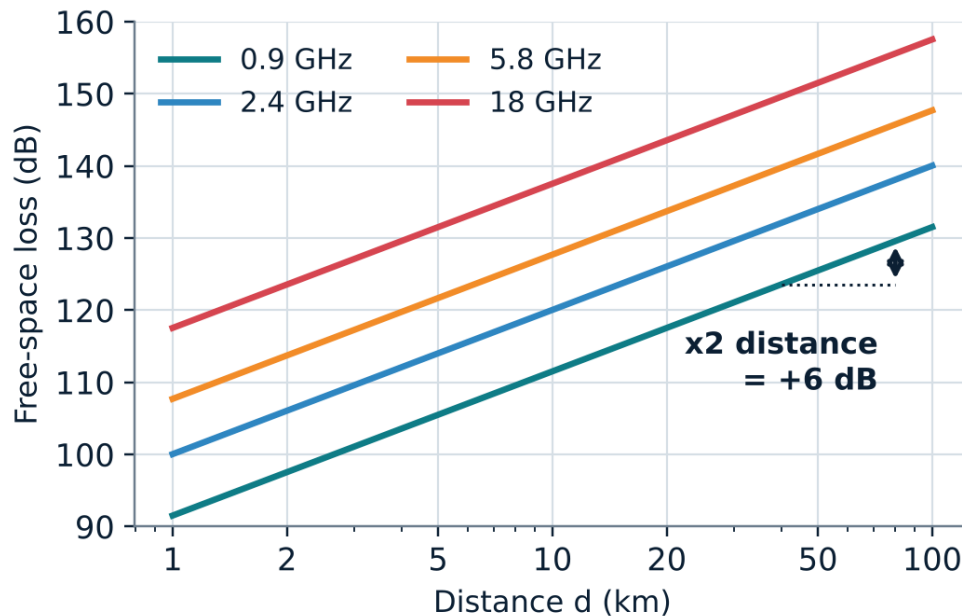
$$dBm = 10 \cdot \log_{10} (P / 1 \text{ mW})$$

Absolute power relative to 1 mW

تذكر: dB3 = ضعف القدرة، dB10 = عشرة أضعاف، والإشارة السالبة تعني توهيناً.

ملاحظة:

Attenuation in the Medium



Guided medium (cable, fiber)

$$\text{Loss (dB)} = \alpha \text{ (dB/km)} \times d \text{ (km)}$$

Loss grows linearly with length

Free space

$$\text{FSPL (dB)} = 32.44 + 20 \cdot \log_{10} d + 20 \cdot \log_{10} f$$

d in km, f in MHz

Double d or f = +6 dB

في الفضاء الحر: مضاعفة المسافة أو التردد تضيق نحو 6 dB من الفقد.

ملاحظة:

Example 1: Attenuation in dB

Problem: A signal with power 10 mW enters a medium and leaves with power 5 mW. Find the gain or attenuation in dB.

P_{in} = 10 mW



Medium



P_{out} = 5 mW

1 Formula

$$G \text{ (dB)} = 10 \cdot \log_{10} (P_{\text{out}} / P_{\text{in}})$$

2 Substitute

$$G = 10 \cdot \log_{10} (5 / 10) = 10 \cdot \log_{10} (0.5)$$

3 Result

$$G \approx -3 \text{ dB} \quad (\text{attenuation} = 3 \text{ dB})$$

النصف دائماً يساوي -3dB؛ والإشارة السالبة تعني أن الوسط وهن الإشارة.

ملاحظة:

Example 2: Attenuation per Kilometer

Problem: A medium attenuates the signal at 3 dB/km. A 20 mW signal enters a 10 km link. What is the output power?

$$P_{in} = 20 \text{ mW}$$



$$3 \text{ dB/km} \times 10 \text{ km}$$



$$P_{out} = ?$$

1 Total loss

$$\text{Loss} = \alpha \times d = 3 \text{ dB/km} \times 10 \text{ km} = 30 \text{ dB}$$

2 Convert to ratio

$$P_{out} = P_{in} \times 10^{(-30/10)} = 20 \text{ mW} \times 10^{-3}$$

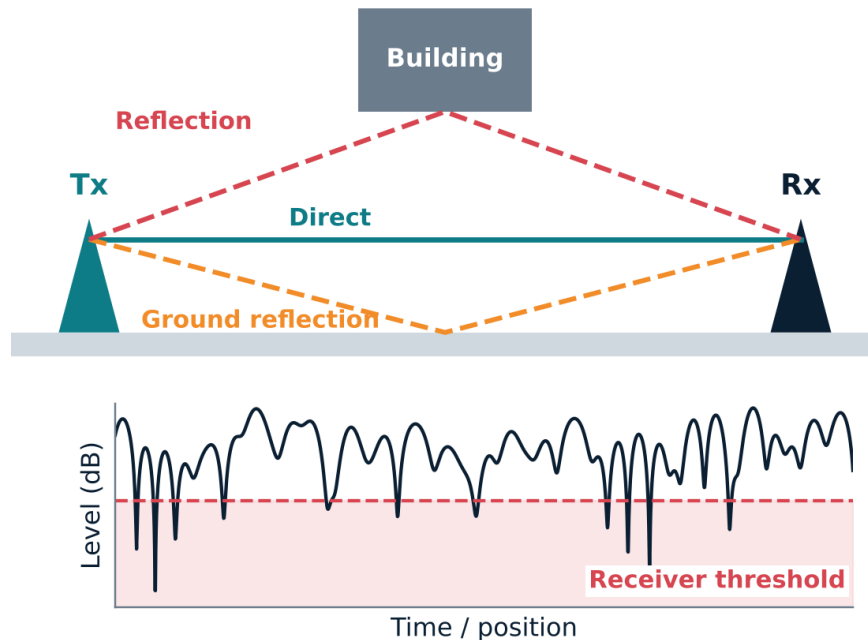
3 Result

$$P_{out} = 0.02 \text{ mW} = 20 \text{ }\mu\text{W}$$

نحسب التوهين الكلي أولاً ($\text{dB}30 = 10 \times 3$) ثم نحوله إلى نسبة قدرة.

ملاحظة:

Fading



What is fading?

The received level fluctuates and may drop below the receiver threshold



Why does it happen?

Multipath: reflected copies arrive out of phase and add or cancel



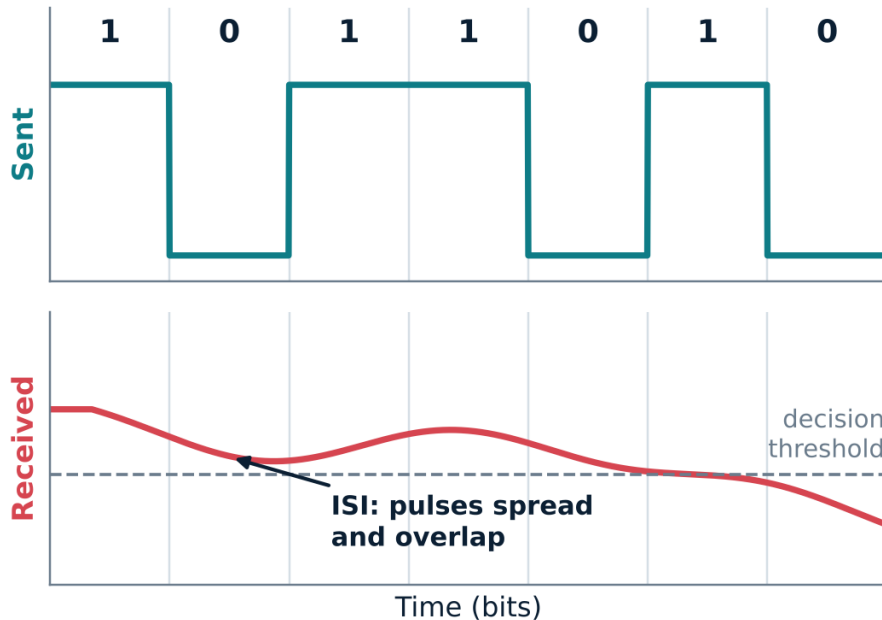
How to fight it?

Fade margin, diversity (2+ antennas), equalizer

الخفوت: هبوط مفاجئ في مستوى الإشارة عند التقاء نسخ منعكسة بأطوار متعاكسة.

ملاحظة:

Distortion



What is distortion?

Different frequencies arrive at different times, changing the signal shape



What does it cause?

Pulses overlap (ISI), so the receiver confuses 0 and 1



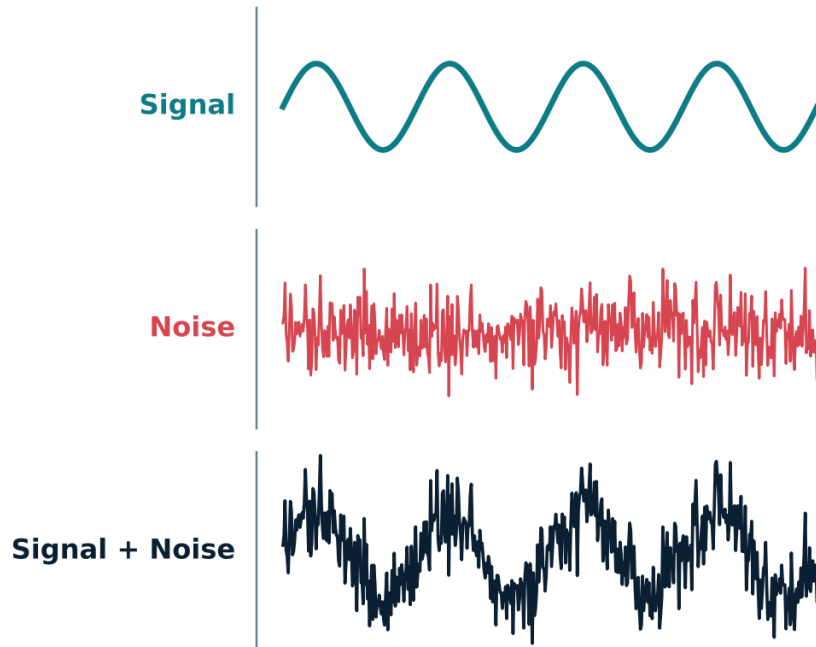
How to fix it?

Use an equalizer, or lower the data rate

ISI = تداخل الرموز. كلما زادت سرعة إرسال البيانات زاد تأثيره.

ملاحظة:

Noise



Thermal Noise (White)

Random motion of electrons



Intermodulation Noise

Extra tones from non-linear devices



Crosstalk

Leakage from neighboring channels



Impulse Noise

Short strong spikes (lightning, motors)

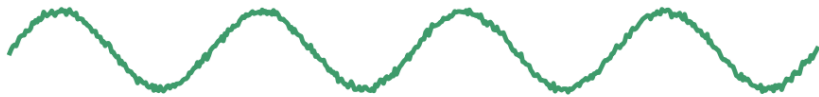
$$N = k \cdot T \cdot B \quad k = 1.38 \times 10^{-23} \text{ J/K}$$

الضوضاء الحرارية موجودة في كل جهاز إلكتروني ولا يمكن إلغاؤها: $kTB = N$.

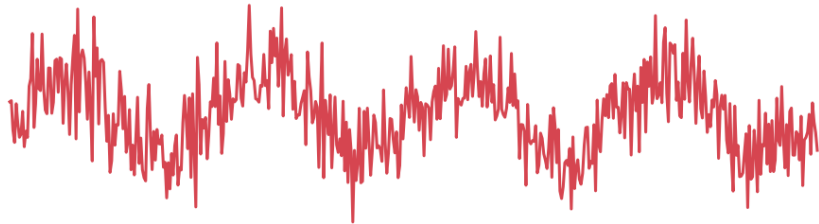
ملاحظة:

Signal-to-Noise Ratio (SNR)

High SNR (about 23 dB): clean



Low SNR (about 0 dB): buried in noise



$$\text{SNR} = P_{\text{signal}} / P_{\text{noise}}$$

$$\text{SNR}_{\text{dB}} = 10 \cdot \log_{10} (\text{SNR})$$



High SNR: clean signal, few errors



Low SNR: signal buried in noise, many errors

Channel capacity (Shannon)

$$C = B \cdot \log_2 (1 + \text{SNR})$$

كلما زادت SNR كانت الإشارة أنقى والاستقبال أفضل.

ملاحظة:

Example 3: SNR and dB Conversion

Problem: A channel has SNR = 1000 (power ratio). Find SNR in dB. Then find the SNR ratio if it falls by 10 dB.

SNR = 1000



SNR_dB = ?



After -10 dB: SNR = ?

1 Part 1

$$\text{SNR}_{\text{dB}} = 10 \cdot \log_{10} (1000) = 30 \text{ dB}$$

2 After the drop

$$\text{SNR}_{\text{dB}} = 30 - 10 = 20 \text{ dB}$$

3 Back to a ratio

$$\text{SNR} = 10^{(20/10)} = 100$$

انخفاض 10 dB يعني قسمة النسبة على 10 (من 1000 إلى 100).

ملاحظة:

Example 4: SNR and SNR_dB

Problem: The power of a signal is 10 mW and the power of the noise is 1 μ W. What are the values of SNR and SNR_dB?

Signal = 10 mW



Noise = 1 μ W



SNR , SNR_dB = ?

1 Unify units

$$1 \mu\text{W} = 10^{-3} \text{ mW} = 0.001 \text{ mW}$$

2 Compute SNR

$$\text{SNR} = 10 \text{ mW} / 0.001 \text{ mW} = 10,000 = 10^4$$

3 Compute SNR_dB

$$\text{SNR}_{\text{dB}} = 10 \cdot \log_{10} (10^4) = 40 \text{ dB}$$

تنبيه: وحدّ الوحدات أولاً! $1 \mu\text{W} = 0.001 \text{ mW}$ ، وإلا ستحصل على جواب خاطئ.

ملاحظة:

Practice Problems

1

A 100 mW signal drops to 25 mW after crossing a medium. Find the attenuation in dB.

2

A 40 km cable has 0.5 dB/km attenuation and receives 1 W at its input. Find the output power.

3

A channel has $\text{SNR}_{\text{dB}} = 13$ dB. Find the SNR as a ratio.

ملاحظة:

حاول الحل بنفسك أولاً؛ الأجوبة موجودة في ملاحظات المحاضر (Notes).

Summary

Problem	Cause	Effect	Remedy
Attenuation	Distance, absorption, obstacles	Weak signal	Repeaters, higher-gain antennas
Fading	Multipath, shadowing, rain	Fluctuating level	Fade margin, diversity
Distortion	Different delay per frequency	Inter-symbol interference	Equalizer
Noise	Thermal, crosstalk, impulse	Lower SNR, more errors	Filters, LNA, more power

الخلاصة: نجاح الاتصال يعتمد على نسبة SNR عند المستقبل.

ملاحظة:

الاختبار البعدي (Post-test)

A 100 mW signal drops to 25 mW after crossing a medium.
Find the attenuation in dB.

A 40 km cable has an attenuation of 0.5 dB/km and receives 1 W at its input. Find the output power.

A channel has $\text{SNR}_{\text{dB}} = 13$ dB. Find the SNR as a power ratio.

In free space, doubling the distance changes the loss by about: (a) +3 dB (b) +6 dB (c) +10 dB (d) +20 dB

Thermal noise power is given by: (a) $N = k \cdot T \cdot B$ (b) $N = P / d$
(c) $N = B \cdot \log_2(1 + \text{SNR})$ (d) $N = 10 \cdot \log_{10}(P)$

Define inter-symbol interference (ISI) and name one remedy.

Lecture-4-

Free Space Losses

الاختبار القبلي (Pre-test)

1. Attenuation means: (a) an increase in signal frequency (b) loss of signal power as it travels (c) addition of unwanted signals (d) a change in signal phase
2. A power ratio of 0.5 (power halves) corresponds to about: (a) +3 dB (b) -3 dB (c) +10 dB (d) -10 dB
3. Unwanted signals that add to the useful signal are called: (a) fading (b) distortion (c) noise (d) gain
4. Multipath propagation mainly causes: (a) fading (b) amplification (c) modulation (d) coding
5. A high signal-to-noise ratio (SNR) means: (a) more bit errors (b) a signal buried in noise (c) a cleaner signal and fewer errors (d) lower channel capacity

In telecommunication, free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction. It does not include factors such as the gain of the antennas used at the transmitter and receiver, nor any loss associated with hardware imperfections. A discussion of these losses may be found in the article on link budget.

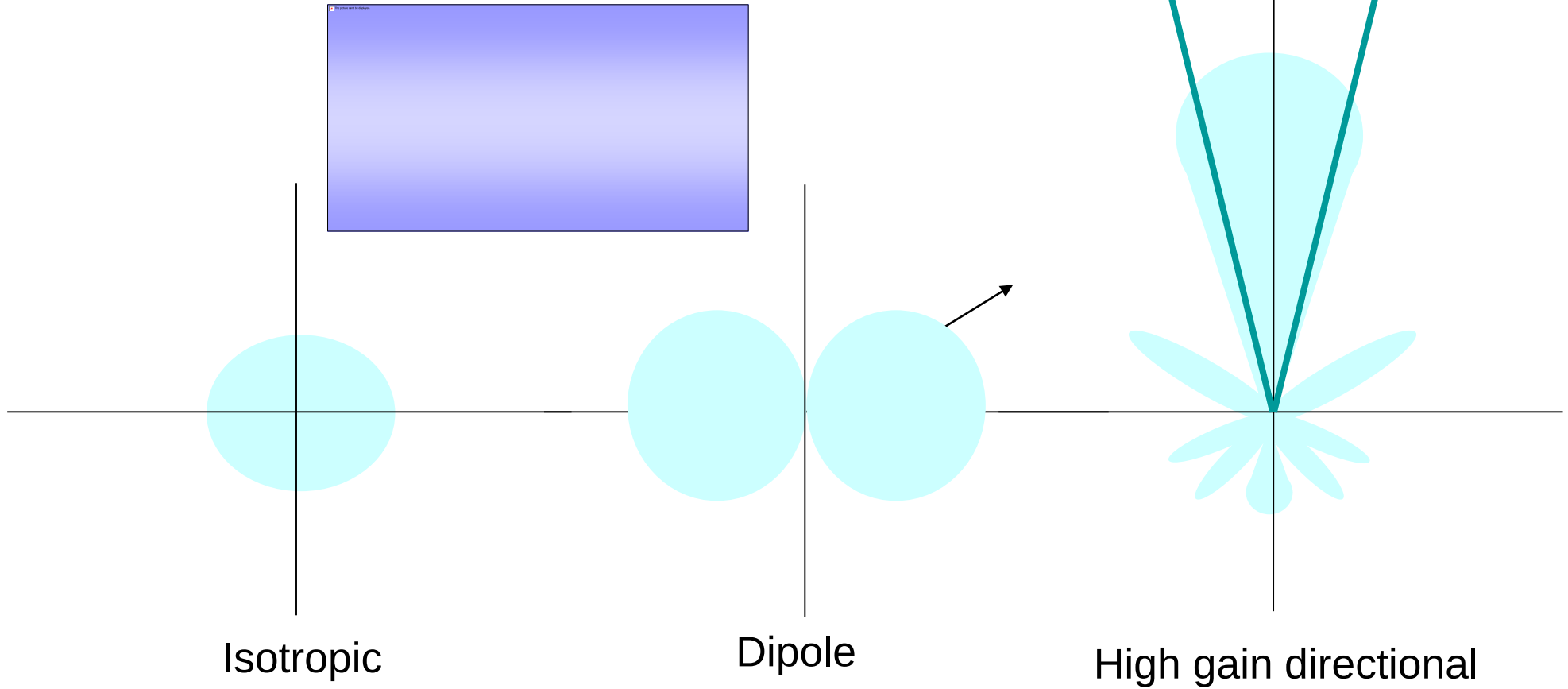
Mechanisms that affect the radio propagation

- **Reflection**
- **Diffraction**
- **Scattering**
- In urban areas, there is no direct line-of-sight path between the transmitter and the receiver, and where the presence of high-rise buildings causes severe diffraction loss.
- Multiple reflections cause multi-path fading.

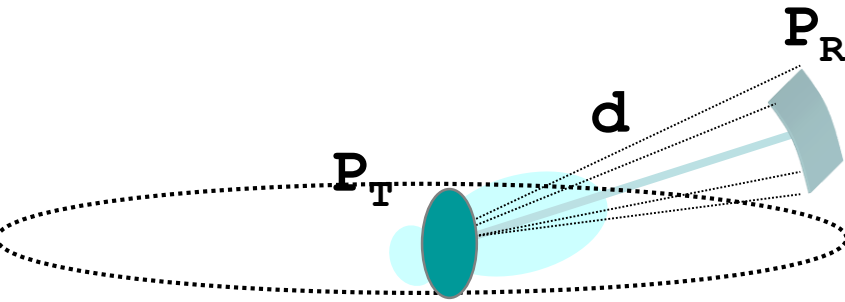
Reflection, Diffraction, Scattering

- Reflections arise when the plane waves are incident upon a surface with dimensions that are very large compared to the wavelength.
- Diffraction occurs according to Huygens's principle when there is an obstruction between the transmitter and receiver antennas, and secondary waves are generated behind the obstructing body.
- Scattering occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less, and causes the energy to be redirected in many directions.

Antenna Basics



Free Space Propagation Model



$$P_{Di} = \frac{P_T}{4\pi d^2} \text{ W / m}^2$$

Isotropic power density

$$P_D = \frac{P_T G_T}{4\pi d^2}$$

Power density along the direction of maximum radiation

$$P_R = P_D A_{eff}$$

Power received by Antenna

$$P_R = \frac{P_T G_T}{4\pi d^2} A_{eff}$$

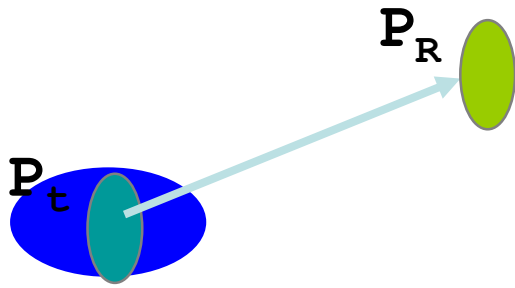
$$\frac{A_{eff}}{G} = \frac{\lambda^2}{4\pi}$$

Predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

Also known as Friis free space formula

Path Loss (relative measure)



$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

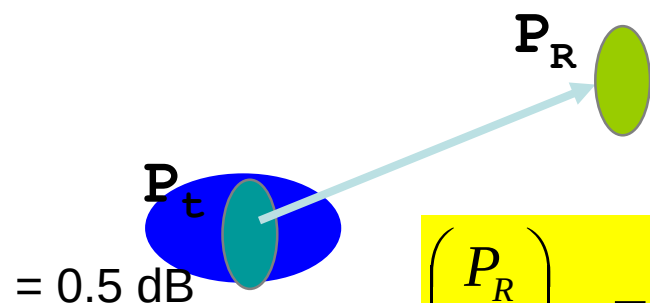
$$\frac{P_R}{P_T} = G_T G_R \frac{0.57 * 10^{-3}}{(df)^2}$$

f is in MHz
 d is in Km

$$\left(\frac{P_R}{P_T} \right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20 \log_{10} d + 20 \log_{10} f)$$

Path Loss represents signal attenuation (measured on dB) between the effective transmitted power and the receive power (excluding antenna gains)

Path Loss (Example)



Assume that antennas are isotropic.

Calculate receive power (in dBm) at free space distance of 100m from the antenna. What is P_R at 10Km? $f = 900$ MHz.

$$\left(\frac{P_R}{P_T} \right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20 \log_{10} d + 20 \log_{10} f)$$

$$\left(\frac{P_R}{P_T} \right)_{dB} = 0 + 0 - (32.5 + 20 \log_{10} 0.1 + 20 \log_{10} 900) \quad \rightarrow \quad 59$$

-20 (for $d = 0.1$)

$$\left(\frac{P_R}{P_T} \right)_{dB} = -71.5 dB$$

20 (for $d = 10$)

$$\left(\frac{P_R}{P_T} \right)_{dB} = -111.5 dB$$

If a transmitter produces 50 watts of power, express the transmit power in units of (a) dBm, and (b) dBW. If 50 watts is applied to a unity gain antenna with a 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna, What is P_r (10 km)? Assume unity gain for the receiver antenna.

Solution

Given:

Transmitter power, $P_t = 50$ W.

Carrier frequency, $f_c = 900$ MHz

Using equation (3.9),

(a) Transmitter power,

$$\begin{aligned}P_t (\text{dBm}) &= 10 \log [P_t (\text{mW}) / (1 \text{ mW})] \\&= 10 \log [50 \times 10^3] = 47.0 \text{ dBm}.\end{aligned}$$

(b) Transmitter power,

$$\begin{aligned}P_t (\text{dBW}) &= 10 \log [P_t (\text{W}) / (1 \text{ W})] \\&= 10 \log [50] = 17.0 \text{ dBW}.\end{aligned}$$

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{50 (1) (1) (1/3)^2}{(4\pi)^2 (100)^2 (1)} = 3.5 \times 10^{-6} \text{ W} = 3.5 \times 10^{-3} \text{ mW}$$

$$P_r (\text{dBm}) = 10 \log P_r (\text{mW}) = 10 \log (3.5 \times 10^{-3} \text{ mW}) = -24.5 \text{ dBm}.$$

The received power at 10 km can be expressed in terms of dBm

where $d_0 = 100$ m and $d = 10$ km

$$\begin{aligned}P_r (10 \text{ km}) &= P_r (100) + 20 \log \left[\frac{100}{10000} \right] = -24.5 \text{ dBm} - 40 \text{ dB} \\&= -64.5 \text{ dBm}.\end{aligned}$$

الاختبار البعدي (Post-test)

A 100 mW signal drops to 25 mW after crossing a medium.

Find the attenuation in dB.

A 40 km cable has an attenuation of 0.5 dB/km and receives 1 W at its input. Find the output power.

A channel has $\text{SNR}_{\text{dB}} = 13$ dB. Find the SNR as a power ratio.

In free space, doubling the distance changes the loss by about:

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Thermal noise power is given by: (a) $N = k \cdot T \cdot B$ (b) $N = P / d$

(c) $N = B \cdot \log_2(1 + \text{SNR})$ (d) $N = 10 \cdot \log_{10}(P)$

Define inter-symbol interference (ISI) and name one remedy.

Lecture-5-

Transmission Line

الاختبار القبلي (Pre-test)

A transmission line consists of: (a) a single conductor (b) two conductors separated by a dielectric (c) a hollow metal tube only (d) an optical fibre

The wave carried by a transmission line is: (a) TE (b) TM (c) TEM (d) hybrid

The characteristic impedance of a lossless line is: (a) purely real (b) purely imaginary (c) zero (d) infinite

When $Z_L = Z_0$, the reflection coefficient Γ equals: (a) +1 (b) -1 (c) 0 (d) ∞

A short-circuited load gives Γ equal to: (a) +1 (b) 0 (c) 0.5 (d) -1

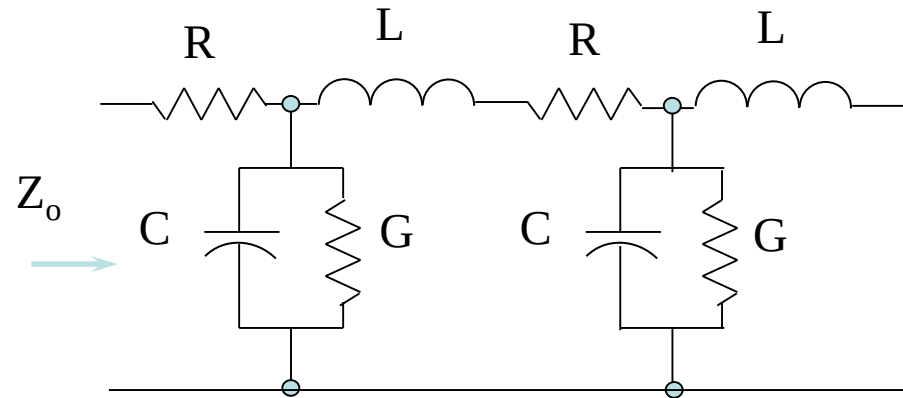
Transmission Lines

- A transmission line (TL) is a distributed-parameter network, where voltages and currents can vary in magnitude and phase over the length of the line.
- TL has two conductors in parallel with a dielectric separating them.
- They transmit TEM waves inside the lines.

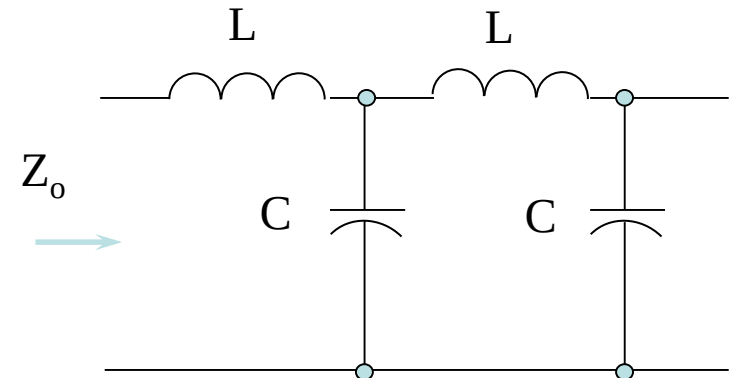
Lumped Element Model for a Transmission Line

- Transmission lines usually consist of 2 parallel conductors.
- A short segment Δz of transmission line can be modeled as a lumped-element circuit.

Transmission Line Equivalent Circuit



“Lossy” Line



Lossless Line

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$Z_o = \sqrt{\frac{L}{C}}$$

R = series resistance per unit length for both conductors.
L = series inductance per unit length for both conductors.
G = shunt conductance per unit length.
C = shunt capacitance per unit length.

- The wavelength on the line:

$$\lambda = \frac{2\pi}{\beta} = \frac{2\pi}{\omega\sqrt{LC}}$$

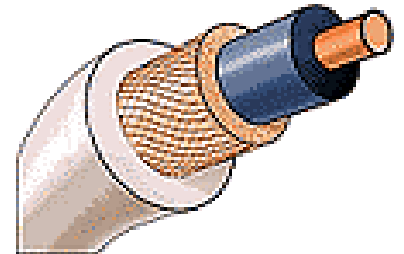
- The phase velocity on the line:

$$v_p = \frac{\omega}{\beta} = \sqrt{\frac{1}{LC}}$$

Note the characteristic impedance of a **lossless** transmission line is purely **real** (i.e., $\text{Im}\{Z_0\} = 0$).

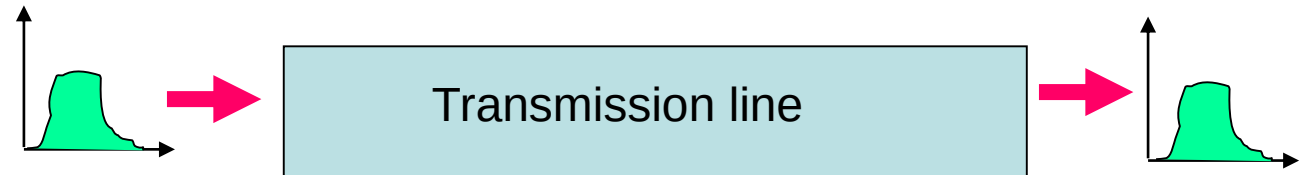
Types of Transmission Lines

- **Differential** or **balanced lines** (where neither conductor is grounded): e.g. twin lead, twisted-cable pair, and shielded-cable pair.
- **Single-ended** or **unbalanced lines** (where one conductor is grounded): e.g. concentric or coaxial cable.
- Transmission lines for microwave use: e.g. striplines, microstrips, and waveguides.

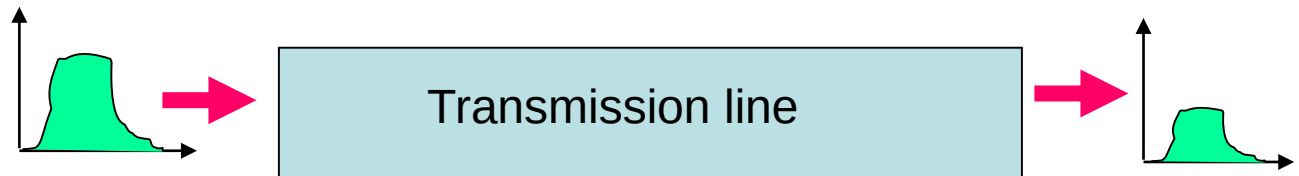


Different cases of TL

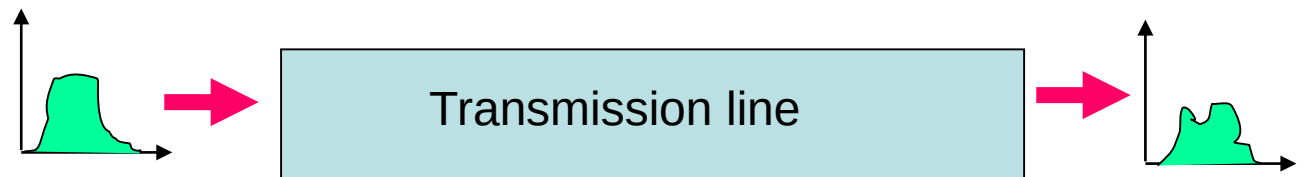
- Lossless



- Distortionless



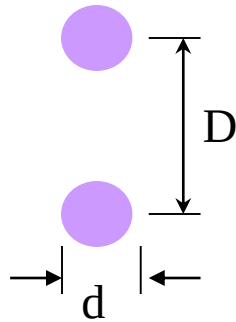
- Lossy



Notes on Transmission Line

- Characteristics of a line is determined by its primary electrical constants or distributed parameters: R (Ω/m), L (H/m), C (F/m), and G (S/m).
- Characteristic impedance, Z_0 , is defined as the input impedance of an infinite line or that of a finite line terminated with a load impedance, $Z_L = Z_0$.

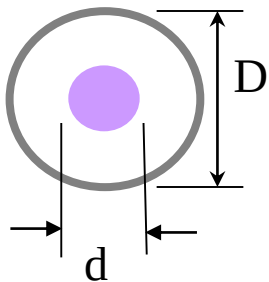
Formulas for Some Lines



For parallel two-wire line:

$$L = \frac{\mu}{\pi} \ln \frac{2D}{d}; \quad C = \frac{\pi\epsilon}{\ln \frac{2D}{d}}; \quad Z_o = \frac{120}{\sqrt{\epsilon_r}} \ln \frac{2D}{d}$$

$$\mu = \mu_0\mu_r; \quad \epsilon = \epsilon_0\epsilon_r; \quad \mu_0 = 4\pi \times 10^{-7} \text{ H/m}; \quad \epsilon_0 = 8.854 \text{ pF/m}$$



For co-axial cable:

$$L = \frac{\mu}{2\pi} \ln \frac{D}{d}; \quad C = \frac{2\pi\epsilon}{\ln \frac{D}{d}}; \quad Z_o = \frac{60}{\sqrt{\epsilon_r}} \ln \frac{D}{d}$$

Transmission-Line Wave Propagation

Electromagnetic waves travel at $< c$ in a transmission line because of the dielectric separating the conductors. The velocity of propagation is given by:

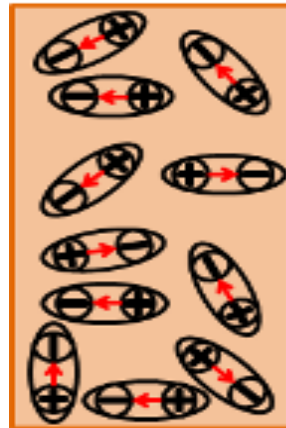
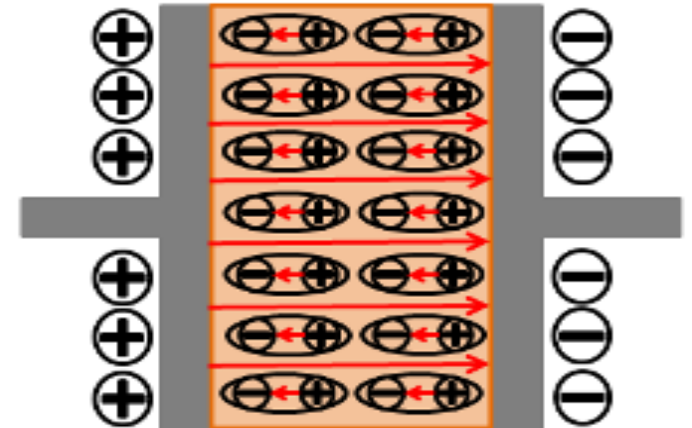
$$v = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\epsilon_r}} \quad \text{m/s}$$

Velocity factor, VF, is defined as:

$$VF = \frac{v}{c} = \frac{1}{\sqrt{\epsilon_r}}$$

Electric Permittivity

- A material with high permittivity polarizes more in response to an applied electric field than a material with low permittivity, thereby storing more energy in the material.
- The molecules normally align randomly with each other in a substance, but when an external electric field is introduced they align themselves in such a way that the electric field their dipole moments produce resists the external electric field.



Propagation Constant

- Used to describe the behavior of an electromagnetic wave along a transmission line.
- Propagation constant, γ , determines the variation of V or I with distance along the line: $V = V_s e^{-x\gamma}$; $I = I_s e^{-x\gamma}$, where V_s , and I_s are the voltage and current at the source end, and x = distance from source.
- $\gamma = \alpha + j\beta$, where α = attenuation coefficient (= 0 for lossless line), and β = phase shift coefficient = $2\pi/\lambda$ (rad./m)

Incident & Reflected Waves

- For an infinitely long line or a line terminated with a matched load, no incident power is reflected. The line is called a flat or nonresonant line.
- For a finite line with no matching termination, part or all of the incident voltage and current will be reflected.

Reflection Coefficient

The reflection coefficient is defined as:

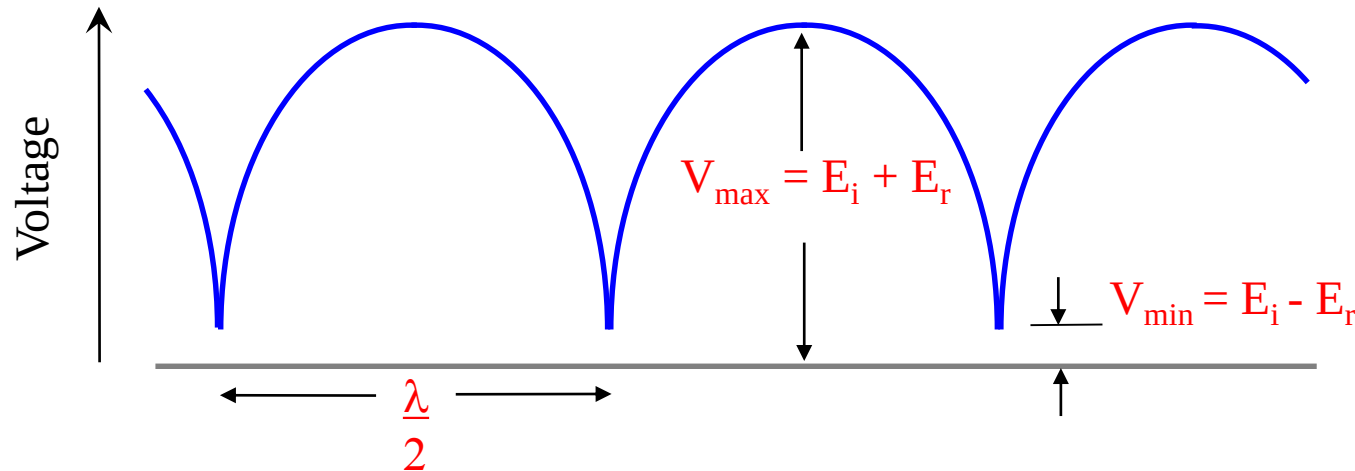
$$\Gamma = \frac{E_r}{E_i} \quad \text{or} \quad \frac{I_r}{I_i}$$

It can also be shown that:

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = |\Gamma| \angle \phi$$

Note that when $Z_L = Z_o$, $\Gamma = 0$; when $Z_L = 0$, $\Gamma = -1$; and when $Z_L = \text{open circuit}$, $\Gamma = +1$.

Standing Waves



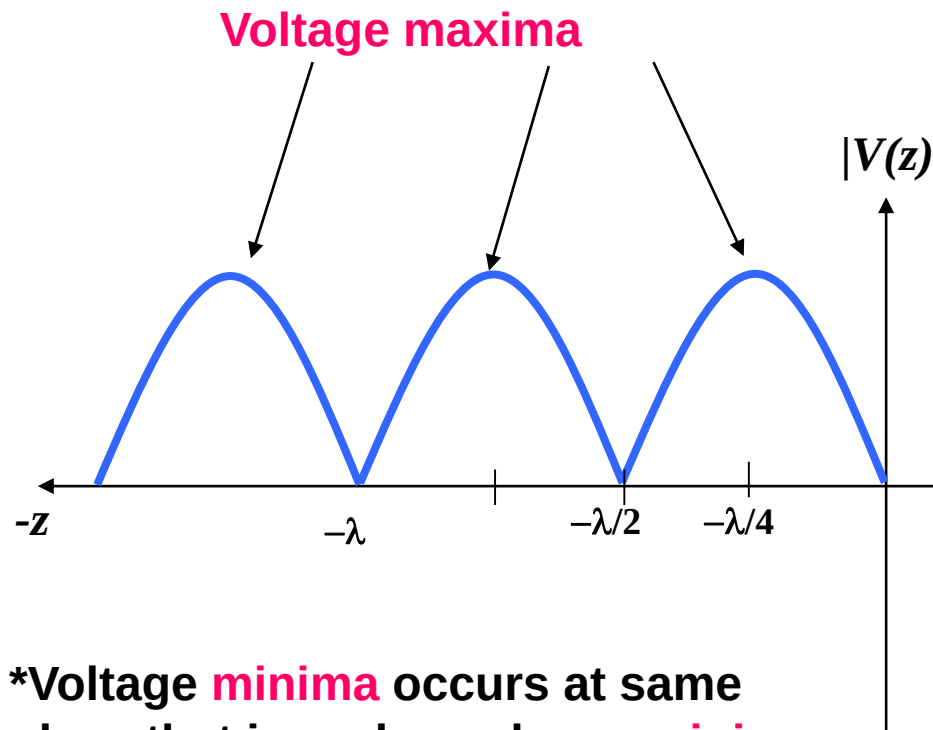
With a mismatched line, the incident and reflected waves set up an interference pattern on the line known as a standing wave ($1 < VSWR < \infty$). the distance between 2 successive voltage maxima (or minima) is $l = \lambda/2$, while the distance between a maximum and a minimum is $l = \lambda/4$.

The standing wave ratio is :

$$SWR = \frac{V_{\max}}{V_{\min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad \text{and} \quad |\Gamma| = \frac{VSWR - 1}{VSWR + 1}$$

Standing Waves -Short

Shorted Line ($Z_L=0$), we had

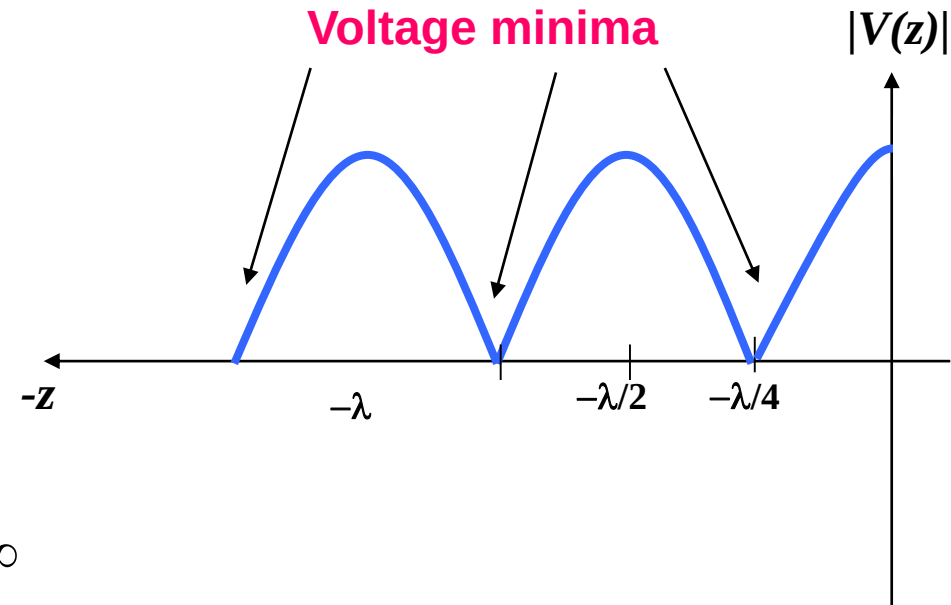


*Voltage **minima** occurs at same place that impedance has a **minimum** on the line

Standing Waves -Open

Open Line ($Z_L = \infty$) ,we had

- So substituting in $V(z)$

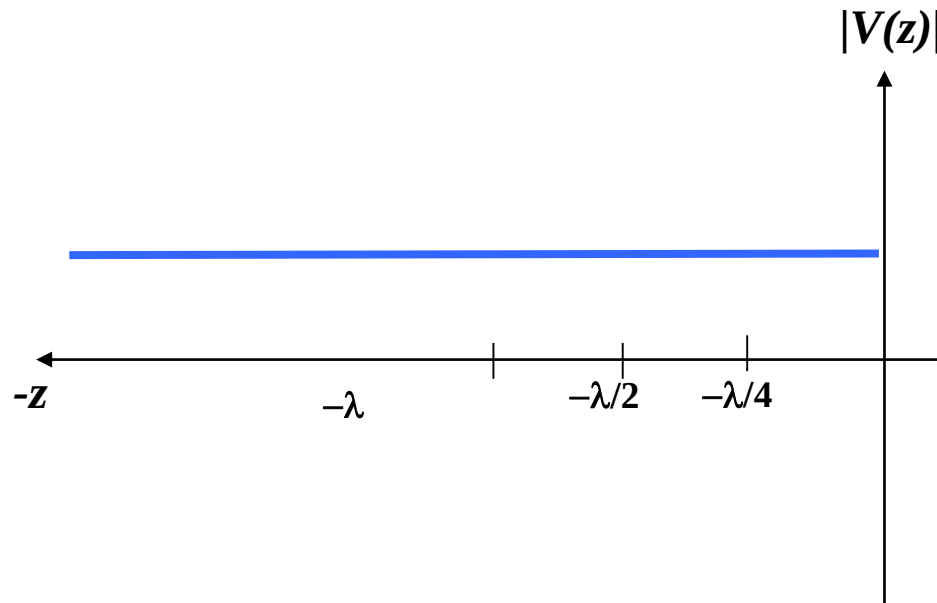


$$Z_{in} = -jZ_o \cot \beta l, \quad \Gamma_L = +1, \quad SWR = \infty$$

Standing Waves -Matched

Matched Line ($Z_L = Z_o$), we had

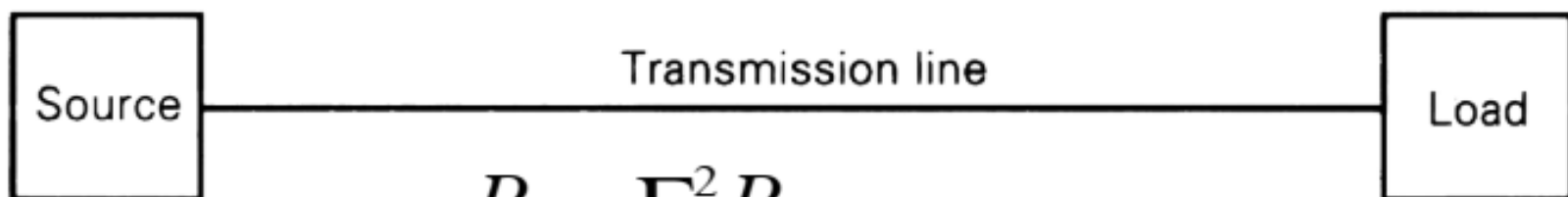
$$Z_{in} = Z_o, \quad \Gamma_L = 0, \quad SWR = 1$$



Example: Evaluate the VSWR for the coaxial cable has the reflection coefficient ($\Gamma = -0.1$).

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + |-0.1|}{1 - |-0.1|} = 1.2$$

Note: if two cables were matched, the *VSWR* would be 1.



$$P_r = \Gamma^2 P_i$$

$$P_L = P_i (1 - \Gamma^2)$$

$$P_L = \frac{4SWR}{(1 + SWR)^2} P_i$$

P_r = reflected power

P_i = incident power

P_L = power delivered to load

Other Formulas

When the load is purely resistive:
(whichever gives an $SWR > 1$)

$$SWR = \frac{Z_L}{Z_o} \text{ or } \frac{Z_o}{Z_L}$$

Return Loss, RL = Fraction of power reflected
= $|\Gamma|^2$, or $-20 \log |\Gamma|$ dB

$$\text{So, } P_r = |\Gamma|^2 P_i$$

Mismatched Loss, ML = Fraction of power
transmitted/absorbed = $1 - |\Gamma|^2$ or $-10 \log(1 - |\Gamma|^2)$ dB

$$\text{So, } P_t = P_i (1 - |\Gamma|^2) = P_i - P_r$$

Transmission-Line Input Impedance

The input impedance at a distance ℓ from the load is:

$$Z_i = Z_o \frac{Z_L + jZ_o \tan(\beta \ell)}{Z_o + jZ_L \tan(\beta \ell)}$$

When the load is a short circuit, $Z_i = jZ_o \tan(\beta \ell)$.

For $0 \rightarrow \ell < \lambda/4$, shorted line is inductive.

For $\ell = \lambda/4$, shorted line = a parallel resonant circuit.

For $\lambda/4 < \ell \rightarrow \lambda/2$, shorted line is capacitive.

T-L Input Impedance (cont'd)

When the load is an open circuit, $Z_i = -jZ_o \cot(\beta\ell)$

For $0 < \ell < \lambda/4$, open circuited line is capacitive.

For $\ell = \lambda/4$, open-line = series resonant circuit.

For $\lambda/4 < \ell < \lambda/2$, open-line is inductive.

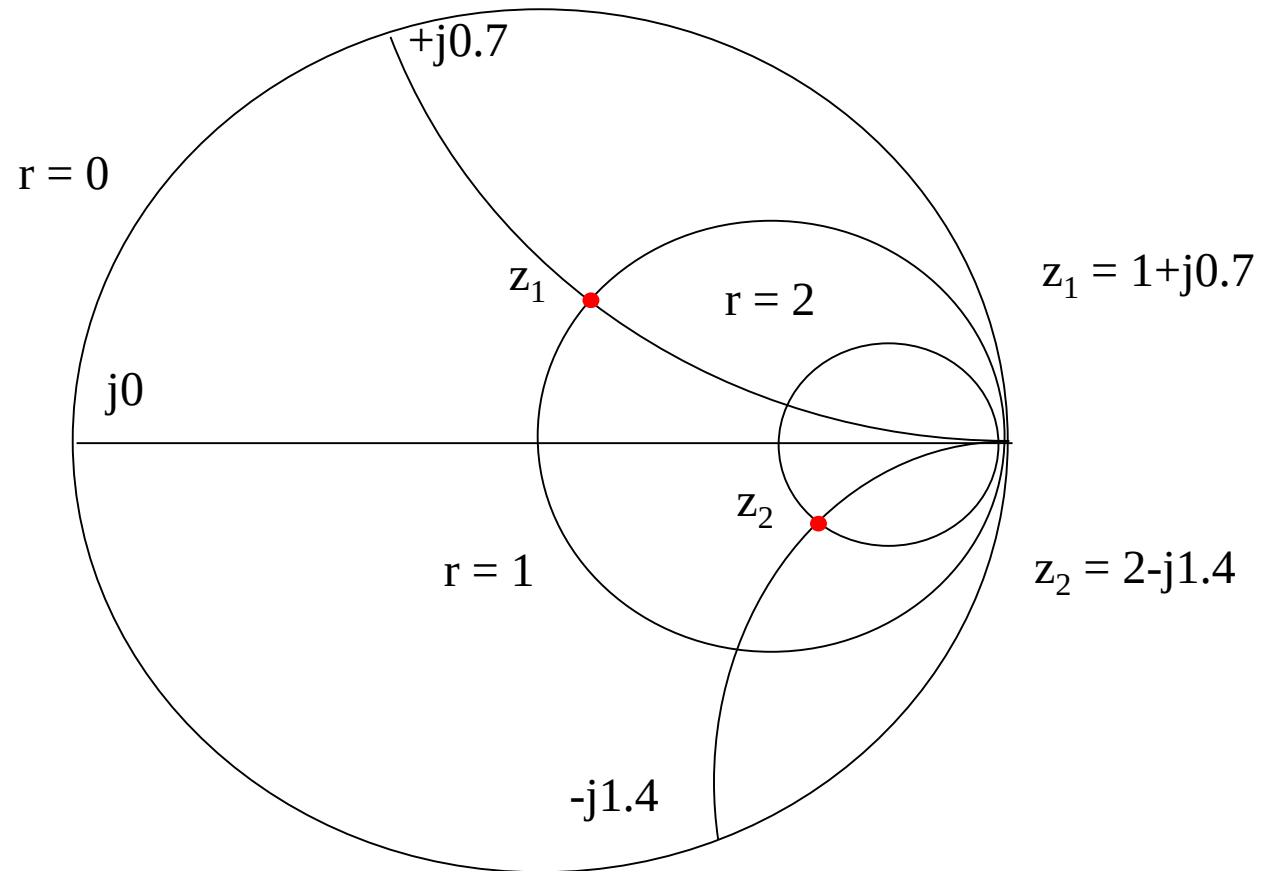
- A $\lambda/4$ line with characteristic impedance, Z_o , can be used as a matching transformer between a resistive load, Z_L , and a line with characteristic impedance, Z_o , by choosing:

$$Z'_o = \sqrt{Z_o Z_L}$$

Smith Chart

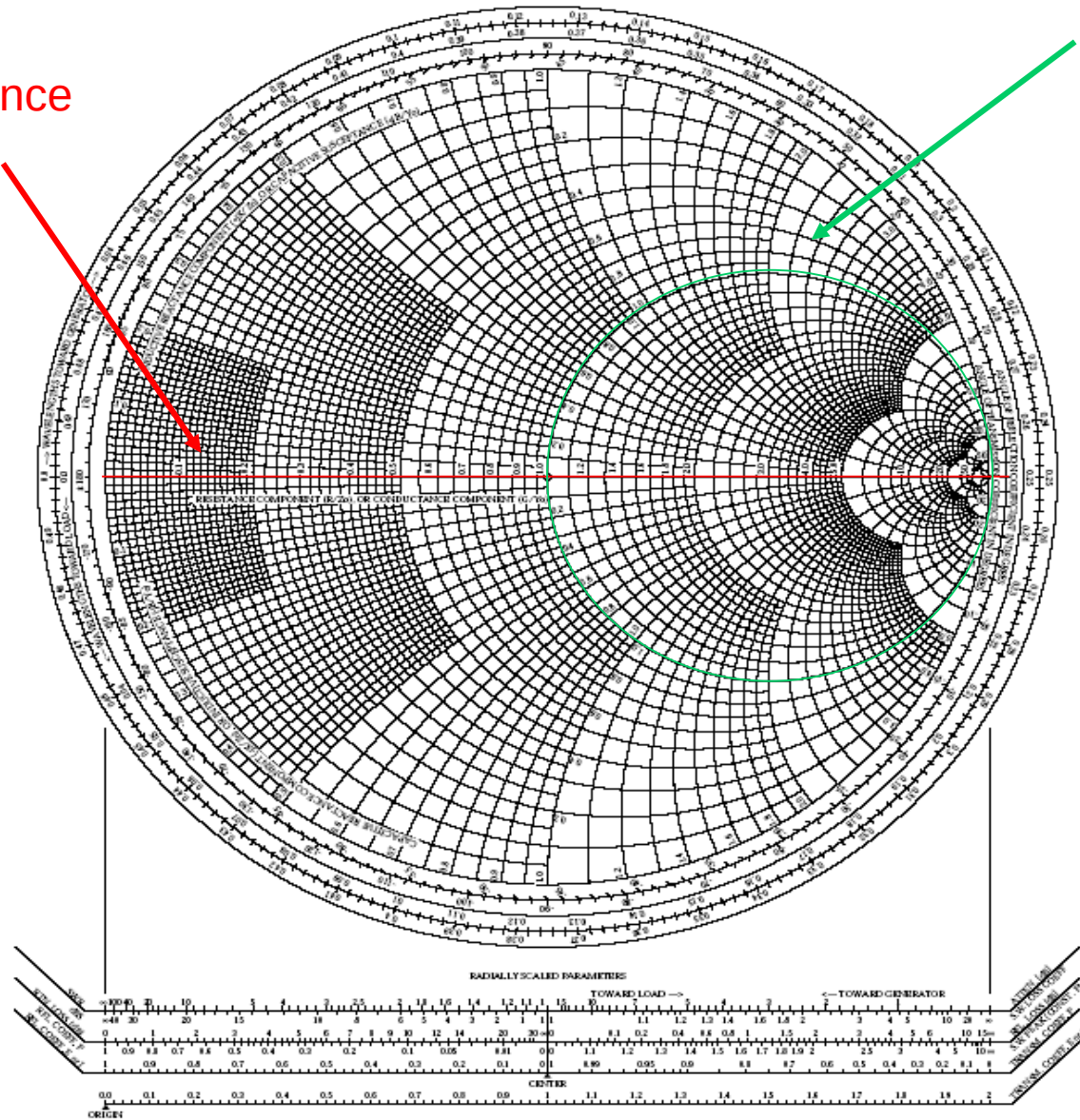
- The Smith chart is a clever graphical tool for solving transmission-line impedance problems.
- The coordinates on the chart are based on the intersection of two sets of orthogonal circles.
- One set represents the normalized resistive component, r ($= R/Z_0$), and the other the normalized reactive component, $\pm jx$ ($= \pm jX/Z_0$).
- The outside of the chart shows location on the line in wavelengths

Smith Chart Basics



Real Impedance
Axis

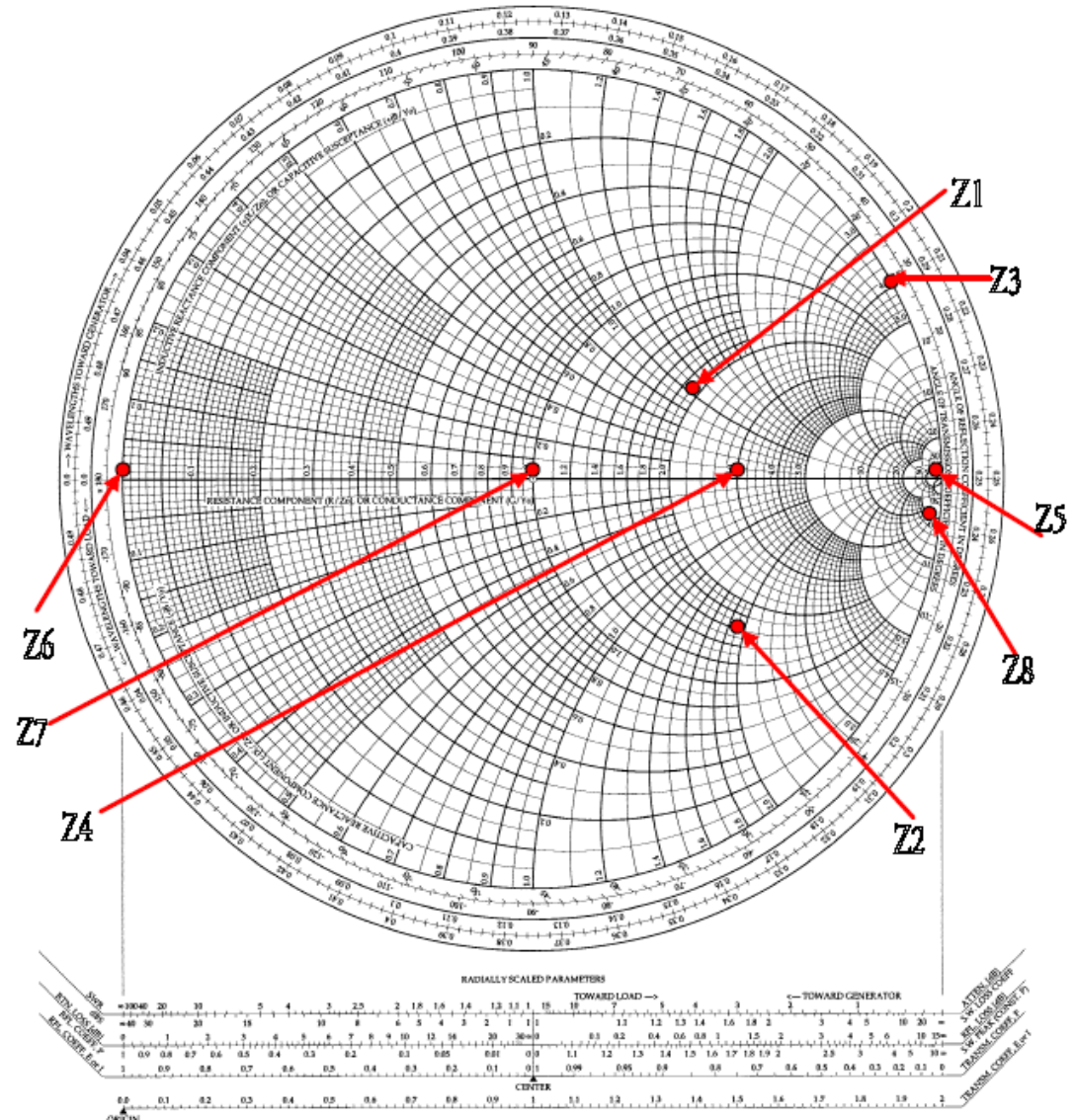
Imaginary
Impedance Axis



Applications of The Smith Chart

- Applications to be discussed in this course:
 - Find SWR, $|\Gamma|$, $\angle\phi$, RL
 - Find Y_L
 - Find Z_i of a shorted or open line of length ℓ
 - Find Z_i of a line terminated with Z_L
 - Find distance to $V_{\max}$ and $V_{\min}$ from Z_L
 - Solution for quarter-wave transformer matching
 - Solution for parallel single-stub matching

- Impedance divided by line impedance (50 Ohms)
 - $Z_1 = 100 + j50$
 - $Z_2 = 75 - j100$
 - $Z_3 = j200$
 - $Z_4 = 150$
 - $Z_5 = \text{infinity}$ (an open circuit)
 - $Z_6 = 0$ (a short circuit)
 - $Z_7 = 50$
 - $Z_8 = 184 - j900$
- Then, normalize and plot. The points are plotted as follows:
 - $z_1 = 2 + j$
 - $z_2 = 1.5 - j2$
 - $z_3 = j4$
 - $z_4 = 3$
 - $z_5 = \text{infinity}$
 - $z_6 = 0$
 - $z_7 = 1$
 - $z_8 = 3.68 - j18S$



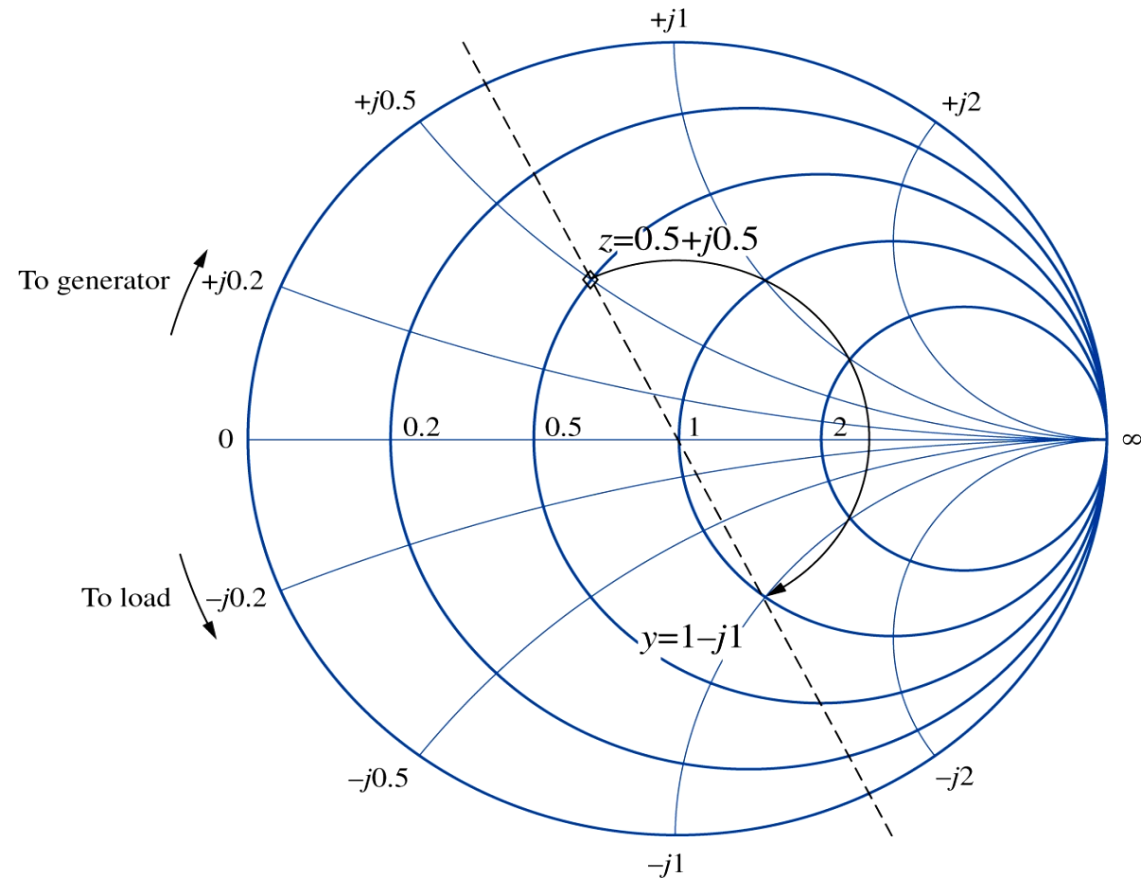
- Thus, the first step in analyzing a transmission line is to locate the normalized load impedance on the chart.
- Next, a circle is drawn that represents the reflection coefficient or SWR. The center of the circle is the center of the chart. The circle passes through the normalized load impedance.
- Any point on the line is found on this circle. Rotate clockwise to move toward the generator (away from the load).
- The distance moved on the line is indicated on the outside of the chart in wavelengths.

For example, the impedance
 $z = 0.5 + j0.5$
corresponds to the admittance

$$y = \frac{1}{0.5 + j0.5} = 1 - j1$$

Surprisingly, this calculation can be done graphically using the Smith chart! First, we locate the normalized impedance on the chart. Second, we draw a circle (or a semicircle “to generator”) centered at the center of the Smith chart and passing through the impedance.

Third, we plot a straight line through the center of the Smith chart and through this impedance. The intersection of the line with the semicircle yields the value for the admittance.



Example: Load Impedance

$Z_R = 50 + j100 \, \Omega$ on a $50 \, \Omega$ line.

Solution:-

- i. Normalize the Impedance; $z = 1 + j2.0 \, \Omega$.
- ii. On horizontal Resistance line move from zero to 1.0 on the right.
- iii. Follow resistance circle upward.
- iv. Locate point where crosses reactance circle $j2.0$
- v. Point of intersection is $z = 1.0 + j2.0 \, \Omega$.

Example:-Voltage Standing Wave Ratio:

$Z_R = 100 - j50\Omega$ on a 50Ω line. Find SWR?

Solution:

- Normalize $Z \dots z_R = 2 - j1.0 \Omega$
- Plot it on the chart
- Draw a circle with center at point (1,0) through point z_R
- VSWR is 2.6

Example: Reflection Coefficient:-

$Z_R = 100 + j75\Omega$ on a 50Ω line Find $|\Gamma|$?

Solution:

- Normalize Load $z_R = 2 + j1.5 \Omega$
- Plot the z_R on the chart
- Draw VSWR circle through z_R , read $SWR... = 3.3$
- $|\Gamma| = (swr - 1)/(swr + 1)$?
- $|\Gamma| = 0.535$
- Draw a radial line through z_R to meet the phase line.... $\Gamma = 0.535 \angle 30^\circ$

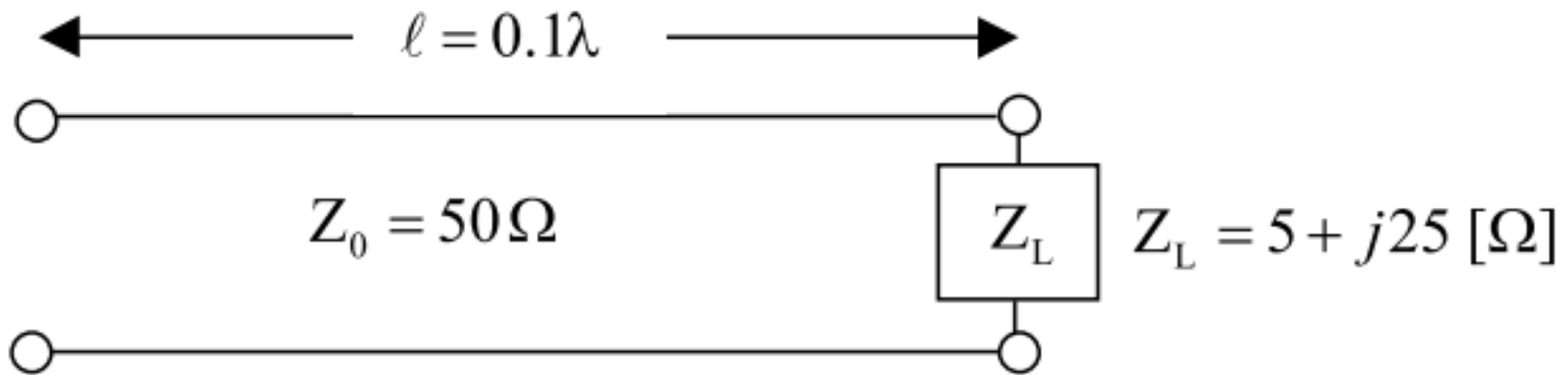
Example: Reflection Coefficient:-

$Z_R = 100 + j75\Omega$ on a 50Ω line Find $|\Gamma|$?

Solution:

- Normalize Load $z_R = 2 + j1.5 \Omega$
- Plot the z_R on the chart
- Draw VSWR circle through z_R , read $VSWR... = 3.3$
- $|\Gamma| = (swr - 1)/(swr + 1)$?
- $|\Gamma| = 0.535$
- Draw a radial line through z_R to meet the phase line.... $\Gamma = 0.535 \angle 30^\circ$

Example: The 0.1λ length line shown has a characteristic impedance of 50 and is terminated with a load impedance of $Z_L = 5 + j25$.



a) Locate $z_L = Z_L / Z_0 = 0.1 + j0.5$ on the Smith chart. See the point plotted on the Smith chart.

b) What is the impedance at $\ell = 0.1\lambda$? Since we want to move toward the generator, read 0.074λ on the wavelengths toward generator scale and add $\ell = 0.1\lambda$ to obtain 0.174λ on the wavelengths toward generator scale. A radial line from the center of the chart intersects the constant reflection coefficient magnitude circle at $z = 0.38 + j1.88$. Hence

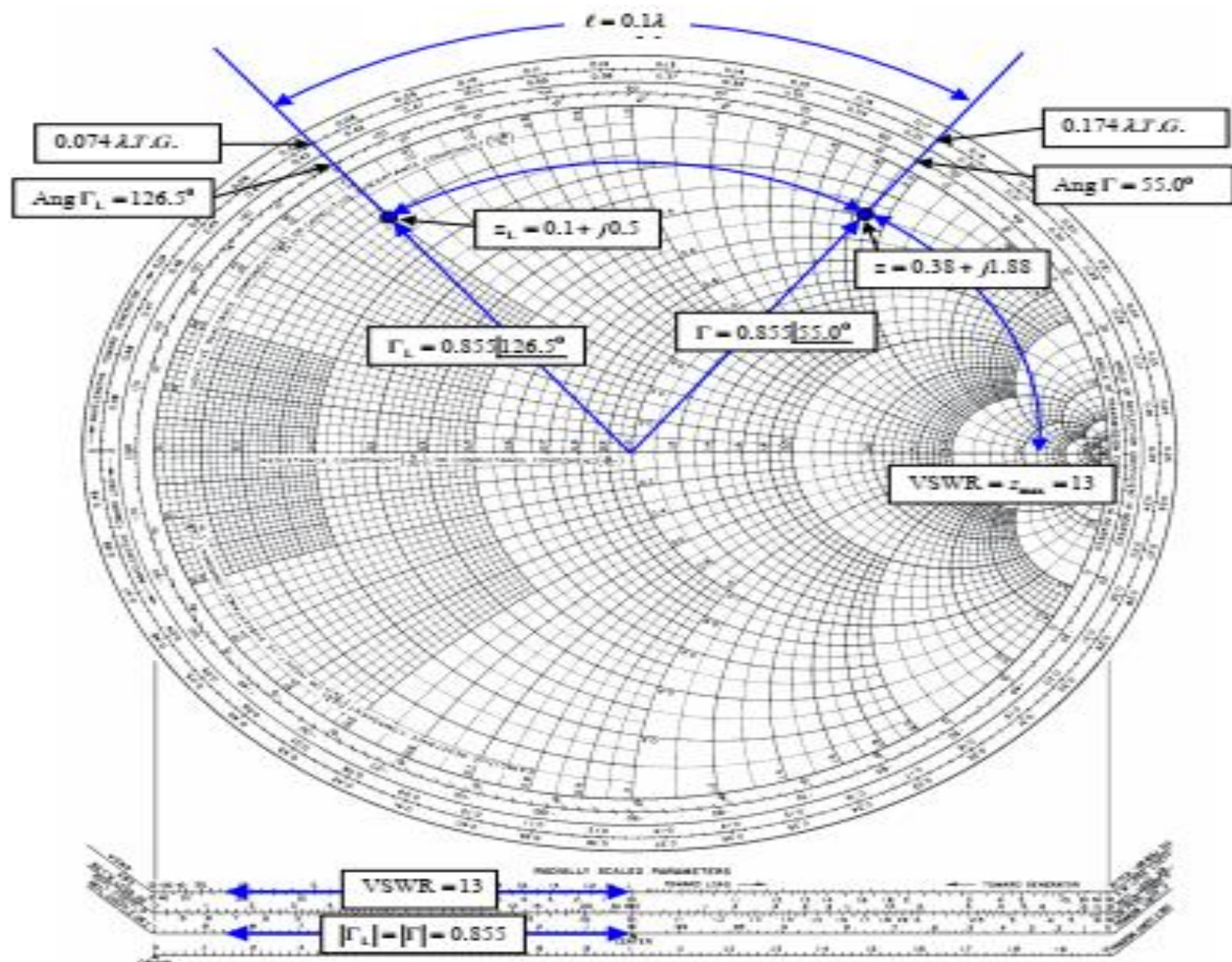
$$Z_L = z \times Z_0 = 50 \times (0.38 + j1.88) = 19 + j94 \Omega.$$

c) What is the VSWR on the line?
Find $\text{SWR} = z_{\max} = 13$ on the horizontal line to the right of the chart's center. Or use the SWR scale on the chart.

d) What is Γ_L ?
From the reflection coefficient scale below the chart, find $|\Gamma_L| = 0.855$. From the angle of reflection coefficient scale on the perimeter of the chart, find the angle of $\Gamma_L = 126.5^\circ$.
Hence $\Gamma_L = 0.855 e^{(j126.5)}$.

e) What is Γ at $\ell = 0.1\lambda$ from the load?

Note that $|\Gamma| = |\Gamma_L| = 0.855$. Read the angle of the reflection coefficient from the ANGLE OF REFLECTION COEFFICIENT scale as 55.0° . Hence $\Gamma = 0.855e^{j55.0^\circ}$.



الاختبار البعدي (Post-test)

1. A coaxial cable has $|\Gamma| = 0.1$. Find the VSWR, the return loss and the mismatch loss.
2. A 100Ω load is connected to a 50Ω line. Find Γ and the VSWR.
3. Find the characteristic impedance of a quarter-wave transformer that matches a 100Ω load to a 50Ω line.
4. Normalize the load $Z = 100 + j50 \Omega$ on a 50Ω line, ready to plot on the Smith chart.
5. The distance between two successive voltage maxima on a mismatched line is: (a) $\lambda/4$ (b) $\lambda/2$ (c) λ (d) 2λ
6. On the Smith chart, moving toward the generator means rotating: (a) clockwise (b) anticlockwise (c) along the real axis only (d) to the centre

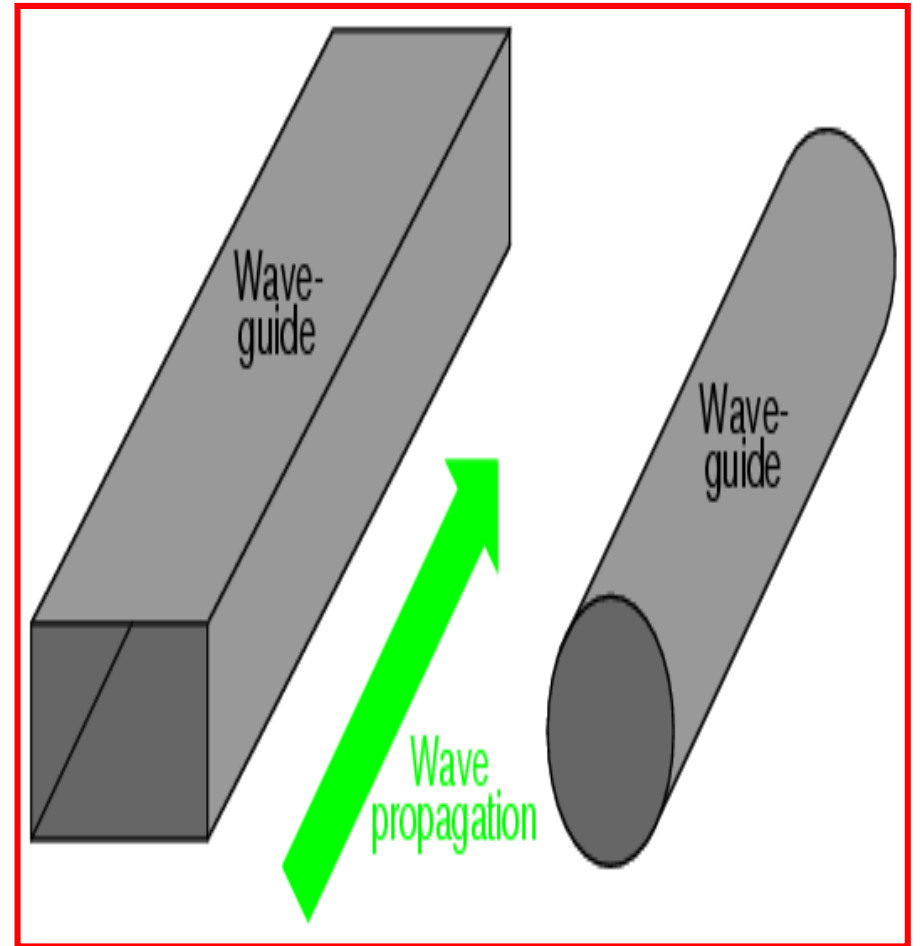
Lecture-6-

Waveguides

- Wave guide
- Basic features
- Rectangular Wave guide
- Circular Wave guide
- Applications

Definition

➤ A Hollow metallic tube of uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called ***waveguide***.



- Pipe through which waves propagate.
- Can have various cross sections:
 - Rectangular
 - Circular
 - Elliptical
- Can be rigid or flexible.
- Waveguides have very low loss.

- At frequencies higher than 3 GHz, transmission of electromagnetic energy along the transmission lines and cables becomes difficult.
- This is due to the losses that occur both in the solid dielectric needed to support the conductor and in the conductors themselves.
- A metallic tube can be used to transmit electromagnetic wave at the above frequencies

Basic features

- Waveguides may be used to carry energy between pieces of equipment or over longer distances to carry transmitter power to an antenna or microwave signals from an antenna to a receiver
- Waveguides are made from copper, aluminum or brass. These metals are extruded into long rectangular or circular pipes.
- An electromagnetic energy to be carried by a waveguide is injected into one end of the waveguide.
- The electric and magnetic fields associated with the signal bounce off the inside walls back and forth as it progresses down the waveguide.

Waveguide components



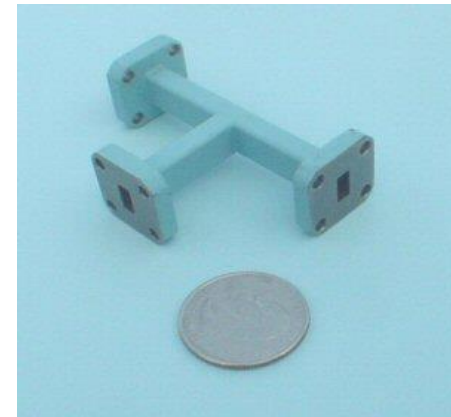
Rectangular waveguide



Waveguide to coax adapter



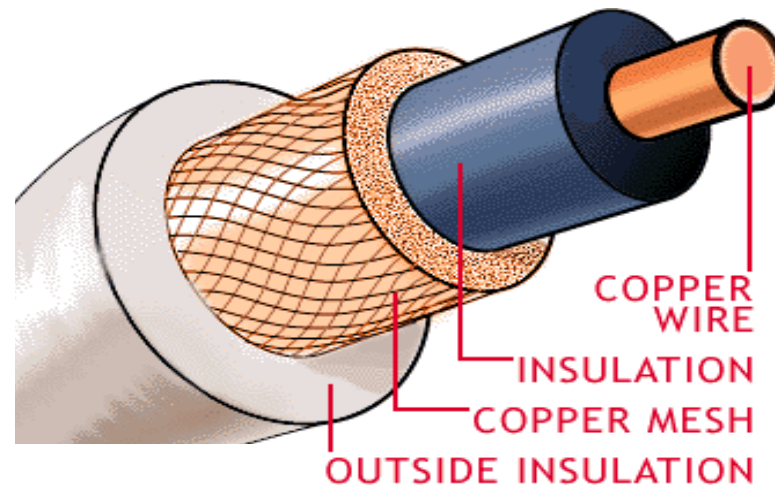
Waveguide bends



E-tee

Why Waveguide

- Skin effect is observed as a result of an induced eddy current field in the outermost layers of the metal.



Modes

- Waves can propagate in various ways.
- Time taken to move down the guide varies with the mode.
- Each mode has a cutoff frequency below which it won't propagate.
- Mode with lowest cutoff frequency is **dominant mode**.

EM field configuration within the waveguide

- In order to determine the EM field configuration within the waveguide, Maxwell's equations should be solved subject to appropriate boundary conditions at the walls of the guide.
- Such solutions give rise to a number of field configurations. Each configuration is known as a *mode*. The following are the different modes possible in a waveguide system

Possible Types of modes

1. Transverse Electro Magnetic (TEM) wave:

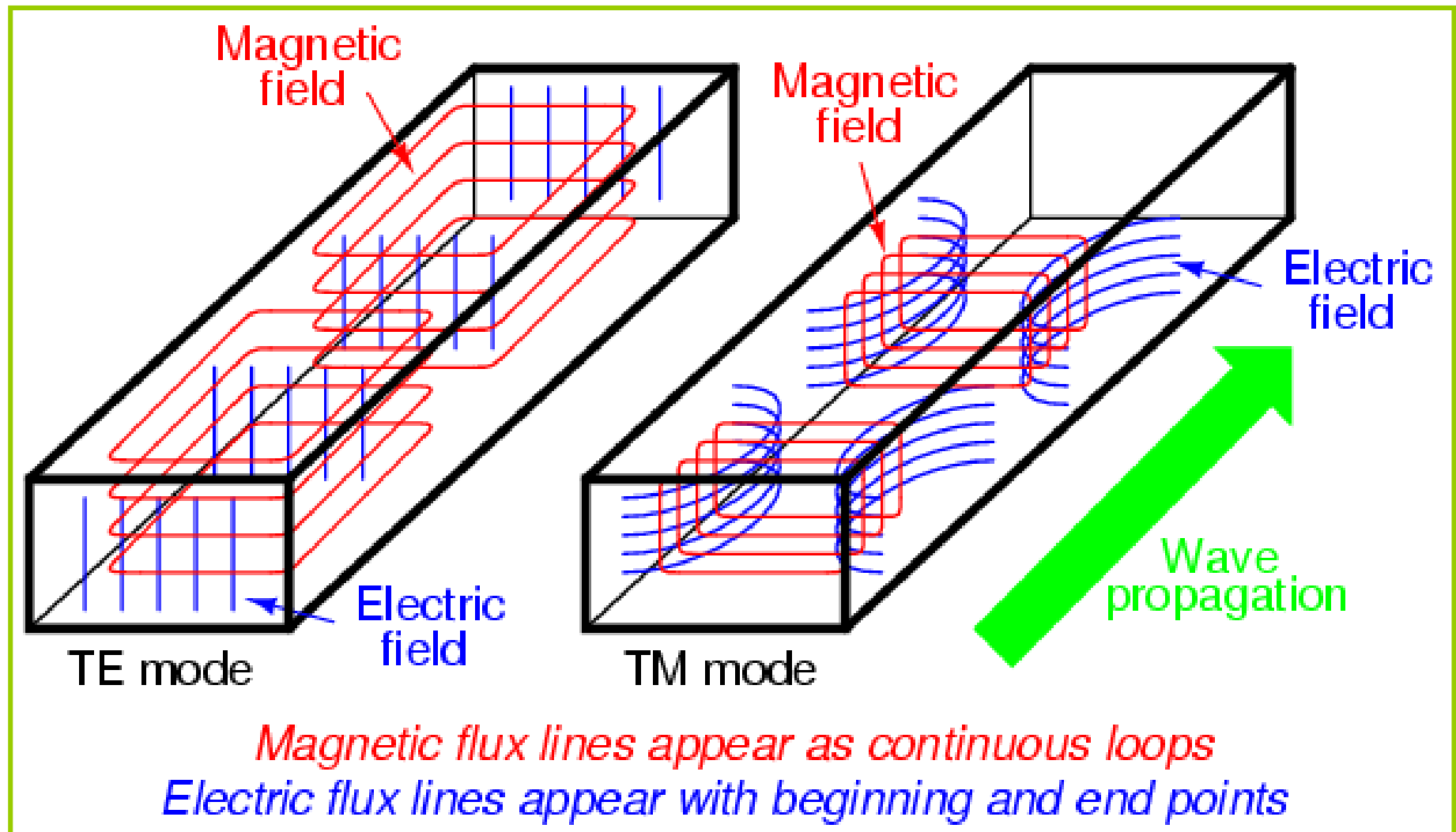
Here both electric and magnetic fields are directed components. (i.e.) $E_z = 0$ and $H_z = 0$

2. Transverse Electric (TE) wave: Here only the electric field is purely transverse to the direction of propagation and the magnetic field is not purely transverse. (i.e.) $E_z = 0, H_z \neq 0$

Possible Types of modes

3. **Transverse Magnetic (TM) wave:** Here only magnetic field is transverse to the direction of propagation and the electric field is not purely transverse. (i.e.) $E_z \neq 0, H_z = 0$.

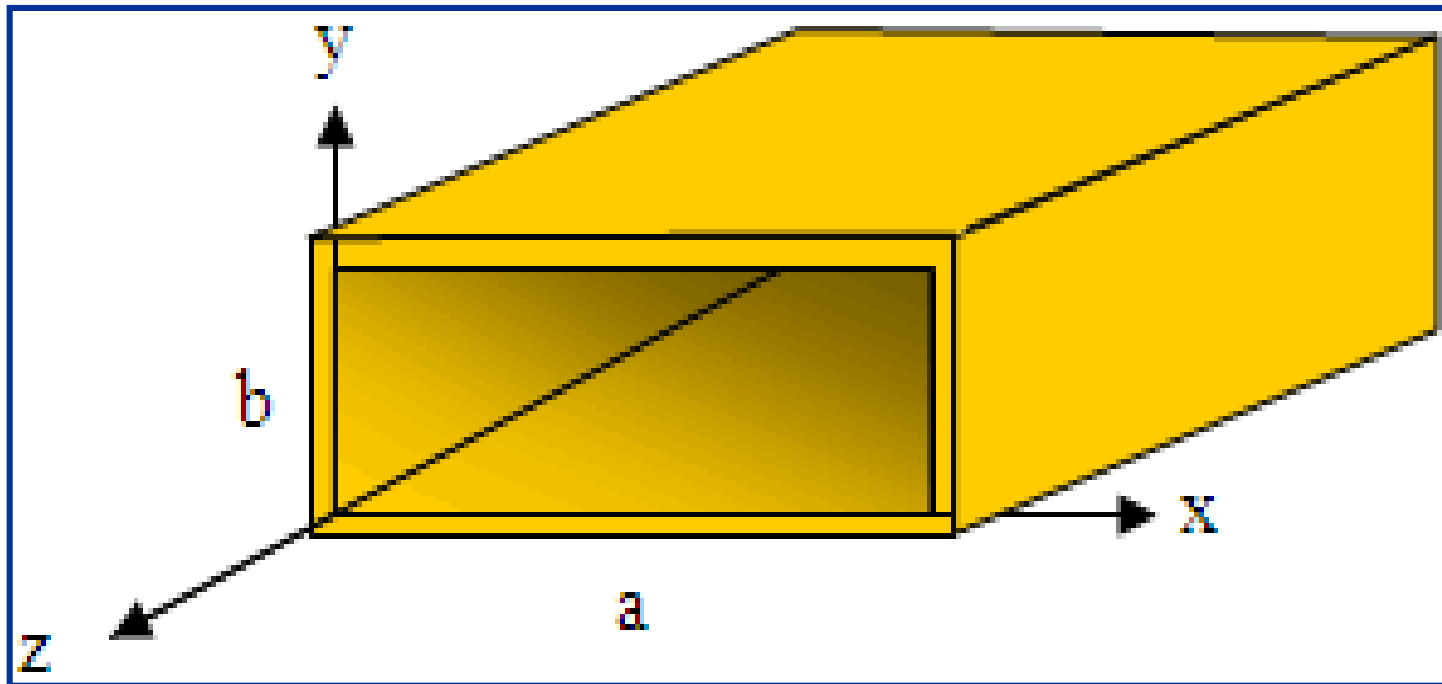
4. **Hybrid (HE) wave:** Here neither electric nor magnetic fields are purely transverse to the direction of propagation. (i.e.) $E_z \neq 0, H_z \neq 0$.



Rectangular Waveguides

- Any shape of cross section of a waveguide can support electromagnetic waves of which rectangular and circular waveguides have become more common.
- A waveguide having rectangular cross section is known as *Rectangular waveguide*

Rectangular waveguide

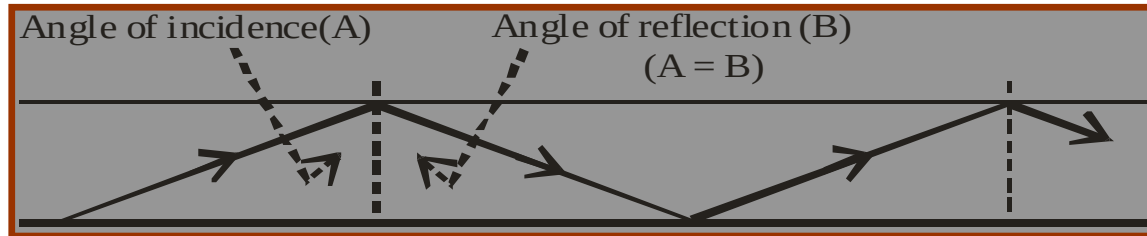


Dimensions of the waveguide which determines the operating frequency range

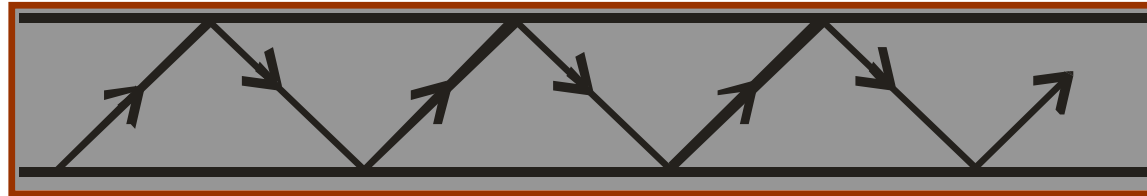
Dimensions of the waveguide which determines the operating frequency range:

1. The size of the waveguide determines its operating frequency range.
2. The frequency of operation is determined by the dimension 'a'.
3. This dimension is usually made equal to one – half the wavelength at the lowest frequency of operation, this frequency is known as the waveguide *cutoff frequency*.
4. At the cutoff frequency and below, the waveguide will not transmit energy. At frequencies above the cutoff frequency, the waveguide will propagate energy.

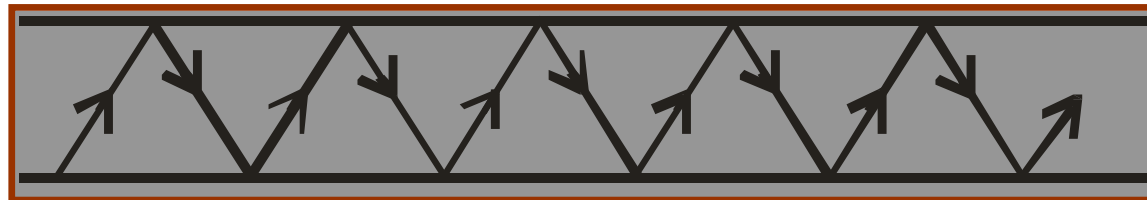
Wave paths in a waveguide at various frequencies



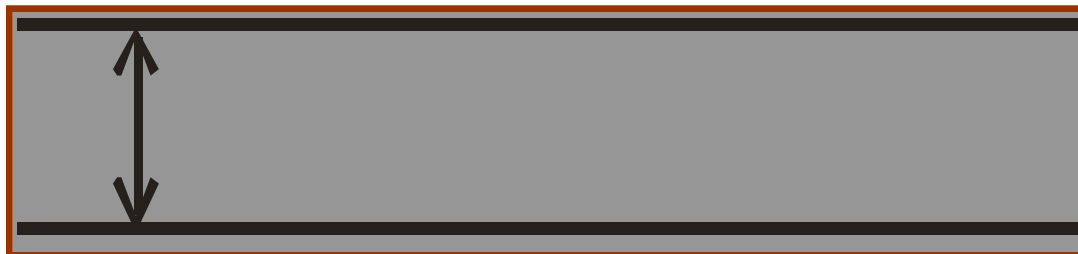
(a) At high frequency



(b) At medium frequency



(c) At low frequency



(d) At cutoff frequency

Wave propagation

- When a probe launches energy into the waveguide, the electromagnetic fields bounce off the side walls of the waveguide as shown in the above diagram.
- The angles of incidence and reflection depend upon the operating frequency. At high frequencies, the angles are large and therefore, the path between the opposite walls is relatively long as shown in Fig.

- At lower frequency, the angles decrease and the path between the sides shortens.
- When the operating frequency reaches the cutoff frequency of the waveguide, the signal simply bounces back and forth directly between the side walls of the waveguide and has no forward motion.
- At cut off frequency and below, no energy will propagate.

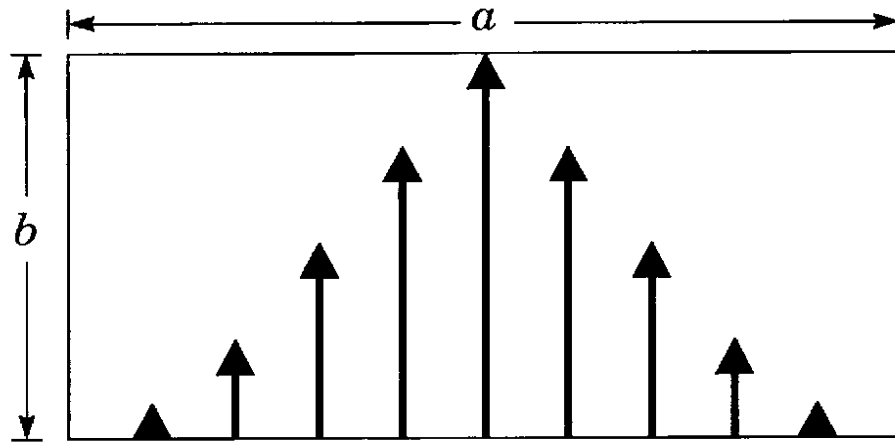
Cut off frequency

- The exact size of the wave guide is selected based on the desired operating frequency.
- The size of the waveguide is chosen so that its rectangular width is greater than one – half the wavelength but less than the one wavelength at the operating frequency.
- This gives a cutoff frequency that is below the operating frequency, thereby ensuring that the signal will be propagated down the line.

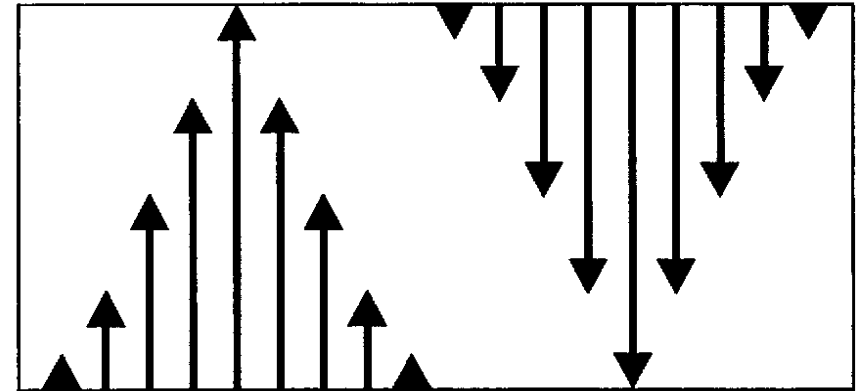
Representation of modes

- The general symbol of representation will be $TE_{m,n}$ or $TM_{m,n}$ where the subscript m indicates the number of half wave variations of the electric field intensity along the a (wide) dimension of the waveguide.
- The second subscript n indicates the number of half wave variations of the electric field in the b (narrow) dimension of the guide.
- The $TE_{1,0}$ mode has the longest operating wavelength and is designated as the dominant mode. It is the mode for the lowest frequency that can be propagated in a waveguide.

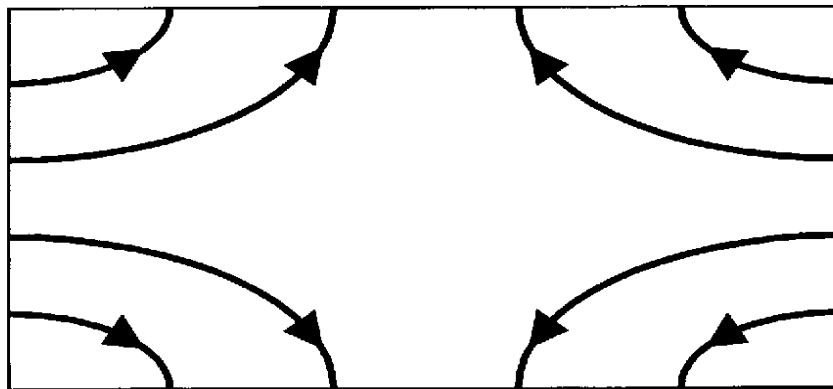
TE Modes in Rectangular Waveguide



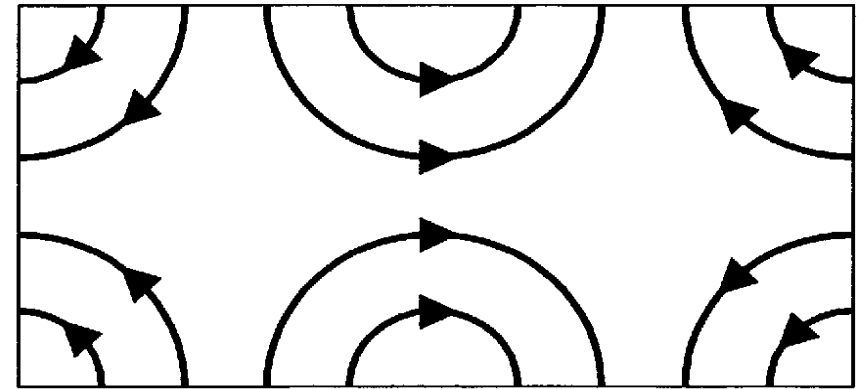
(a) TE_{10}



(b) TE_{20}



(c) TE_{11}



(d) TE_{21}

Expression for cut off wavelength

- For a standard rectangular waveguide, the cutoff wavelength is given by,

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$

$$f_{c_{mn}} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

Where a and b are measured in centimeters

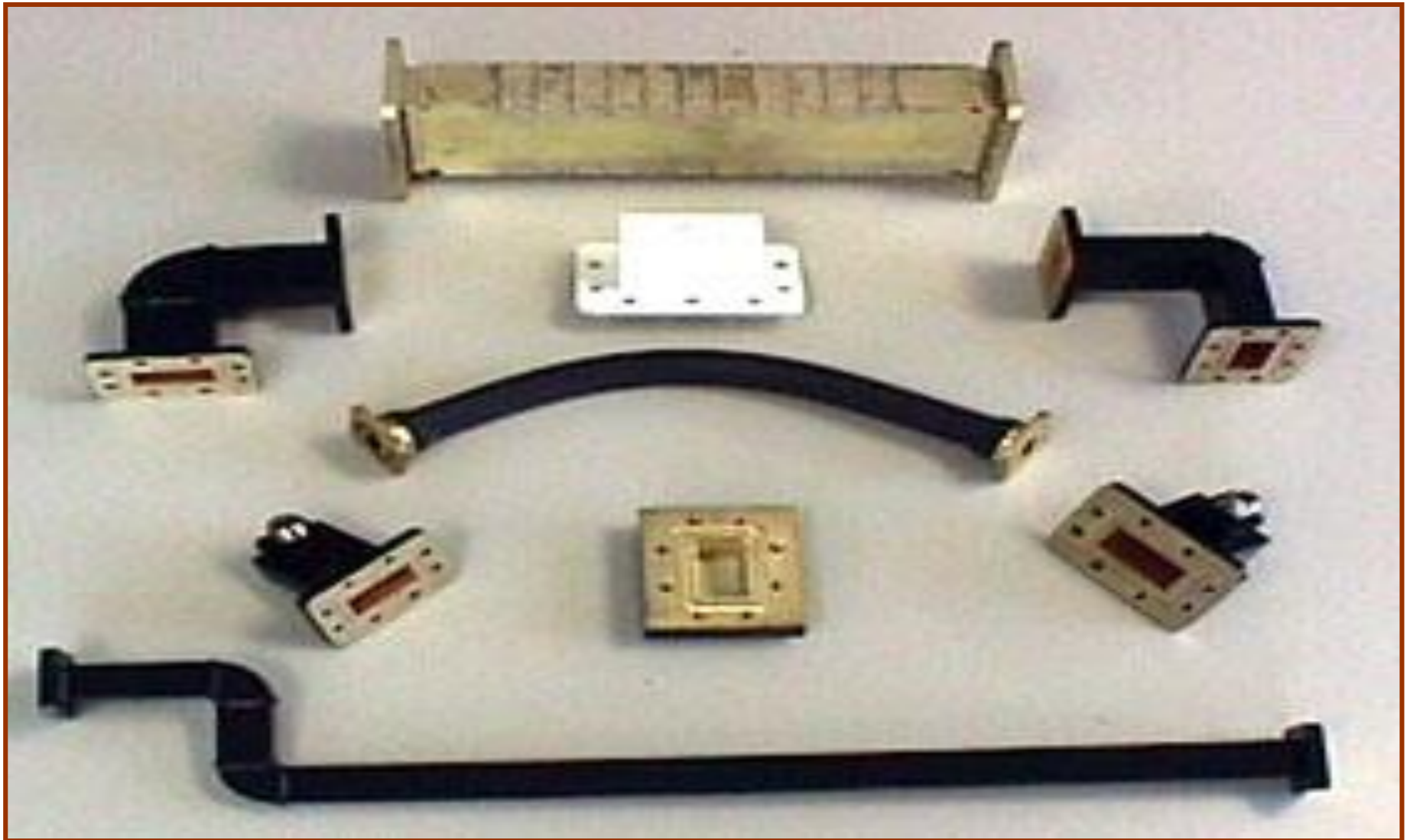
Circular wave guide

A Hollow metallic tube of uniform circular cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called ***Circular waveguide***.



Circular wave guide

- The circular waveguide is used in many special applications in microwave techniques.
- It has the advantage of greater power – handling capacity and lower attenuation for a given cutoff wavelength. However, the disadvantage of somewhat greater size and weight.
- The polarization of the transmitted wave can be altered due to the minor irregularities of the wall surface of the circular guide, whereas the rectangular wave guide the polarization is fixed.



Description

- The wave of lowest frequency or the dominant mode in the circular waveguide is the TE_{11} mode.
- The first subscript m indicates the number of full – wave variations of the radial component of the electric field around the circumference of the waveguide.
- The second subscript n indicates the number of half – wave variations across the diameter.
- The field configurations of TE_{11} mode in the circular waveguide is shown in the diagram below

Cut off wavelength

- The cutoff wavelength for dominant mode of propagation TE_{11} in circular waveguide of radius 'a' is given by

$$\lambda_c = \frac{2\pi a}{1.841}$$

- The cutoff wavelength for dominant mode of propagation TM_{01} in circular waveguide of radius 'a' is given by

$$\lambda_c = \frac{2\pi a}{2.405}$$

Applications of circular waveguide

- Rotating joints in radars to connect the horn antenna feeding a parabolic reflector (which must rotate for tracking)
- TE_{01} mode suitable for long distance waveguide transmission above 10 GHz.
- Short and medium distance broad band communication (could replace / share coaxial and microwave links)

Example

- *The dimensions of the waveguide are 2.5 cm × 1 cm. The frequency is 8.6 GHz. Find (i) possible modes and (ii) cut – off frequency for TE waves.*

Solution:

Given $a = 2.5$ cm , $b = 1$ cm and $f = 8.6$ GHz

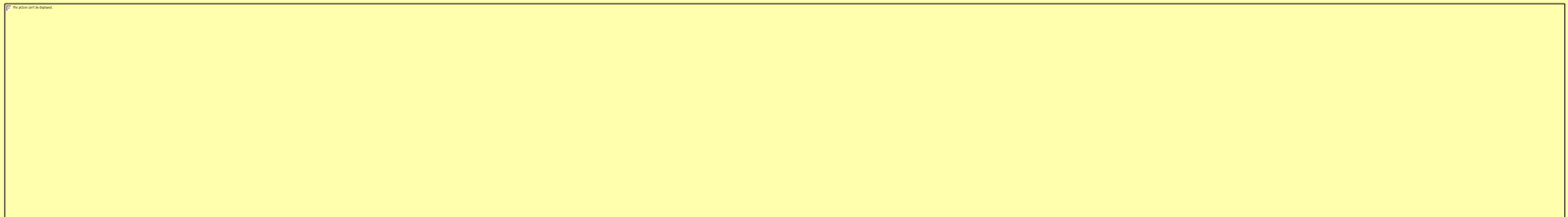
Free space wavelength

$$\lambda_0 = \frac{C}{f} = \frac{3 \times 10^{10}}{8 \times 10^9} = 3.488 \text{ cm}$$

Solution

The condition for the wave to propagate is that $\lambda_c > \lambda_0$

For TE₀₁ mode



Since $\lambda_c < \lambda_0$, TE₀₁ *does not* propagate

- For TE₁₀ mode, $\lambda_C = 2a = 2 \times 2.5 = 5$ cm
- Since $\lambda_C > \lambda_0$, TE₁₀ mode is a possible mode.

$$\text{Cut – off frequency} = f_C = \frac{C}{\lambda_C} = \frac{3 \times 10^{10}}{5} = 6 \text{ GHz}$$

$$\begin{aligned} \text{Cut-off wavelength for TE}_{11} \text{ mode} &= \frac{2ab}{\sqrt{a^2 + b^2}} \\ &= \frac{2 \times 2.5 \times 1}{\sqrt{(2.5)^2 + (1)^2}} = 1.856 \text{ cm} \end{aligned}$$

For TE₁₁ $\lambda_C < \lambda_0$, TE₁₁ is not possible.

- The possible mode is TE₁₀ mode.
- The cut – off frequency = 6 GHz

Example

- *For the dominant mode propagated in an air filled circular waveguide, the cut – off wavelength is 10 cm. Find (i) the required size or cross sectional area of the guide and (ii) the frequencies that can be used for this mode of propagation*

The cut – off wavelength = $\lambda_c = 10$ cm

The radius of the circular waveguide ,

$$r = \frac{10 \times 1.841}{2\pi} = 2.93 \text{ cm}$$

Solution

- Area of cross section =

$$\pi r^2 = \pi(2.93)^2 = 26.97 \text{ cm}^2$$

The cut – off frequency

$$= f_c = \frac{C}{\lambda_c} = \frac{3 \times 10^{10}}{10} = 3 \text{ GHz}$$

➤ Therefore the frequency above 3 GHz can be propagated through the waveguide.

Area of cross section = 26.97 cm²

Cut – off frequency = 3 GHz

Exercise Problem

➤ *A rectangular waveguide has $a = 4$ cm and $b = 3$ cm as its sectional dimensions. Find all the modes which will propagate at 5000 MHz.*

Hint:

The condition for the wave to propagate is that $\lambda_C > \lambda_0$

Here $\lambda_0 = 6$ cm ; λ_C for TE₀₁ mode = 6 cm

Hence λ_C is not greater than free space wavelength λ_0 .

TE₀₁ mode is not possible.

Exercise problem

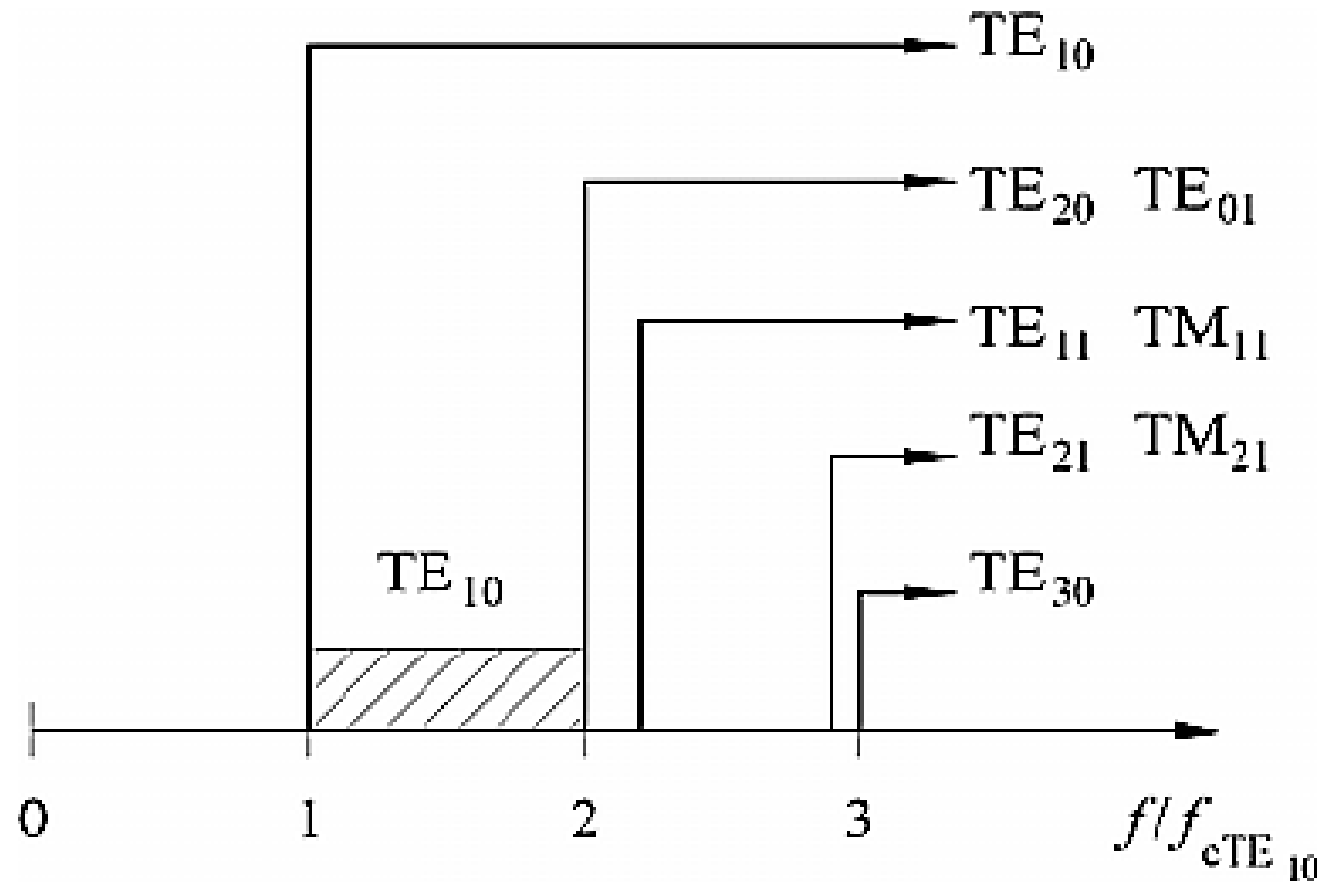
- *For the dominant mode of operation is an air filled circular waveguide of inner diameter 4 cm. Find (i) cut – off wavelength and (ii) cut – off frequency.*

Hint: $\lambda_c = 6.8148$ cm and $f_c = 4.395$ GHz

Rectangular Waveguides

- Dominant mode is TE_{10}
 - 1 half cycle along long dimension (a)
 - No half cycles along short dimension (b)
 - Cutoff for $a = \lambda_c/2$
- Modes with next higher cutoff frequency are TE_{01} and TE_{20}
 - Both have cutoff frequency twice that for TE_{10}

The sequence of propagating modes in a rectangular waveguide



Rectangular Waveguide

Example

Let us calculate the cutoff frequency for the first four modes of WR284 waveguide. The guide dimensions are $a = 7.214$ cm and $b = 3.404$ cm.

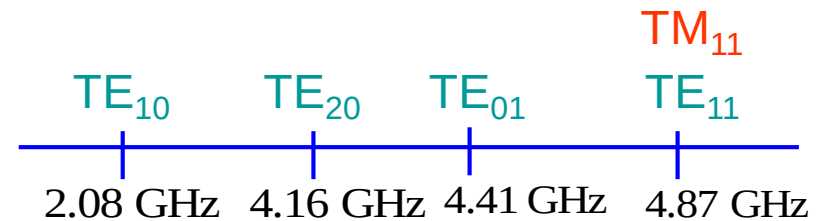
$$f_{c_{mn}} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad \text{where } c = 3 \times 10^8 \text{ m/s}$$

$$\text{TE}_{10}: f_{c_{10}} = \frac{c}{2a} = \frac{3 \times 10^8 \text{ m/s}}{2(7.214 \text{ cm})} \frac{100 \text{ cm}}{1 \text{ m}} = 2.08 \text{ GHz}$$

$$\text{TE}_{01}: f_{c_{01}} = \frac{c}{2b} = \frac{3 \times 10^8 \text{ m/s}}{2(3.404 \text{ cm})} \frac{100 \text{ cm}}{1 \text{ m}} = 4.41 \text{ GHz}$$

$$\text{TE}_{20}: f_{c_{20}} = \frac{c}{a} = 4.16 \text{ GHz}$$

$$\text{TE}_{11}: f_{c_{11}} = \frac{3 \times 10^8 \text{ m/s}}{2} \sqrt{\left(\frac{1}{7.214 \text{ cm}}\right)^2 + \left(\frac{1}{3.404 \text{ cm}}\right)^2} \frac{100 \text{ cm}}{1 \text{ m}} = 4.87 \text{ GHz}$$



Group Velocity (V_g)

- Waves propagate at speed of light c in guide.
- Waves don't travel straight down guide.
- Speed at which signal moves down guide is the group velocity and is always less than c .

$$v_g = c \sqrt{1 - \left(\frac{f_c}{f} \right)^2} \text{ m/s}$$

Assuming an air dielectric, the wave travels inside the waveguide at the speed of light. However, it does not travel straight down the guide but reflects back and forth from the walls. The actual speed at which a signal travels down the guide is called the **group velocity**, and it is considerably less than the speed of light. The group velocity in a rectangular waveguide is given by the equation

$$v_g = c \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}$$

since $f_c = c/2a$

where v_g = group velocity
 λ = free-space wavelength
 a = larger dimension of the interior cross section

Phase Velocity (V_p)

- The velocity at which the wave changes its phase.
- V_p always equal to or greater than (v_g).
- It may exceed the velocity of light (velocity in free space).

$$v_p = \frac{c}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \text{ m/s}$$

From the above equation, it can be seen that the group velocity is a function of frequency and becomes zero at the cutoff frequency. At frequencies below cut-off, of course, there is no propagation, so the equation does not apply. The physical explanation of the variation of group velocity is that the angle the wave makes with the wall of the guide varies with frequency. At frequencies near the cutoff value, the wave moves back and forth across the guide more often while traveling a given distance down the guide than it does at higher frequencies.

Example: Find the group velocity for the waveguide has ($f_c=3.75$) GHz and operating frequency ($f=5$ GHz).

$$\begin{aligned}v_g &= c \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \\&= (300 \times 10^6 \text{ m/s}) \sqrt{1 - \left(\frac{3.75}{5}\right)^2} \\&= 198 \times 10^6 \text{ m/s}\end{aligned}$$

Example

For a rectangular waveguide with a wall separation of 3 cm and a desired frequency of operation of 6 GHz, determine:

- a) Cutoff frequency.
- b) Cutoff wavelength.
- c) Group velocity.
- d) Phase velocity.

Solution:

(a) The cutoff frequency,

$$a = 3 \text{ cm} = 0.03 \text{ m}$$

$$\begin{aligned} f_c &= \frac{c}{2a} \\ &= \frac{3 \times 10^8 \text{ m/s}}{2(0.03 \text{ m})} \\ &= \mathbf{5 \text{ GHz}} \end{aligned}$$

(b) The cutoff wavelength,

$$\lambda_c = 2a = 2(0.03 \text{ m}) = \mathbf{0.06 \text{ m}}$$

(c) The phase velocity,

$$\begin{aligned} v_p &= \frac{c}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} = \frac{3 \times 10^8 \text{ m/s}}{\sqrt{1 - \left(\frac{5 \text{ GHz}}{6 \text{ GHz}}\right)^2}} \\ &= \mathbf{5.43 \times 10^8 \text{ m/s}} \end{aligned}$$

(d) The group velocity,

$$\begin{aligned}v_g &= \frac{c^2}{v_{ph}} = c \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \\&= (3 \times 10^8 \text{ m/s}) \left(\sqrt{1 - \left(\frac{5 \text{ GHz}}{6 \text{ GHz}}\right)^2} \right) \\&= \mathbf{1.66 \times 10^8 \text{ m/s}}\end{aligned}$$

Problem 1

A rectangular waveguide having an inner dimension of (3.5×1.5) cm is used for propagating a microwave signal at mode TE_{11} . If the microwave frequency given is 13.8 GHz, calculate the cut-off frequency (f_c), cut-off wavelength (λ_c), guide wavelength (λ_g) and velocity inside waveguide (V_g) of this waveguide. (CS, CLO2) (Sesi Dis 2015)

Problem 2

An rectangular air-filled copper waveguide with a dimension of (3.1×2.0) cm is operated at 9.5 GHz with a dominant mode. Calculate:

- i. Cut-off frequency, f_c
- ii. Guide wavelength, λ_g
- iii. Phase velocity, V_p

Lecture-7-

Magnetron Oscillator

Conventional Tubes

- Conventional Device tubes cannot be used for frequencies above 100MHz.
- Interelectrode capacitance (stray capacitance), this occurs due to the close proximity of electrical devices or electrodes.
- Lead Inductance effect.
- Transit time effect.
- Gain Bandwidth limitation.
- Effect of RF losses (Conductance, dielectric).
- Effect due to radiation losses.

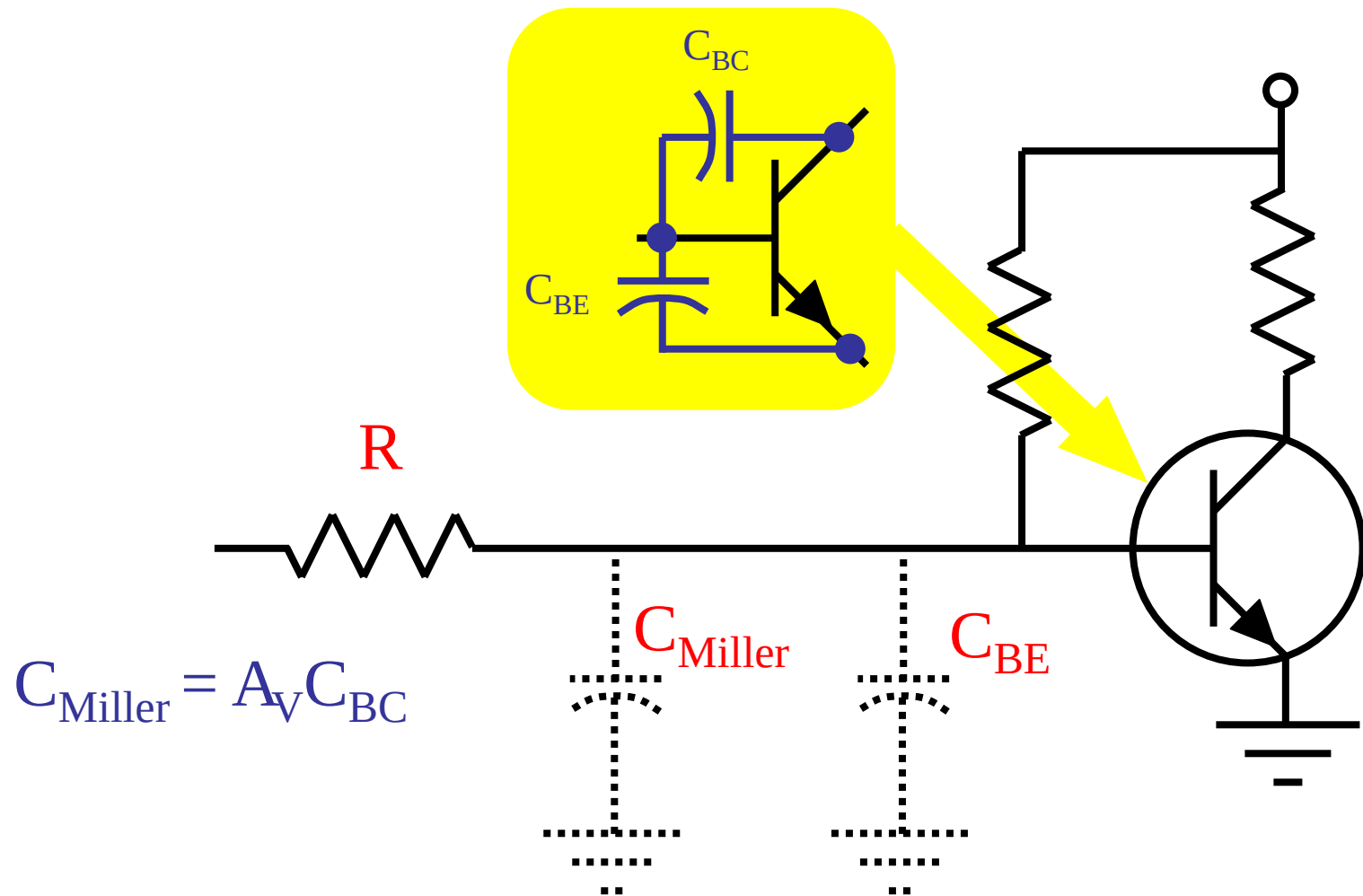
Frequency Limitations of Conventional Tubes

Three characteristics of ordinary vacuum tubes become increasingly important as frequency rises. These characteristics are:

- Interelectrode Capacitance
- Lead Inductance
- Electron Transit Time.

Interelectrode Capacitance

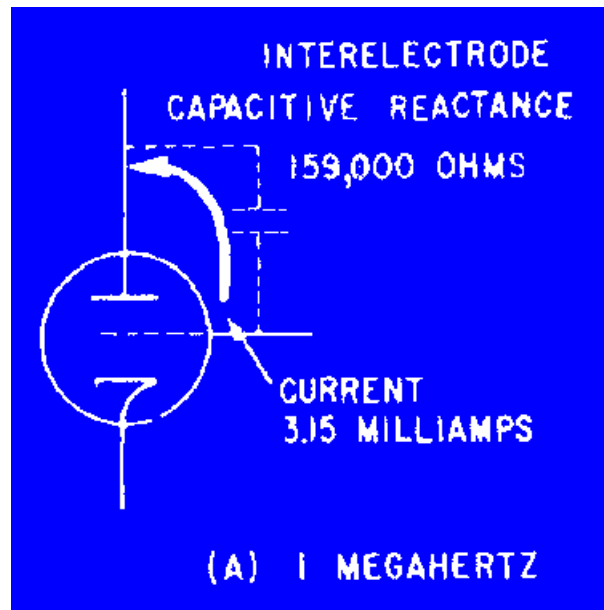
The interelectrode capacitances in a vacuum tube, at low or medium radio frequencies, produce capacitive reactances that are so large that no serious effects upon tube operation are noticeable. However, as the frequency increases, the reactances become small enough to materially affect the performance of a circuit. For example, in figure below, view (A), a 1-picofarad capacitor has a reactance of 159,000 ohms at 1 megahertz. If this capacitor was the interelectrode capacitance between the grid and plate of a tube, and the rf voltage between these electrodes was 500 volts, then 3.15 milliamperes of current would flow through the interelectrode capacitance. Current flow in this small amount would not seriously affect circuit performance. On the other hand, at a frequency of 100 megahertz the reactance would decrease to approximately 1,590 ohms and, with the same voltage applied, current would increase to 315 milliamperes (view (B)). Current in this amount would definitely affect circuit performance.



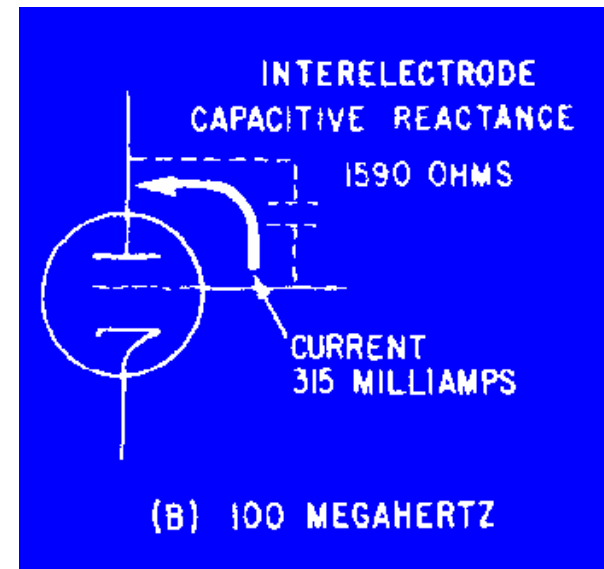
$$C_{\text{Miller}} = A_v C_{BC}$$

$$C_{\text{Input}} = C_{\text{Miller}} + C_{BE}$$

$$f_b = \frac{1}{2\pi R C_{\text{Input}}}$$



A



B

Lead Inductance

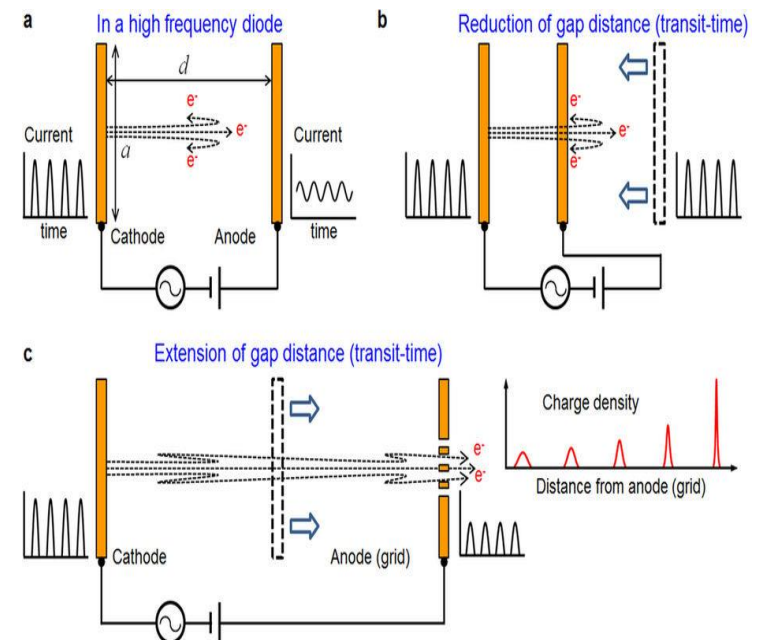
Another frequency-limiting factor is the lead inductance of the tube elements. since the lead inductances within a tube are effectively in parallel with the interelectrode capacitance, the net effect is to raise the frequency limit. however, the inductance of the cathode lead is common to both the grid and plate circuits. this provides a path for degenerative feedback which reduces overall circuit efficiency.

Transit Time

Transit time is the time required for electrons to travel from the cathode to the plate. While some small amount of transit time is required for electrons to travel from the cathode to the plate, the time is insignificant at low frequencies. In fact, the transit time is so insignificant at low frequencies that it is generally not considered to be a hindering factor. However, at high frequencies, transit time becomes an appreciable portion of a signal cycle and begins to hinder efficiency. For example, a transit time of 1 nanosecond, which is not unusual, is only 0.001 cycle at a frequency of 1 megahertz. The same transit time becomes equal to the time required for an entire cycle at 1,000 megahertz. Transit time depends on electrode spacing and existing voltage potentials. Transit times in excess of 0.1 cycle cause a significant decrease in tube efficiency.

Several methods are available to reduce the limitations of conventional tubes, but none work well when frequency increases beyond 1,000 megahertz.

- Interelectrode capacitance can be reduced by moving the electrodes further apart or by reducing the size of the tube and its electrodes.
- Moving the electrodes apart increases the problems associated with transit time, and reducing the size of the tube lowers the power-handling capability. You can see that efforts to reduce certain limitations in conventional tubes are compromises that are often in direct opposition to each other. The net effect is an upper limit of approximately 1,000 megahertz, beyond which conventional tubes are not practical.

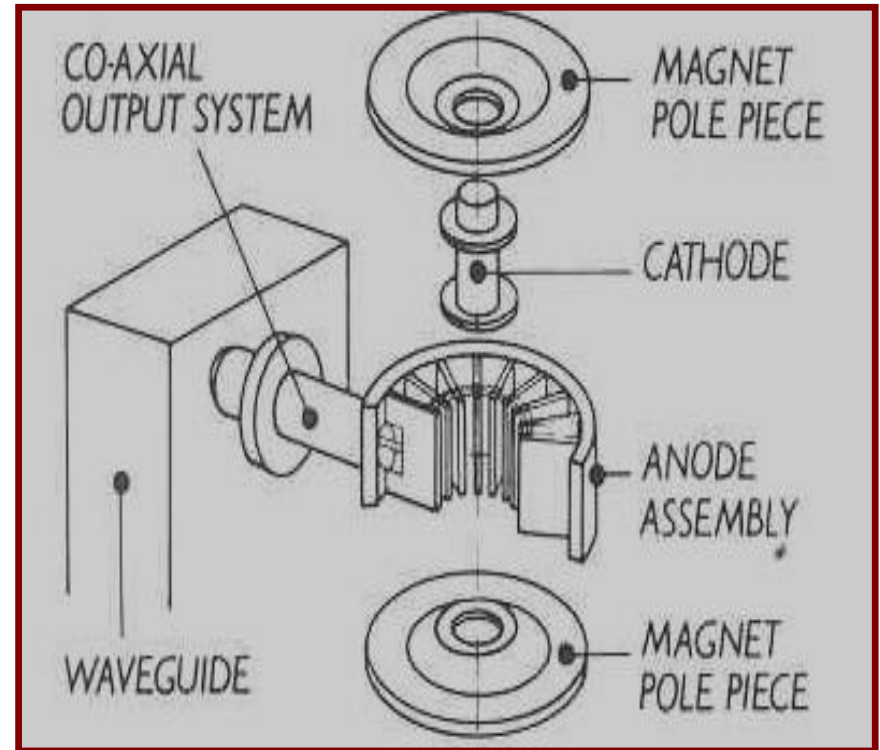


Linear Beam O tubes

- The paramount O – type tube is the two cavity klystron followed by the reflex klystron.
- Slow wave structures are also O-type but have non-resonant periodic structures for electron interactions.
- Twystron is a hybrid amplifier which uses a combination of klystron and Slow wave structures.

Magnetron Oscillator

- The **magnetron** is a high-powered vacuum tube.
- Crossed electron and magnetic fields are used in the magnetron to produce the high-power output.
- These multi-cavity devices may be used in radar transmitters as either pulsed or cw oscillators at frequencies ranging from approximately 600 to 30,000 megahertz.



Physical construction of a magnetron

The magnetron is classed as a diode because it has no grid. The anode of a magnetron is fabricated into a cylindrical solid copper block. The cathode and filament are at the centre of the tube and are supported by the filament leads. The filament leads are large and rigid enough to keep the cathode and filament structure fixed in position. The cathode is indirectly heated and is constructed of a high-emission material. The 8 up to 20 cylindrical holes around its circumference are resonant cavities. A narrow slot runs from each cavity into the central portion of the tube dividing the inner structure into as many segments as there are cavities. Each cavity works like a parallel resonant circuit. The rear wall of the structure of the anode block may be considered to be the inductive portion (a coil with a single turn). The vane tip region may be considered as the capacitor portion of the equivalent parallel resonant circuit. The resonant frequency of a microwave cavity is thereby determined by the physical dimension of the resonator. If a single resonant cavity oscillates, then it excites the next one to oscillate too. This one oscillates at a phase delay of 180 degrees and excites the next resonant cavity, and so on. From a resonant cavity to the next always occurs this delay of 180 degrees. The chain of resonators thus forms a slow-wave structure which is closed in itself. Because of this slow-wave structure, this design is also called “Multi-cavity Travelling Wave Magnetron” in some publications.

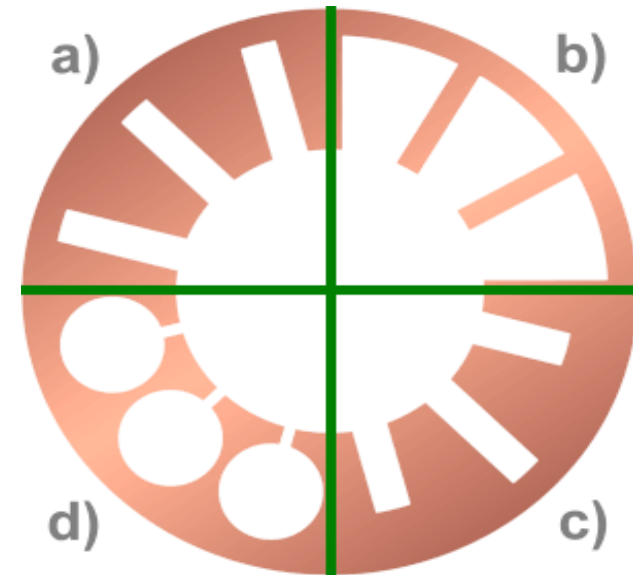
The cathode of a magnetron provides the electrons through which the mechanism of energy transfer is accomplished. The cathode is located in the centre of the anode and is made up of a hollow cylinder of emissive material (mostly Barium Oxide) surrounding a heater. The feeding wires of the filament must centre the whole cathode. Any eccentricity between anode and cathode can cause serious internal arcing or malfunction.

The open space between the anode bloc and the cathode is called the interaction space. In this space the electric and magnetic fields interact to exert force upon the electrons. The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode.

It generally consists of an even number of microwave cavities arranged in radial fashion. The form of the cavities varies, shown in the figure.

- A. slot- type
- B. vane- type
- C. rising sun- type
- D. hole-and-slot- type

The slot type, hole-and slot type and the rising sun type are usually machined by hobbing methods out of solid copper stock. But it can be difficult to cut softly metal (such as copper) in a lathe. The vane type is generally made up of individual vanes assembled and brazed into a support ring therefore. The resonance behaviour can be already tested and calibrated in the laboratory before the anode is installed in the tube. The output lead is usually a probe or loop extending into one of the tuned cavities and coupled into a wave-guide or coaxial line.



Magnetron Basic Operation

As when all [velocity-modulated tubes](#) the electronic events at the production microwave frequencies at a magnetron can be subdivided into four phases too:

[phase](#): Production and acceleration of an electron beam in a dc field

[phase](#): Velocity-modulation of the electron beam

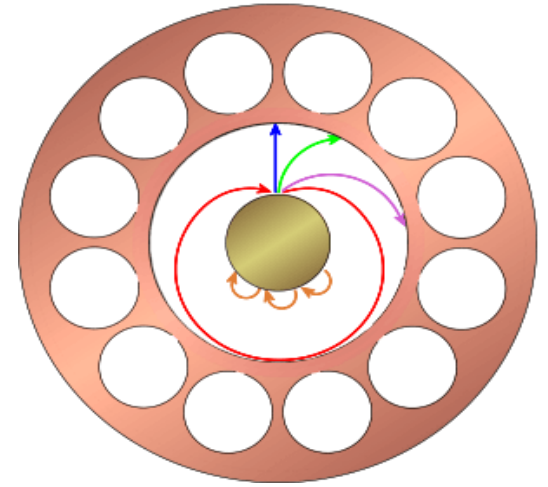
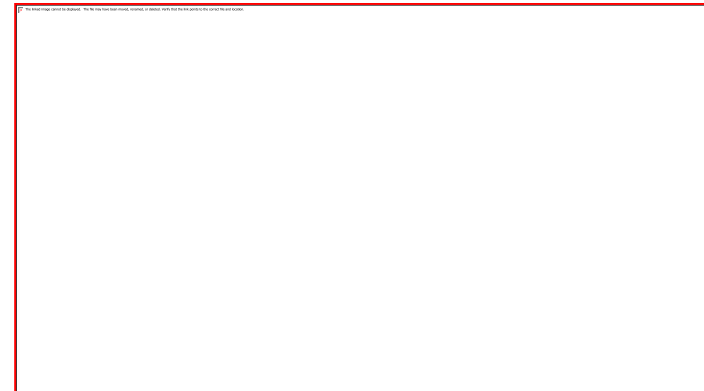
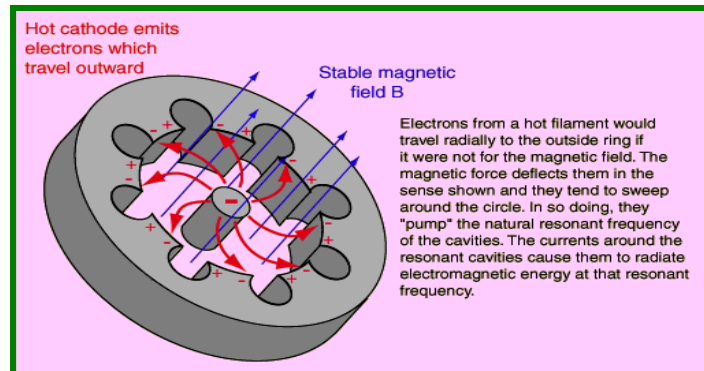
[phase](#): Formation of electron bunches by velocity modulation (here in form of a “Space-Charge Wheel”)

[phase](#): Dispense energy to the ac field

Production and acceleration of an electron beam

Since the cathode is kept at negative voltage, the static electric field is in radial direction from (grounded) anode block to the cathode. When no magnetic field exists, heating the cathode results in a uniform and direct movement of the electron from the cathode to the anode block (the blue path in the figure). A weak permanent magnetic field B perpendicular to the electric field bends the electron path as shown with the green path in the figure. If the electron flow reaches the anode, so a large amount of plate current is flowing. If the strength of the magnetic field is increased, the path of the electron will have a sharper bend. Likewise, if the velocity of the electron increases, the field around it increases and the path will bend more sharply. However, when the critical field value is reached, as shown in the figure 5 as a red path, the electrons are deflected away from the plate and the plate current then drops quickly to a very small value. When the field strength is made still greater, the plate current drops to zero.

These values of the anode voltage and magnetic field strength that prevent an anode current are called Hull cut-off magnetic field and cut-off voltage. When the magnetron is adjusted to the cut-off, or critical value of the plate current and the electrons just fail to reach the plate in their circular motion, it can produce oscillations at microwave frequencies.

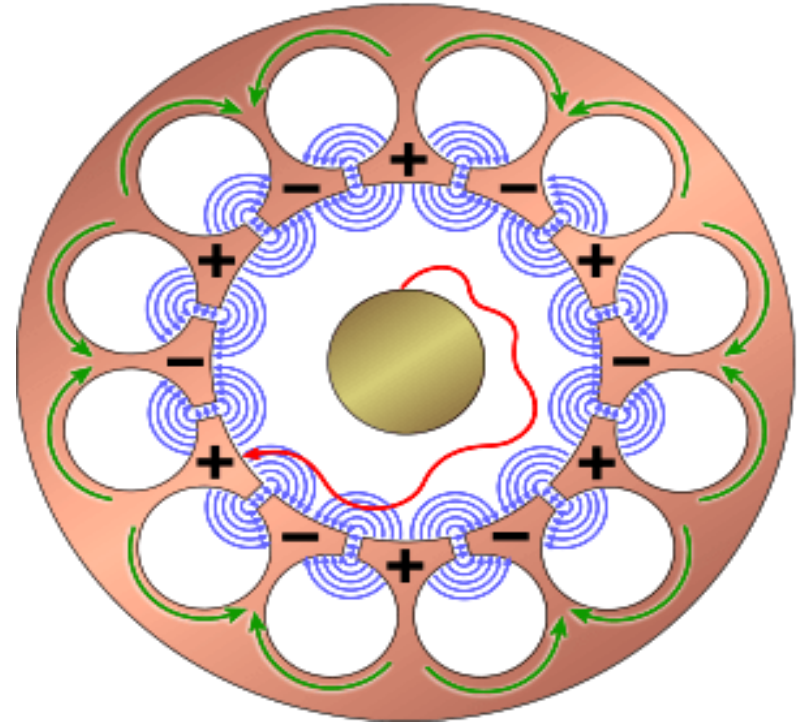


Velocity-modulation of the electron beam

The electric field in the magnetron oscillator is a product of AC and DC fields. The DC field extends radially from adjacent anode segments to the cathode. The AC fields, extending between adjacent segments, are shown at an instant of maximum magnitude of one alternation of the RF oscillations occurring in the cavities.

In the figure is shown only the assumed high-frequency electrical AC field. This AC field work in addition to the to the permanently available DC field. The AC field of each individual cavity increases or decreases the DC field like shown in the figure.

Well, the electrons which fly toward the anode segments loaded at the moment more positively are accelerated in addition. These get a higher tangential speed. On the other hand the electrons which fly toward the segments loaded at the moment more negatively are slow down. These get consequently a smaller tangential speed.

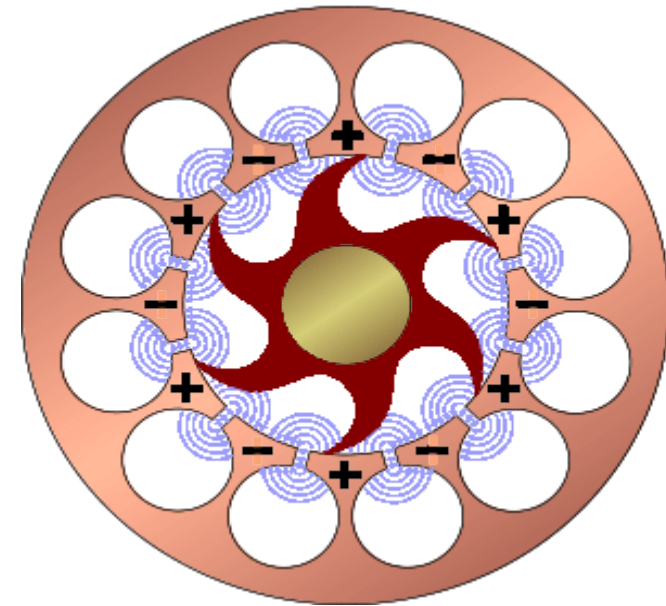


Forming of a Space-Charge Wheel

On reason the different speeds of the electron groups the [velocity modulation](#) leads to a density modulation therefore.

The cumulative action of many electrons returning to the cathode while others are moving toward the anode forms a pattern resembling the moving spokes of a wheel known as a “Space-Charge Wheel”, as indicated in figure 7. The space-charge wheel rotates about the cathode at an angular velocity of 2 poles (anode segments) per cycle of the AC field. This phase relationship enables the concentration of electrons to continuously deliver energy to sustain the RF oscillations.

One of the spokes just is near an anode segment which is loaded a little more negatively. The electrons are slowed down and pass her energy on to the AC field. This state isn't static, because both the AC- field and the wire wheel permanently circulate. The tangential speed of the electron spokes and the cycle speed of the wave must be brought in agreement so.

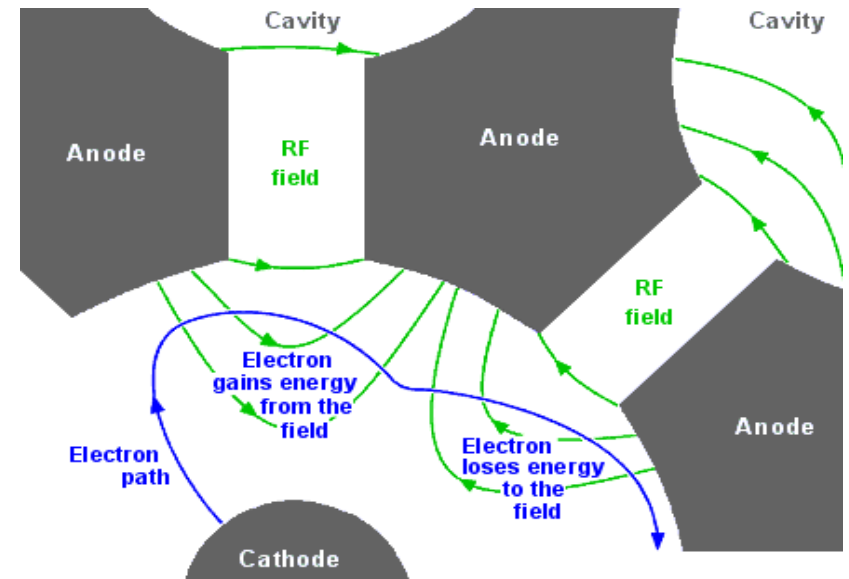
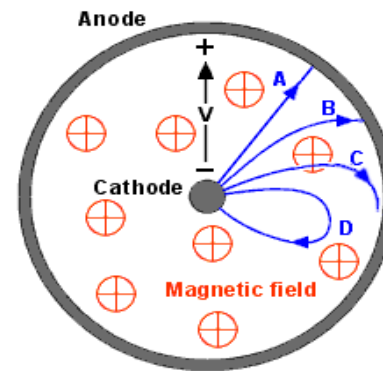
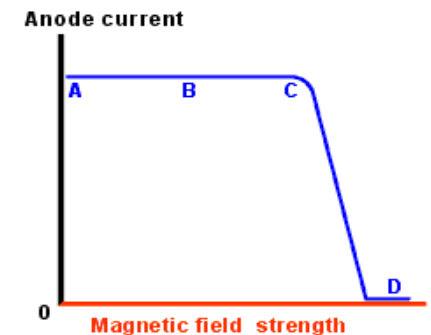


In other words, the electron current is noisy. It contains energy at all sorts of frequencies. And this noisy current is circulating close to a series of resonant cavities, which act as tuned circuits. If they see energy at frequencies near their resonant frequency, they seize it, and store it, swapping the energy between their electric and magnetic fields just like any other tuned circuit.

The energy oscillating around inside each cavity establishes its own field - the RF field - which itself now interacts with the circulating electron current.

Electrons passing through the RF field may give up some of their energy to it, slowing them down and leaving them to fall into the anode. Or they may gain energy from it, sending them back towards the cathode.

The effect is to thin out the cloud, causing the electrons to collect into bunches that rotate like the sails of a windmill (but not really).



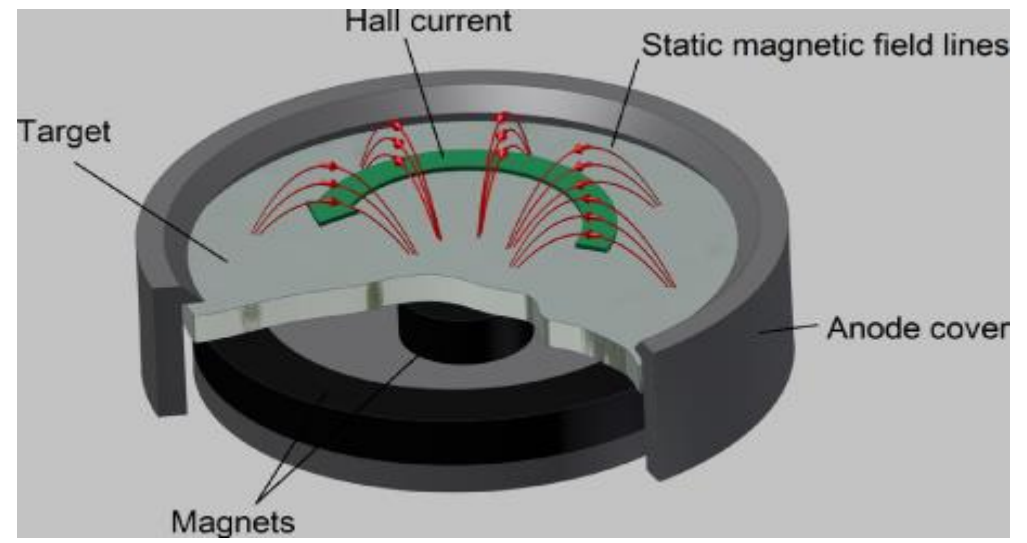
Dispense energy to the AC field

Recall that an electron moving against an E field is accelerated by the field and takes energy from the field. Also, an electron dispenses energy to a field and slows down if it is moving in the same direction as the field (positive to negative). The electron spends energy to each cavity as it passes and eventually reaches the anode when its energy is expended. Thus, the electron has helped sustain oscillations because it has taken energy from the DC field and given it to the ac field. This electron describes the path shown in figure 5 over a longer time period looked. By the multiple breaking of the electron the energy of the electron is used optimally. The effectiveness reaches values up to 80%.

Transient oscillation

After switching the anode voltage, there is still no RF field. The single electron moves under the influence of the static electric field of the anode voltage and the effect of the magnetic field as shown in Figure 5 by the red electron path. Electrons are charge carriers: during the flyby at a gap, they give off a small part of energy to the cavities. (Similar to a flute: A flute produces sound when a stream of air is flowing past an edge of a hole.) The cavity resonator begins to oscillate at its natural resonant frequency. Immediately begins the interaction between this RF field (with an initial low power) and the electron beam. The electrons are additionally influenced by the alternating field. It begins the process described in sequence of phase 1 to 4 of the interaction between RF field and the now velocity-modulated electrons.

Unfortunately, the transient oscillation doesn't begin with a predictable phase. Each transient oscillation occurs with a random phase. The transmitting pulses that are generated by a magnetron are therefore not coherent.



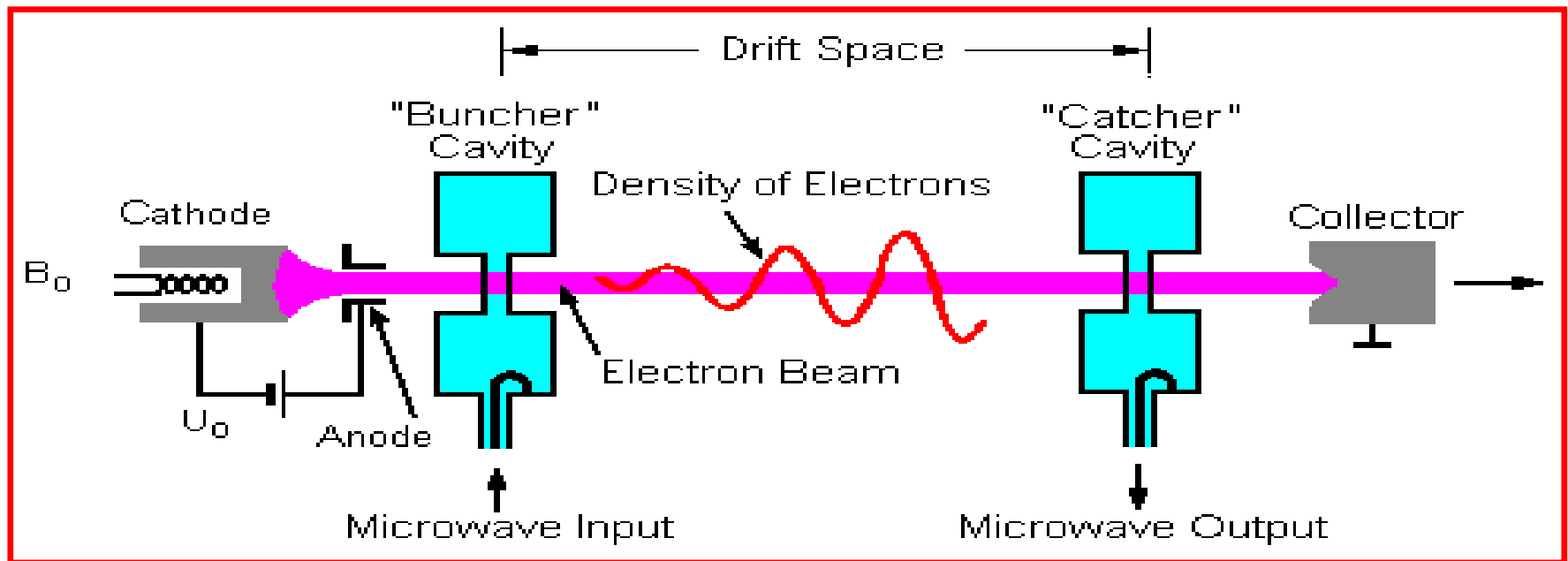
Lecture-7-

Klystron

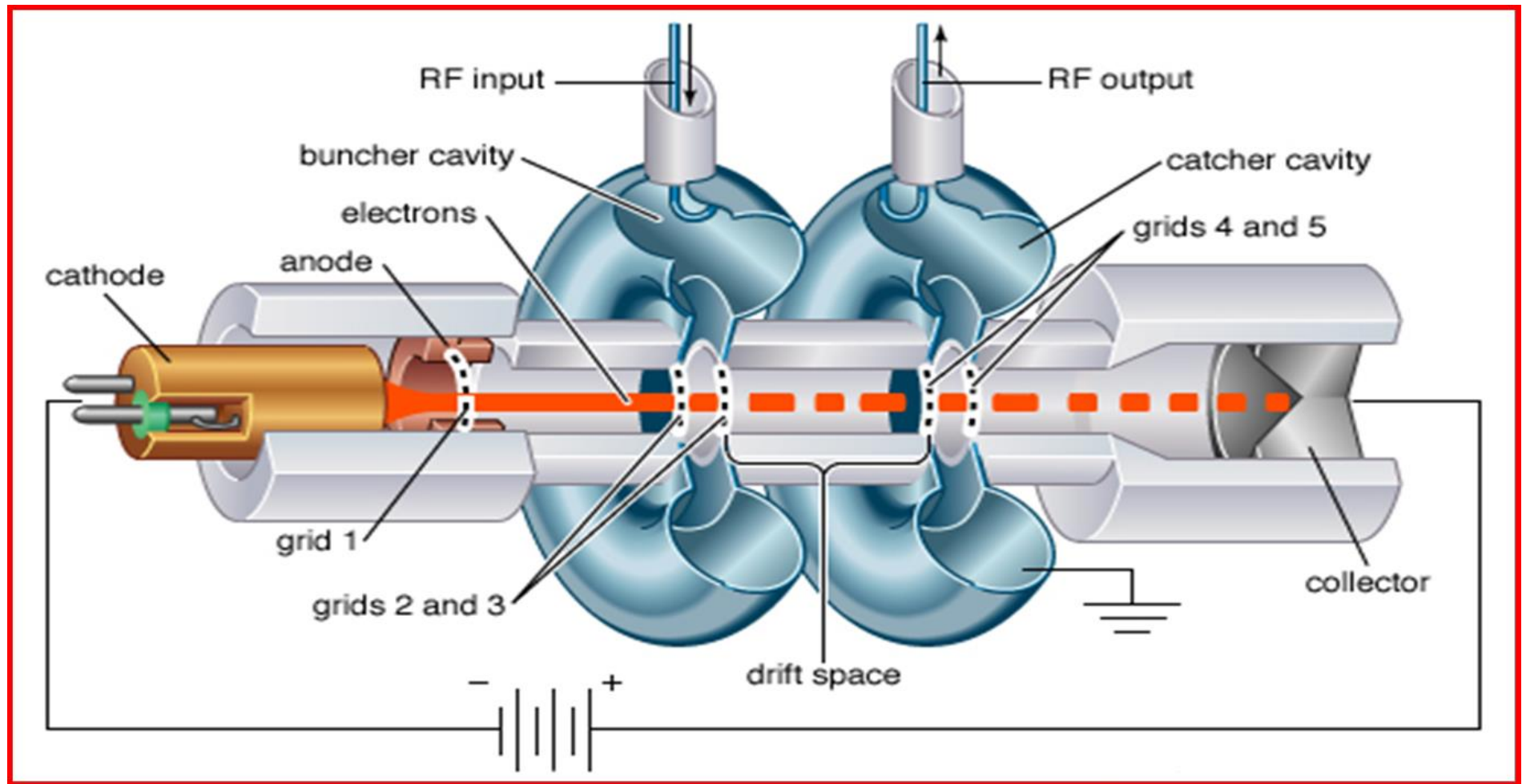
- Klystron Oscillator (amplifier)
- Reflex Klystron
- Traveling Wave Tube
- Biological effect of microwaves

Klystron Oscillator

A klystron is a vacuum tube that can be used either as a generator or as an amplifier of power, at microwave frequencies.



Two cavity Klystron Amplifier

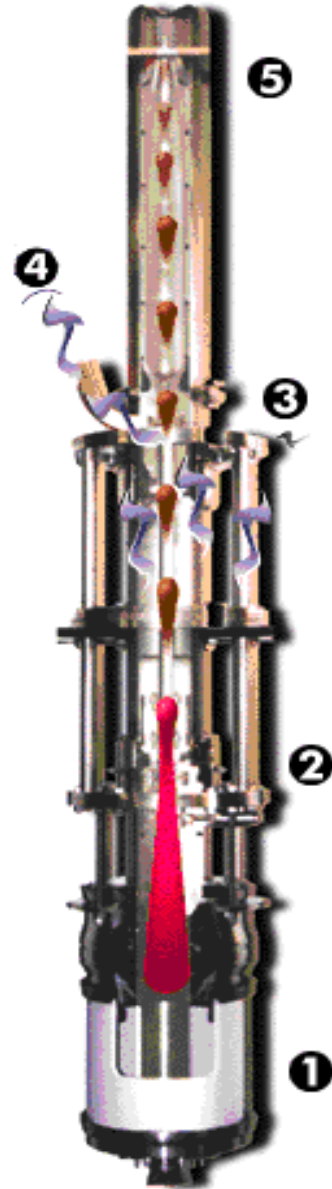


Applications

- **As power output tubes**
 1. in UHF TV transmitters.
 2. in troposphere scatter transmitters.
 3. satellite communication ground station.
 4. radar transmitters.
- **As power oscillator** (5 – 50 GHz), if used as a klystron oscillator.

In a klystron:

1. The electron gun produces a flow of [electrons](#) .
2. The bunching cavities regulate the speed of the electrons so that they arrive in bunches at the output cavity.
3. The bunches of electrons excite microwaves in the output cavity of the klystron.
4. The microwaves flow into the waveguide, which transports them to the [accelerator](#) .
5. The electrons are absorbed in the beam stop.



Example: The parameters of a two cavity Klystron are:

Input power = 10 mW

Voltage gain = 20 dB

$R_{sh}(\text{Input cavity}) = 25 \text{ k}\Omega$

$R_{sh}(\text{Output cavity}) = 35 \text{ k}\Omega$

Load resistance = 40 k Ω

Calculate (a) Input voltage (b) Output voltage (c) Power output .

Solution:

$$P_{ac \text{ in}} = \frac{V_1^2}{R_{sh \text{ in}}}$$

$$V_1 = \sqrt{P_{ac \text{ in}} * R_{sh \text{ in}}} = \sqrt{250} = 15.81 \text{ V}$$

$$A_v = 20 \log \frac{V_2}{V_1} = 20 \text{ dB}$$

$$\log \frac{V_2}{V_1} = 1, \quad \frac{V_2}{V_1} = 10, \quad V_2 = 158.1 \text{ V}$$

$$\text{Power output} = \frac{V_2^2}{R_L || R_{sh \text{ out}}} = 1.339 \text{ W}$$

Reflex Klystrons

- The reflex klystron has been the most used source of microwave power in laboratory applications.

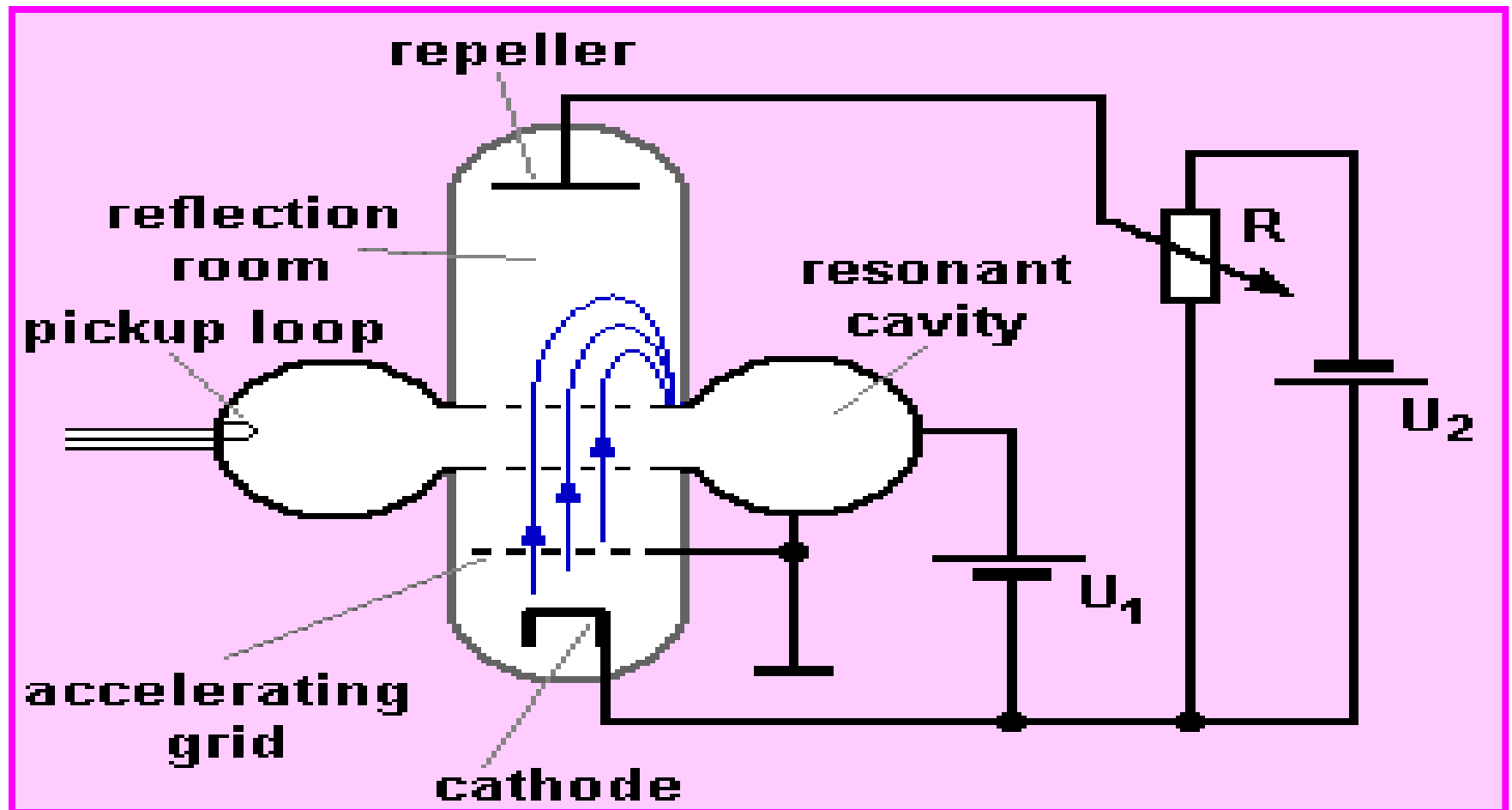
Construction

- A reflex klystron consists of an electron gun, a cavity with a pair of grids and a repeller plate as shown in the above diagram.
- In this klystron, a single pair of grids does the functions of both the buncher and the catcher grids.
- The main difference between two cavity reflex klystron amplifier and reflex klystron is that the output cavity is omitted in reflex klystron and the repeller or reflector electrode, placed a very short distance from the single cavity, replaces the collector electrode.

Working

- The cathode emits electrons which are accelerated forward by an accelerating grid with a positive voltage on it and focused into a narrow beam.
- The electrons pass through the cavity and undergo velocity modulation, which produces electron bunching and the beam is repelled back by a repeller plate kept at a negative potential with respect to the cathode.
- On return, the electron beam once again enters the same grids which act as a buncher, thereby the same pair of grids acts simultaneously as a buncher for the forward moving electron and as a catcher for the returning beam.

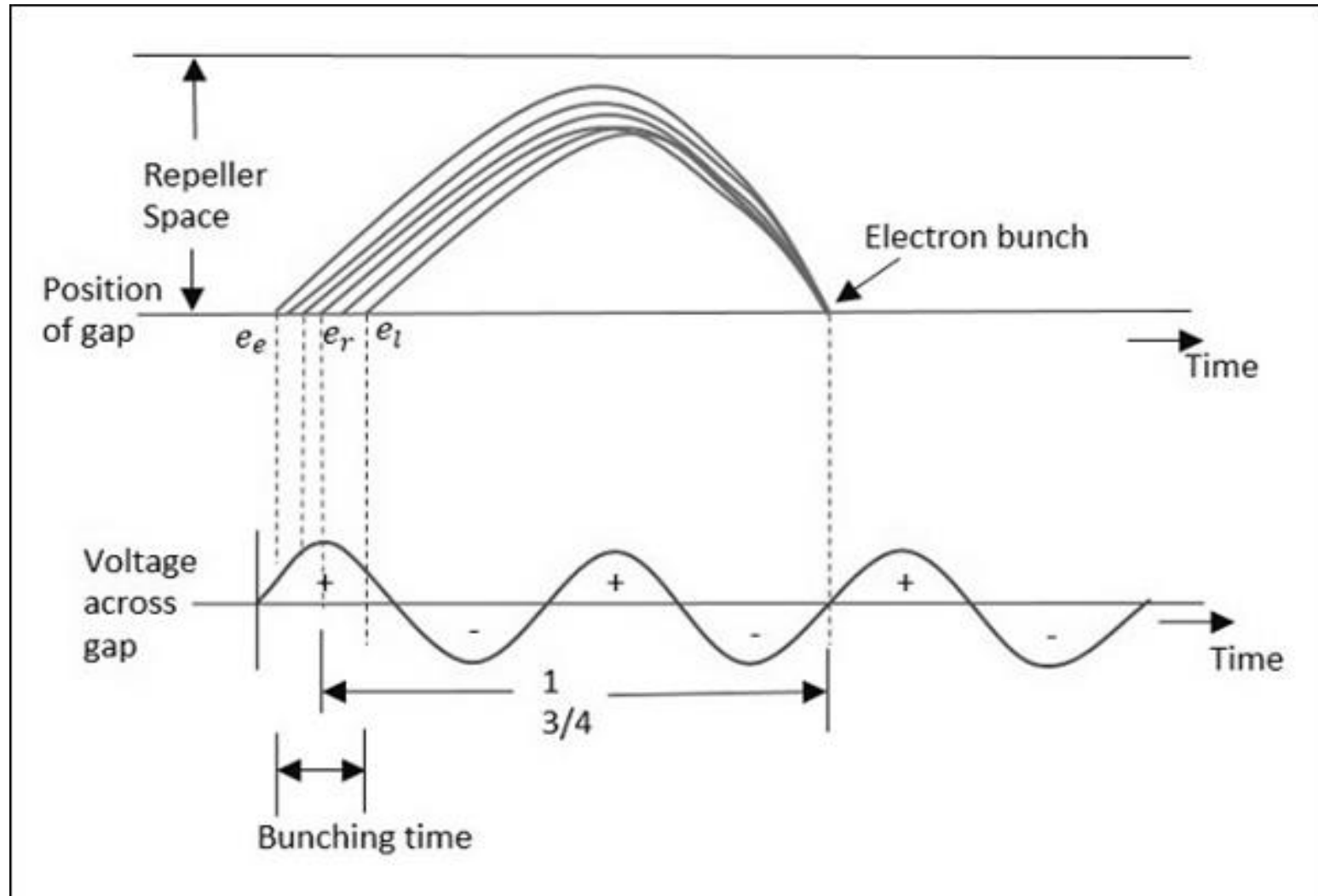
Reflex Klystron oscillator



Working

- The feedback necessary for electrical oscillations is developed by reflecting the electron beam, the velocity modulated electron beam does not actually reach the repeller plate, but is repelled back by the negative voltage.
- The point at which the electron beam is turned back can be varied by adjusting the repeller voltage.
- Thus the repeller voltage is so adjusted that complete bunching of the electrons takes place at the catcher grids, the distance between the repeller and the cavity is chosen such that the repeller electron bunches will reach the cavity at proper time to be in synchronization.
- Due to this, they deliver energy to the cavity, the result is the oscillation at the cavity producing RF frequency.

Applegate Diagram



Mode of Oscillation

- The electrons should return after $1\frac{3}{4}$, $2\frac{3}{4}$ or $3\frac{3}{4}$ cycles – most optimum departure time.
- If **T is the time period at the resonant frequency**, t_0 is the time taken by the reference electron to travel in the repeller space between entering the repeller space and returning to the cavity at positive peak voltage on formation of the bunch

Then, $t_0 = (n + \frac{3}{4})T = NT$

Where $N = n + \frac{3}{4}$, $n = 0, 1, 2, 3, \dots$

N – mode of oscillation.

Performance Characteristics

1. Frequency: 4 – 200 GHz
2. Power: 1 mW – 2.5 W
3. Theoretical efficiency : 22.78 %
4. Practical efficiency : 10 % - 20 %
5. Tuning range : 5 GHz at 2 W – 30 GHz at 10 mW

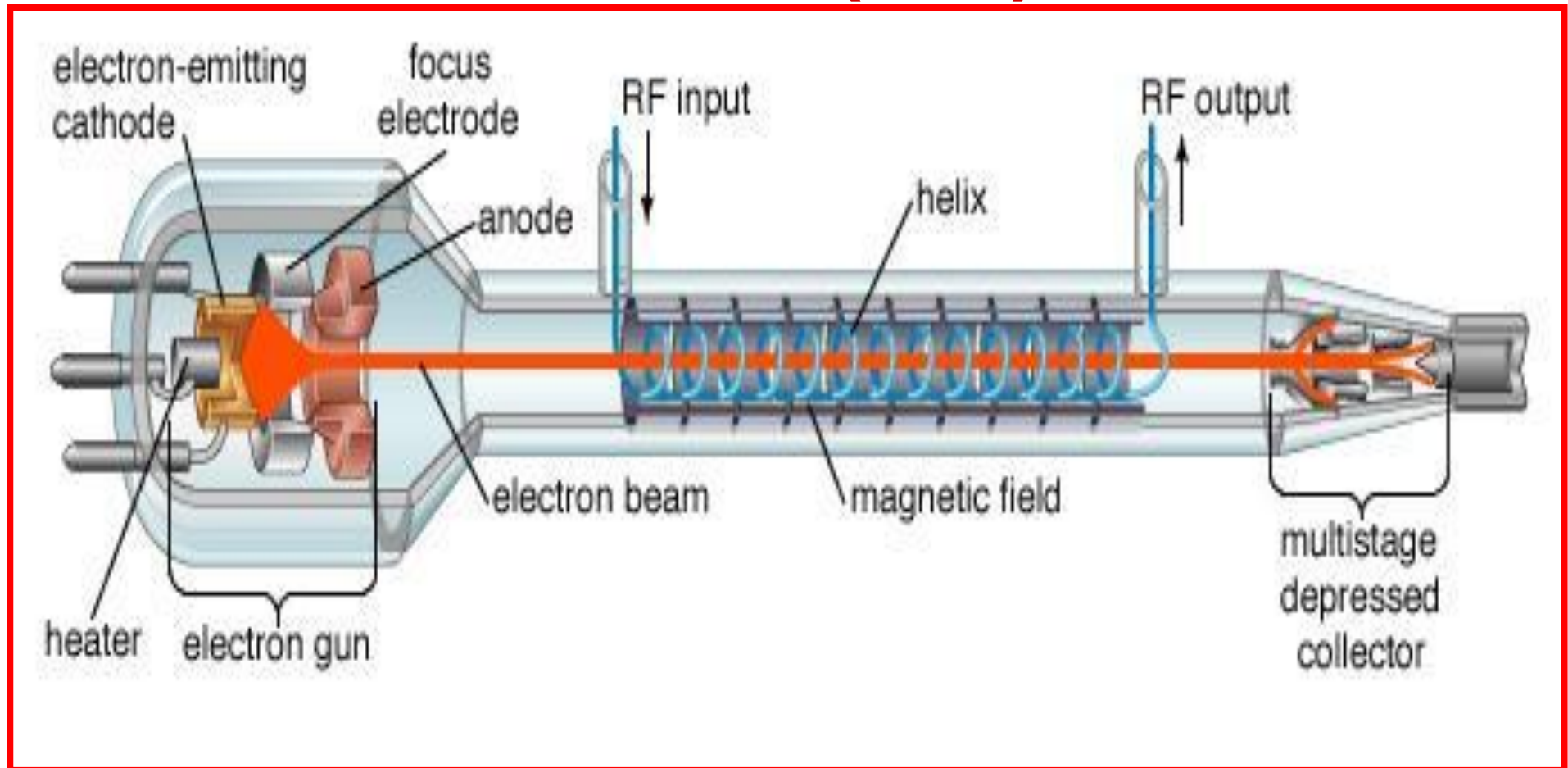
Applications

- The reflex klystrons are used in
 1. Radar receivers
 2. Local oscillator in microwave receivers
 3. Signal source in microwave generator of variable frequency
 4. Portable microwave links
 5. Pump oscillator in parametric amplifier

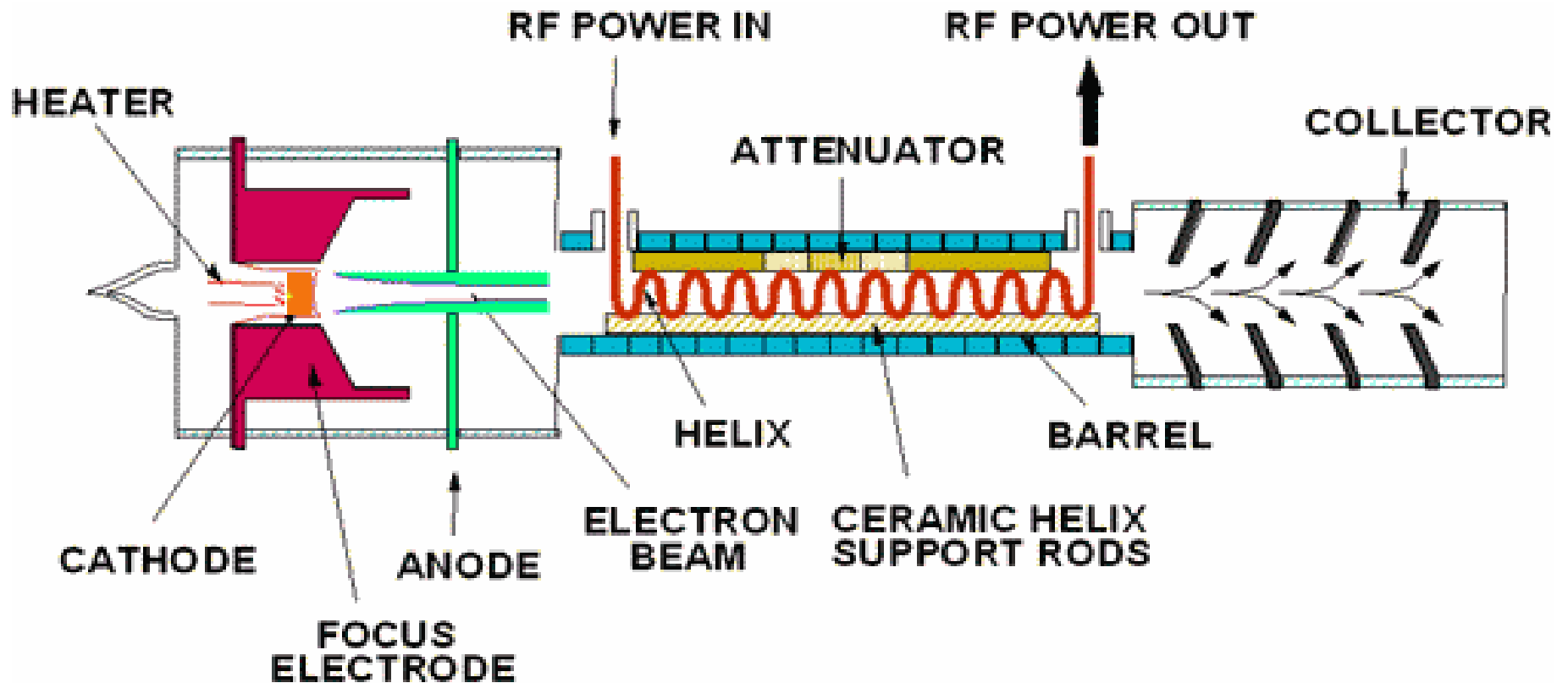
Traveling Wave Tube (TWT)

- Traveling Wave Tube (TWT) is the most versatile microwave RF power amplifiers.
- The main virtue of the TWT is its extremely wide band width of operation.

Basic structure of a Traveling Wave Tube (TWT)



BASICS of Traveling Wave Tube (TWT) Amplifier



Basic structure

- The basic structure of a TWT consists of a cathode and filament heater plus an anode that is biased positively to accelerate the electron beam forward and to focus it into a narrow beam.
- The electrons are attracted by a positive plate called the collector, which has given a high dc voltage.
- The length of the tube is usually many wavelengths at the operating frequency.
- Surrounding the tube are either permanent magnets or electromagnets that keep the electrons tightly focused into a narrow beam.

Features

- The unique feature of the TWT is a helix or coil that surrounds the length of the tube and the electron beam passes through the centre or axis of the helix.
- The microwave signal to be amplified is applied to the end of the helix near the cathode and the output is taken from the end of the helix near the collector.
- The purpose of the helix is to provide path for RF signal.
- The propagation of the RF signal along the helix is made approximately equal to the velocity of the electron beam from the cathode to the collector.

Functioning

- The passage of the microwave signal down the helix produces electric and magnetic fields that will interact with the electron beam.
- The electromagnetic field produced by the helix causes the electrons to be speeded up and slowed down, this produces velocity modulation of the beam which produces density modulation.
- Density modulation causes bunches of electrons to group together one wavelength apart and these bunch of electrons travel down the length of the tube toward the collector.

Functioning

- The electron bunches induce voltages into the helix which reinforce the voltage already present there. Due to that the strength of the electromagnetic field on the helix increases as the wave travels down the tube towards the collector.
- At the end of the helix, the signal is considerably amplified. Coaxial cable or waveguide structures are used to extract the energy from the helix.

Advantages

1. TWT has extremely wide bandwidth. Hence, it can be made to amplify signals from UHF to hundreds of gigahertz.
2. Most of the TWT's have a frequency range of approximately 2:1 in the desired segment of the microwave region to be amplified.
3. The TWT's can be used in both continuous and pulsed modes of operation with power levels up to several thousands watts.

Performance characteristics

1. Frequency of operation : 0.5 GHz – 95 GHz
2. Power outputs:
 - 5 mW (10 – 40 GHz – low power TWT)
 - 250 kW (CW) at 3 GHz (high power TWT)
 - 10 MW (pulsed) at 3 GHz
3. Efficiency : 5 – 20 % (30 % with depressed collector)

Applications of TWT

1. Low noise RF amplifier in broad band microwave receivers.
2. Repeater amplifier in wide band communication links and long distance telephony.
3. Due to long tube life (50,000 hours against $\frac{1}{4}$ th for other types), TWT is power output tube in communication satellite.
4. Continuous wave high power TWT's are used in troposcatter links (due to larger power and larger bandwidths).
5. Used in Air borne and ship borne pulsed high power radars.

Key Notes of TWTA:

- Heater/Filament is closest to Cathode Voltage.
- Heater and Cathode act as electron gun, and they are on the side RF Input.
- Collectors sits on RF output.
- Electrons are fired from Cathode and received from Collectors.
- RF signal is amplified through bunching effect after traveling along the path of Helix coil.
- Higher Cathode voltage → Higher RF Power.
- Advantage of TWTA (over solid state amplification) is the linearity and output power.
- TWTA Efficiency: 50% to 60% vs. Solid State: 25% to 30%
- Ranges of Frequency for TWTA: 1Ghz – 40 Ghz.

Application of TWTA

- Point to Point Communication.
- Satellite communication and Radar.
- Missile tracking application for military.
- Television live broadcasting
 - LIVE news vans with satellite dishes on the roof carry TWTA inside



BASIS OF COMPARISON	TRAVELLING WAVE TUBE (TWT)	KLYSTRON
Interaction Of Electron	The interaction of an electron beam and EM field in the TWT is continuous over the entire length of circuit.	Interaction of the electron in the klystron occurs only at the gaps of a few resonant cavities.
Type of Microwave Circuit	The microwave circuit is non-resonant.	Its microwave circuit is a resonant type.
Type Of Wave	The wave in the TWT is the propagating wave.	The wave in klystron is not propagating wave.
Input And Output	Travelling wave tube uses non-resonant wave circuits for input and output and is a wide band device.	Klystron uses cavities for input and output circuits and is a narrow band device.
Cavities	In coupled cavity TWT, coupling effect takes place between cavities.	In klystron, each cavity operates independently and there is no mutual coupling.
Bandwidth	It has wider bandwidth of operation.	It has smaller bandwidth of operation.
Efficiency	TWT operates on lower efficiency.	It has comparatively high efficiency.
Power Output	Travelling wave has high power output.	Travelling wave has high power output.
Types	There two types of TWT, that is, helix and coupled cavity.	There are two types of klystron, that is, Two or multi-cavity and reflex klystron.
Frequency	Frequency of operation is from 300MHz to 50 GHz.	Frequency of operation is from 4 GHz to 200GHz.
Life Span	Has a long life when compared to klystron.	Has a short life when compared to TWT.
Power	Handles CW power upto 200Watt.	Handles power of 1mW to 2.5W.

Microwave Devices

Microwave Concepts

Microwave Communication Systems

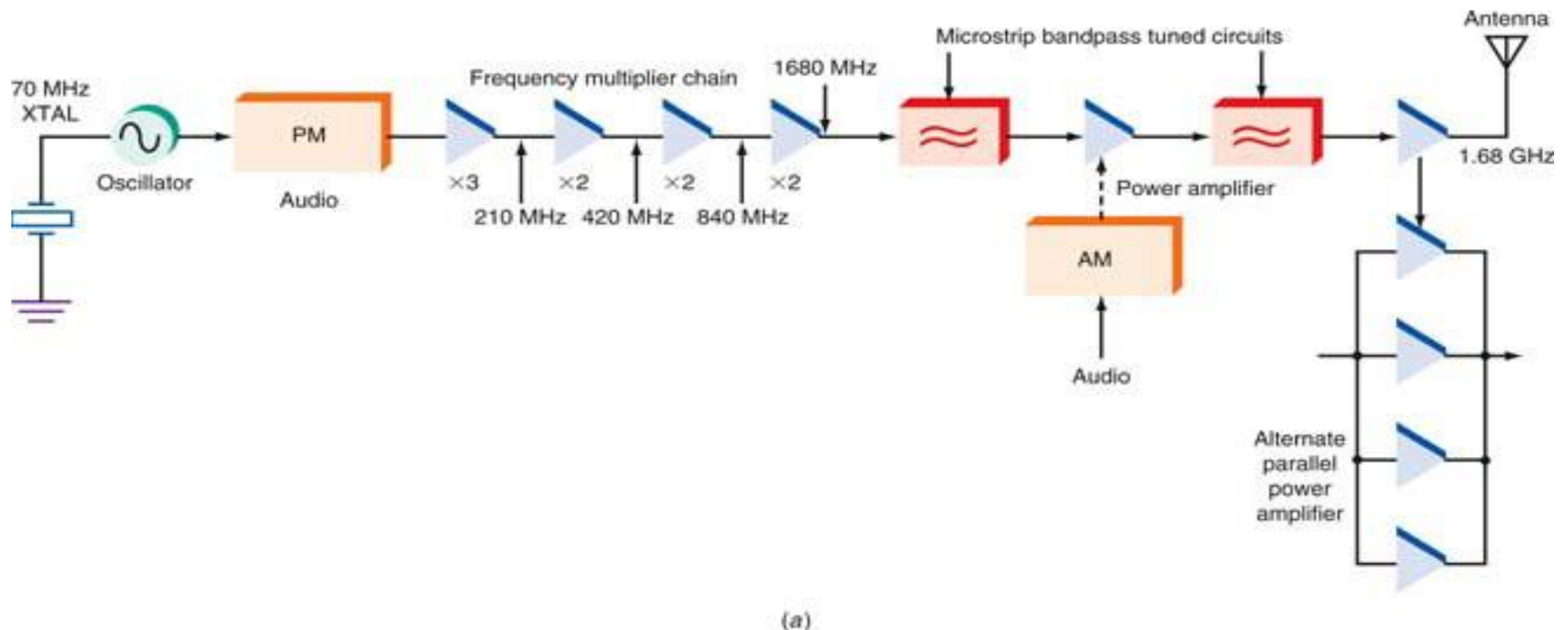
- Like any other communication system, a microwave communication system uses transmitters, receivers, and antennas.
- The same modulation and multiplexing techniques used at lower frequencies are also used in the microwave range.
- The RF part of the equipment, however, is physically different because of the special circuits and components that are used to implement the components.

Microwave Concepts

Microwave Communication Systems: Transmitters

- Like any other transmitter, a microwave transmitter starts with a carrier generator and a series of amplifiers.
- It also includes a modulator followed by more stages of power amplification.
- The final power amplifier applies the signal to the transmission line and antenna.
- A transmitter arrangement could have a mixer used to up-convert an initial carrier signal with or without modulation to the final microwave frequency.

Microwave Concepts



Microwave transmitters using frequency multipliers to reach the microwave frequency. The shaded stages operate in the microwave region.

Microwave Concepts

Microwave Communication Systems: Receivers

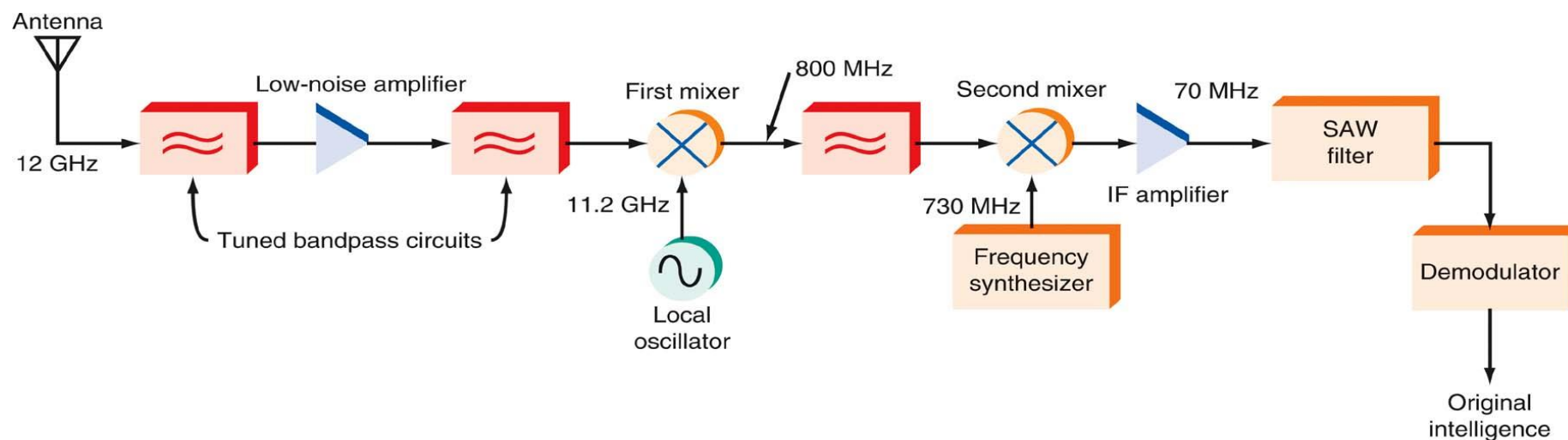
- Microwave receivers, like low-frequency receivers, are the superheterodyne type.
- Their front ends are made up of microwave components.
- Most receivers use double conversion.

Microwave Concepts

Microwave Communication Systems: Receivers

- The antenna is connected to a tuned circuit, which could be a cavity resonator or microstrip or stripline tuned circuit.
- The signal is then applied to a special RF amplifier known as a low-noise amplifier (LNA).
- Another tuned circuit connects the amplified input signal to the mixer.
- The local oscillator signal is applied to the mixer.
- The mixer output is usually in the UHF or VHF range.
- The remainder of the receiver is typical of other superheterodynes.

Microwave Concepts



A microwave receiver

Microwave Concepts

Microwave Communication Systems: Transmission Lines

- Coaxial cable, most commonly used in lower-frequency communication has very high attenuation at microwave frequencies and conventional cable is unsuitable for carrying microwave signals.
- Special microwave coaxial cable that can be used on bands L, S, and C is made of hard tubing. This low-loss coaxial cable is known as **hard line cable**.
- At higher microwave frequencies, a special hollow rectangular or circular pipe called **waveguide** is used for the transmission line.

Microwave Concepts

Microwave Communication Systems: Antennas

- At low microwave frequencies, standard antenna types, including the simple dipole and one-quarter wavelength vertical antenna, are still used.
- At these frequencies antennas are very small; for example, a half-wave dipole at 2 GHz is about 3 inch.
- At higher microwave frequencies, special antennas are generally used.

Microwave Lines and Devices

- Although vacuum and microwave tubes like the klystron and magnetron are still used, most microwave systems use **transistor amplifiers**.
- Special geometries are used to make bipolar transistors that provide voltage and power gain at frequencies up to 10 GHz.
- Microwave FET transistors have also been created.
- Monolithic microwave integrated circuits (MMICs) are widely used.

Microwave Lines and Devices

Microwave Transistors

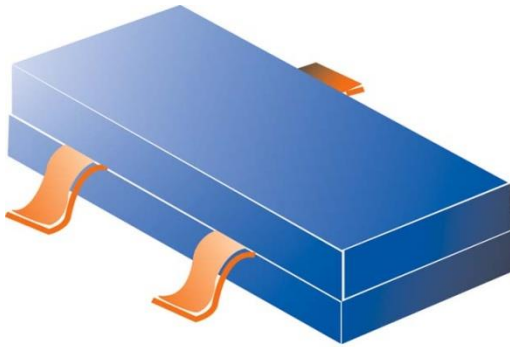
- The primary differences between standard lower-frequency transistors and microwave types are internal geometry and packaging.
- To reduce internal inductances and capacitances of transistor elements, special chip configurations known as **geometries** are used.
- Geometries permit the transistor to operate at higher power levels and at the same time minimize distributed and stray inductances and capacitances.

Microwave Lines and Devices

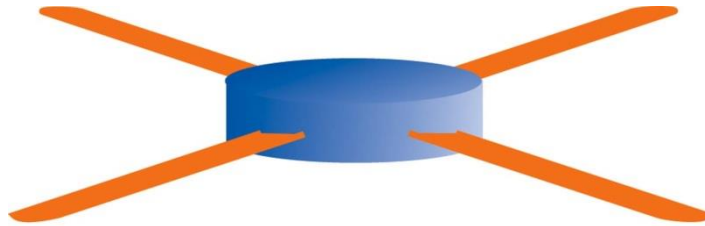
Microwave Transistors

- The GaAs MESFET, a type of JFET using a Schottky barrier junction, can operate at frequencies above 5 GHz.
- A **high electron mobility transistor (HEMT)** is a variant of the MESFET and extends the range beyond 20 GHz by adding an extra layer of semiconductor material such as AlGaAs.
- A popular device known as a **heterojunction bipolar transistor (HBT)** is making even higher-frequency amplification possible in discrete form and in integrated circuits.

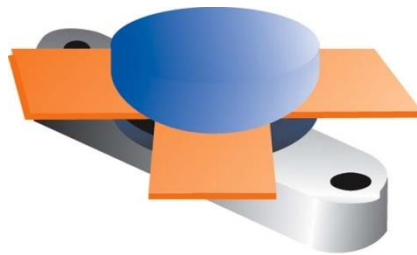
Microwave Lines and Devices



(a)



(b)



(c)



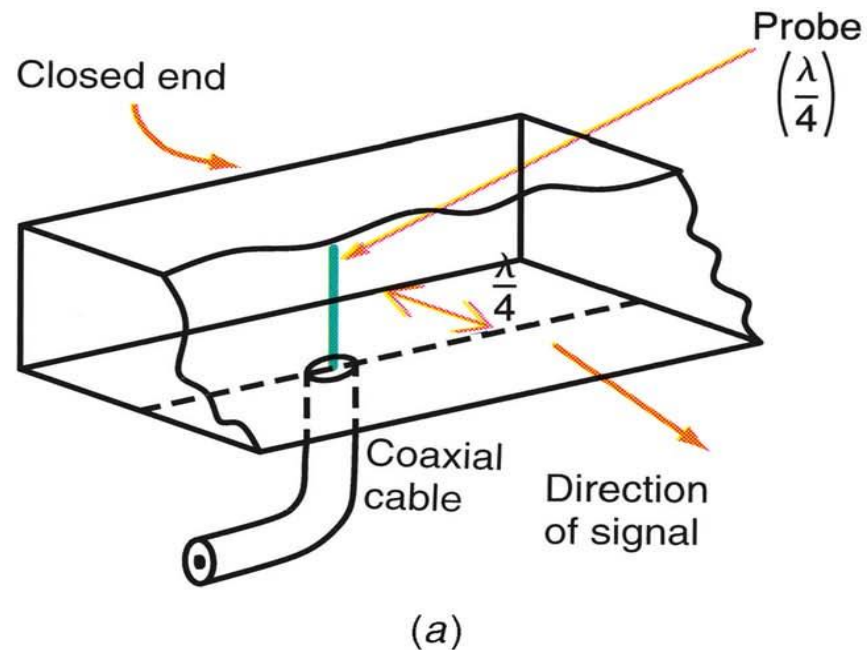
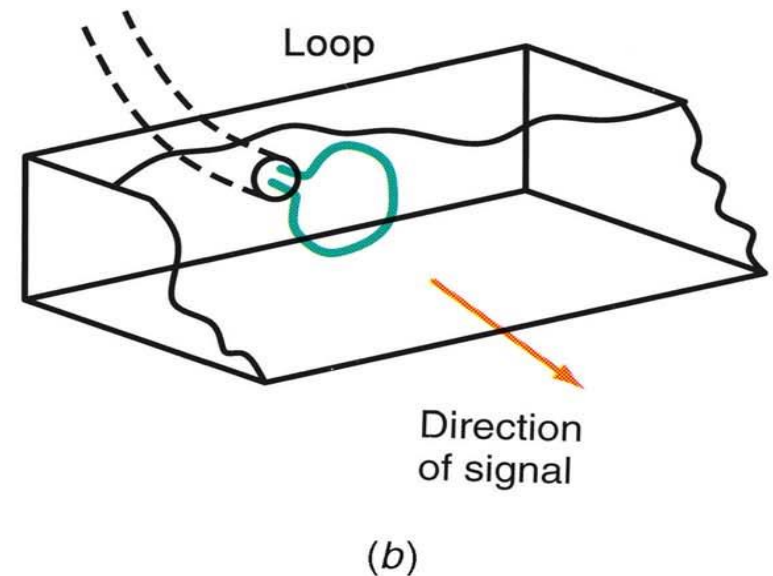
(d)

Microwave transistors. (a) and (b) Low-power small signal. (c) FET power. (d) NPN bipolar power.

Waveguides: Signal Injection and Extraction

- A microwave signal to be carried by a waveguide is introduced into one end of the waveguide with an antennalike probe.
- The probe creates an electromagnetic wave that propagates through the waveguide.
- The electric and magnetic fields associated with the signal bounce off the inside walls back and forth as the signal progresses down the waveguide.
- The waveguide totally contains the signal so that none escapes by radiation.

Waveguides: Signal Injection and Extraction



Injecting a sine wave into a waveguide and extracting a signal.

Waveguides: Signal Injection and Extraction

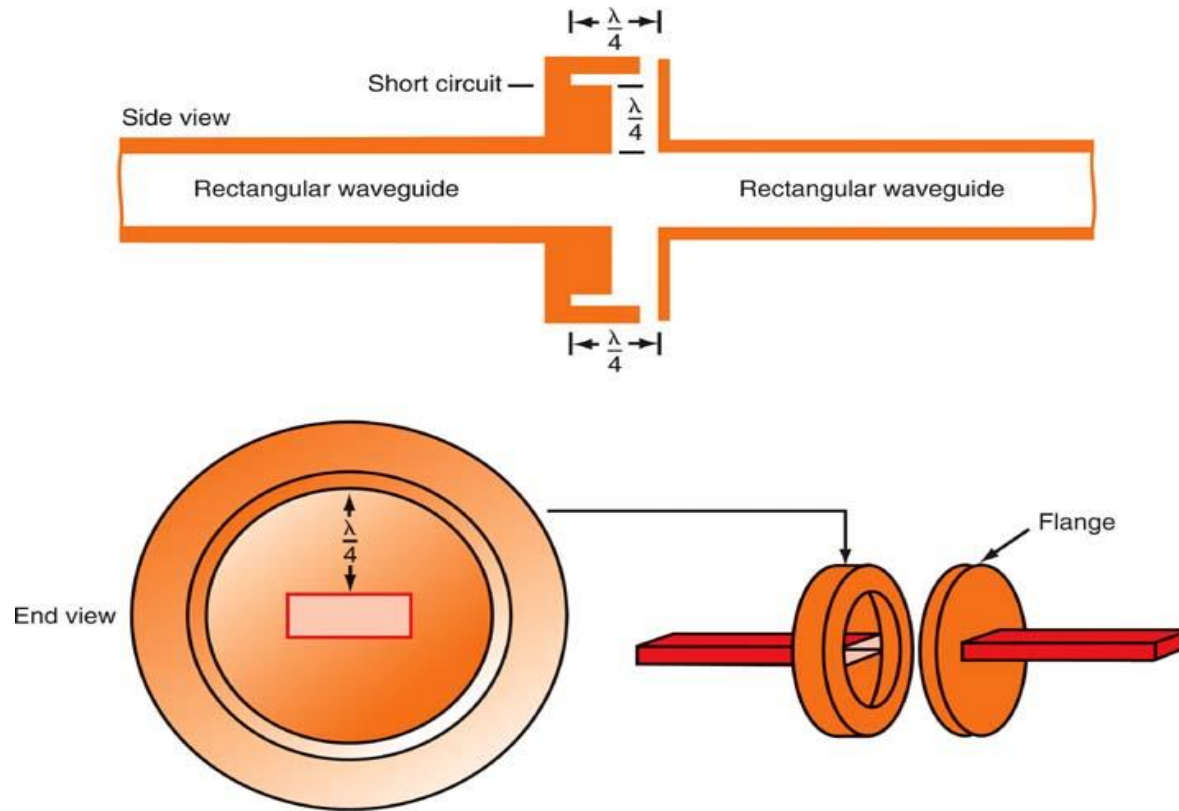
Waveguides: Signal Injection and Extraction

- Probes and loops can be used to extract a signal from a waveguide.
- When the signal strikes a probe or a loop, a signal is induced which can then be fed to other circuitry through a short coaxial cable.

Waveguide Hardware and Accessories

- Waveguides have a variety of special parts, such as couplers, turns, joints, rotary connections, and terminations.
- Most waveguides and their fittings are precision-made so that the dimensions match perfectly.
- A **choke joint** is used to connect two sections of waveguide. It consists of two flanges connected to the waveguide at the center.
- A **T junction** is used to split or combine two or more sources of microwave power.

Waveguide Hardware and Accessories



A choke joint permits sections of waveguide to be interconnected with minimum loss and radiation.

Waveguide Hardware and Accessories

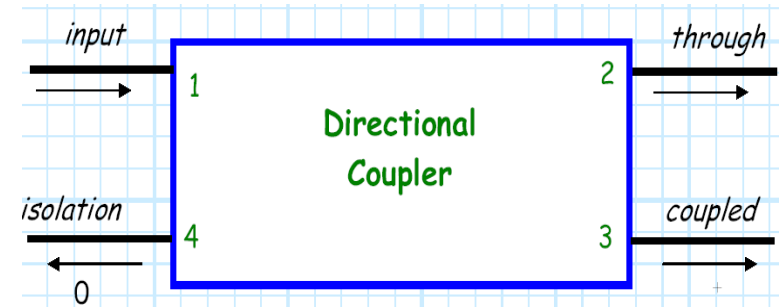
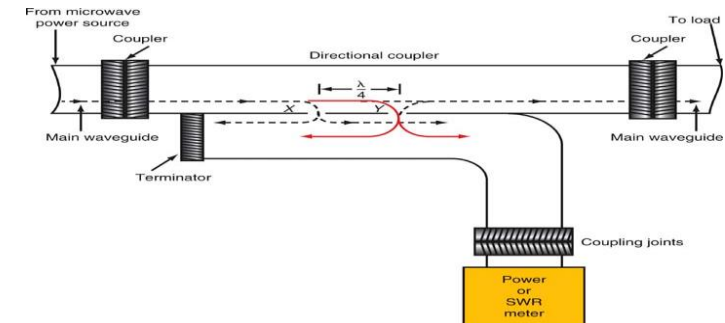
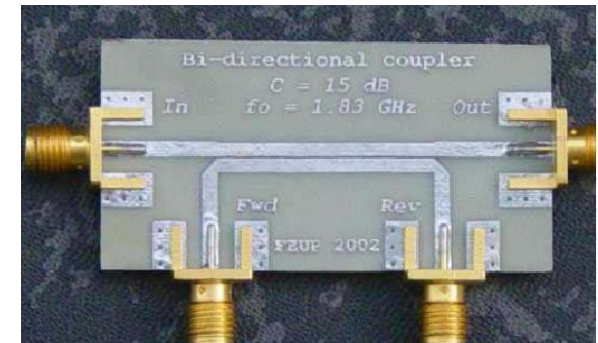
A **directional coupler** is a 4-port network that is designed to **divide** and **distribute** power.

Although this would seem to be a particularly **mundane** and simple task, these devices are both very **important** in microwave systems, and very **difficult** to design and construct.

Two of the **reasons** for this difficulty are our desire for the device to be:

1. Matched
2. Lossless

In the terminology of the directional coupler, we say that port 1 is the **input** port, port 2 is the **through** port, port 3 is the **coupled** port, and port 4 is the **isolation** port. Note however, that **any** of the coupler ports can be an input, with a different through, coupled and isolation port for each case.



Waveguide Hardware and Accessories

Thus, from the scattering matrix of a directional coupler, we can form the following table:

Input	Through	Coupled	Isolation
Port 1	Port 2	Port 3	Port 4
Port 2	Port 1	Port 4	Port 3
Port 3	Port 4	Port 1	Port 2
Port 4	Port 3	Port 2	Port 1

Coupling (C)

The **coupling** value is the ratio of the coupled output power (P3) to the input power (P1), expressed in decibels:

$$C(dB) = 10 \log_{10} \left[\frac{P_1}{P_3} \right]$$

This is the **primary** specification of a directional coupler. Note the **larger** the coupling value, the **smaller** the coupled power.

Directivity (D)

The **directivity** is the ratio of the power **out** of the coupling port (P3) to the power **out** of the isolation port (P4), expressed in decibels.

$$D(dB) = 10 \log_{10} \left[\frac{P_3}{P_4} \right]$$

This value indicates how effective the device is in “**directing**” the coupled energy into the correct port (i.e., into the coupled port, **not** the isolation port).

Ideally this is infinite (i.e., P4=0) , so the **higher** the directivity, the **better**.

Isolation I

Isolation is the ratio of the **input power** (P1) to the power out of the **isolation** port (P4), expressed in decibels.

$$I(dB) = 10 \log_{10} \left[\frac{P_1}{P_4} \right]$$

This value indicates how “isolated” the isolation port actually is. **Ideally** this is infinite (i.e., $P_4=0$), so the **higher** the isolation, the better. Note that isolation, directivity, and coupling are **not** independent values! **You** should be able to quickly show that:

$$I(dB) = C(dB) + D(dB)$$

Mainline Loss ML

The **mainline loss** is the ratio of the **input** power (P1) to the power out of the **through** port (P2), expressed in decibels.

$$ML(dB) = 10 \log_{10} \left[\frac{P_1}{P_2} \right]$$

It indicates how much power the signal **loses** as it travels from the input to the through port.

Coupling Loss ML

The **coupling loss** indicates the **portion** of the mainline loss that is due to coupling some of the input power into the coupling port.

$$CL(dB) = 10 \log_{10} \left[\frac{P_1}{P_1^+ - P_3^-} \right]$$

Insertion Loss IL

Q: But wait, shouldn't ($P_1 - P_3 = P_2$), meaning the coupling loss and the mainline loss will be the **same exact value**?

A: **Ideally** this would be true.

But, the reality is that couplers are **not perfectly lossless**, so there will additionally be loss due to **absorbed** energy (i.e., heat). This loss is called **insertion loss** and is simply the **difference** between the mainline loss and coupling loss:

$$IL(dB) = ML(dB) - CL(dB)$$

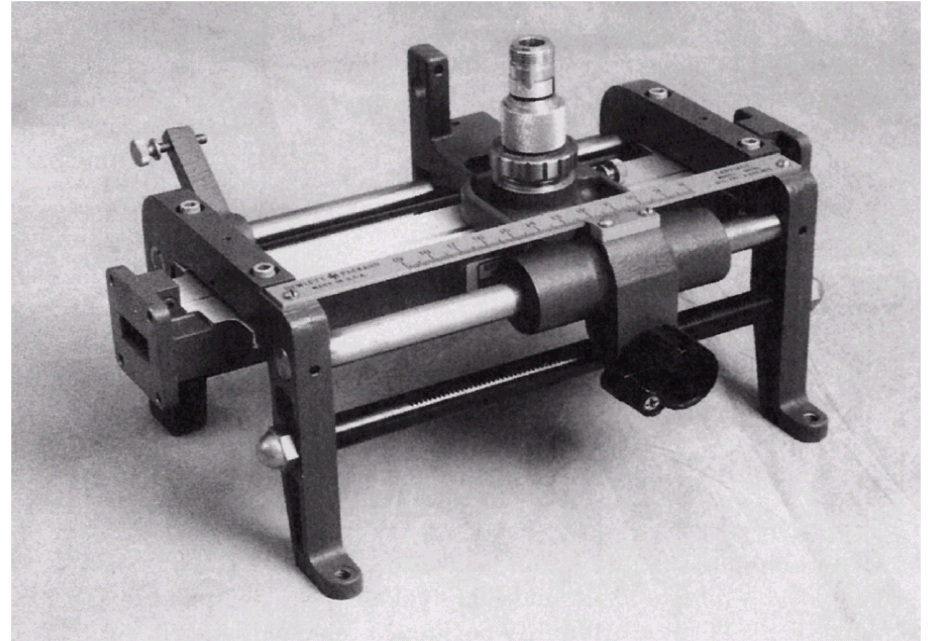
The insertion loss thus indicates the portion of the mainline loss that is **not** due to coupling some input power to the coupling port. This insertion loss **is** avoidable, and thus the **smaller** the insertion loss, the better. For couplers with **very small coupling** coefficients (e.g., $C(dB) > 20$) the coupling loss is so small that the mainline loss is almost entirely due to insertion loss (i.e., $ML = IL$) often then, the two terms are used **interchangeably**.

The Slotted Line

- A transmission line allowing the sampling of E field amplitude of a standing wave on a terminated line.
- With this device the SWR and the distance of the first voltage minimum from the load can be measured, from this data Z_L can be determined.
- Z_L is complex $\rightarrow$ 2 distinct quantities must be measured.
- Replaced by vector network analyzer.

The Slotted Line

Slotted lines can be made with any type of transmission line (waveguide, coax, microstrip, etc.), but in all cases the electric field magnitude is measured along the line with a small probe antenna and diode detector. The diode operates in the square-law region, so its output voltage is proportional to power on the line.



Lecture-10-

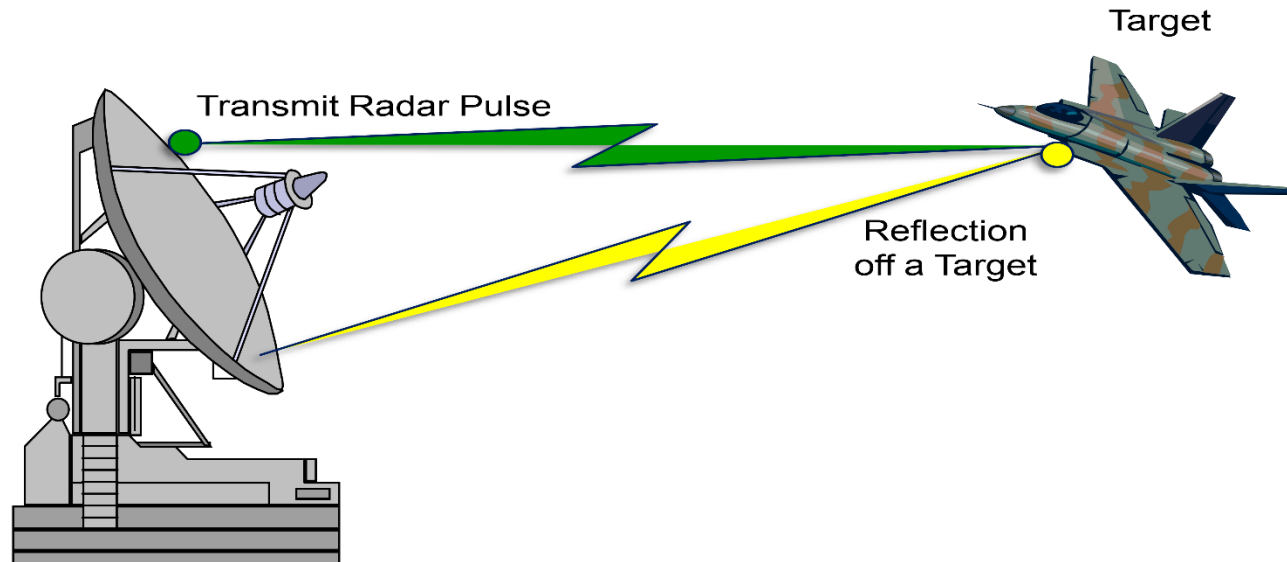
*Radar , Microwave
oven, Stealth*

Introduction to RADAR

RADAR is a method of using electromagnetic waves to determine the position (range and direction), velocity and identifying characteristics of targets.

Radar is used to expand the individual's ability to perceive the environment, especially vision. The value of radar is not to replace the eyes, but to do things that the eyes cannot do.

The advantage of radar is that it can measure the distance or range to an object. This may be its most important attribute.



Radar Directional Antenna

Radar Applications

- Military

- Search and Detection
- Targeting and Target Tracking
- Missile Guidance
- Fire Control – Acquisition, Track
- Airborne Intercept
- Ground and Battle field Surveillance
- Air Mapping Systems
- Submarine and Sub-Chasers

- Commercial

- Weather, Navigation, Air Traffic Control
- Space and Range
- Road and Speeding
- Biological Research – Bird and Insect Surveillance and Tracking
- Medical – diagnosis, organ movements, water condensation in the lungs, monitor heart rate and pulmonary motion, range(distance), remote sensor of heart and respiration rates without electrodes, patient movement and falls in the home
- Miniature – Seeing aids, early warning collision detection and situational awareness

Two Basic Radar Types

- Pulse Radar

- Transmits a pulse stream with a low duty cycle
- Receives reflected pulses during the time off or dead time between pulses
- Single Antenna
- Determines Range and Altitude
- Susceptible To Jamming
- Physical Range Determined By PW and PRF
- Low average power
- Time synchronization

- Continuous Wave CW Radar

- Transmits a CW signal and receives a Doppler frequency for moving targets
- Frequency Modulated CW FM-CW also provides both range and velocity
- Requires 2 Antennas and high SNR
- More Difficult to Jam But Easily Deceived
- Simpler to operate, timing not required

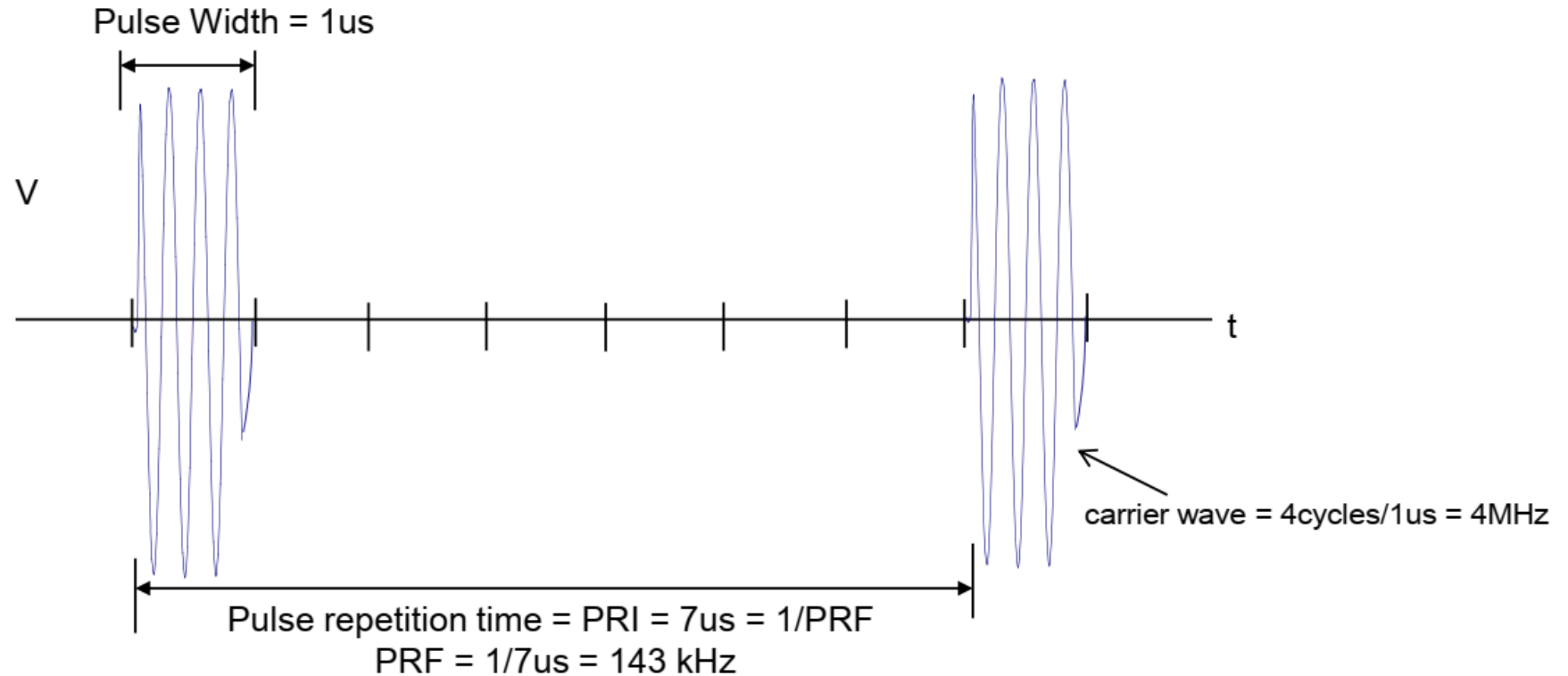
Pulsed Radar

- Most radar systems are pulsed
- Transmit a pulse and then listen for receive signals, or echoes
- Avoids problem of a sensitive receiver simultaneously operating with a high power transmitter.
- Radar transmits a low duty cycle, short duration high-power RF pulses
- Time synchronization between the transmitter and receiver of a radar set is required for range measurement.
- Returns that come from the 1st pulse causes distortion in the returns after the next pulse

Radar Modulation

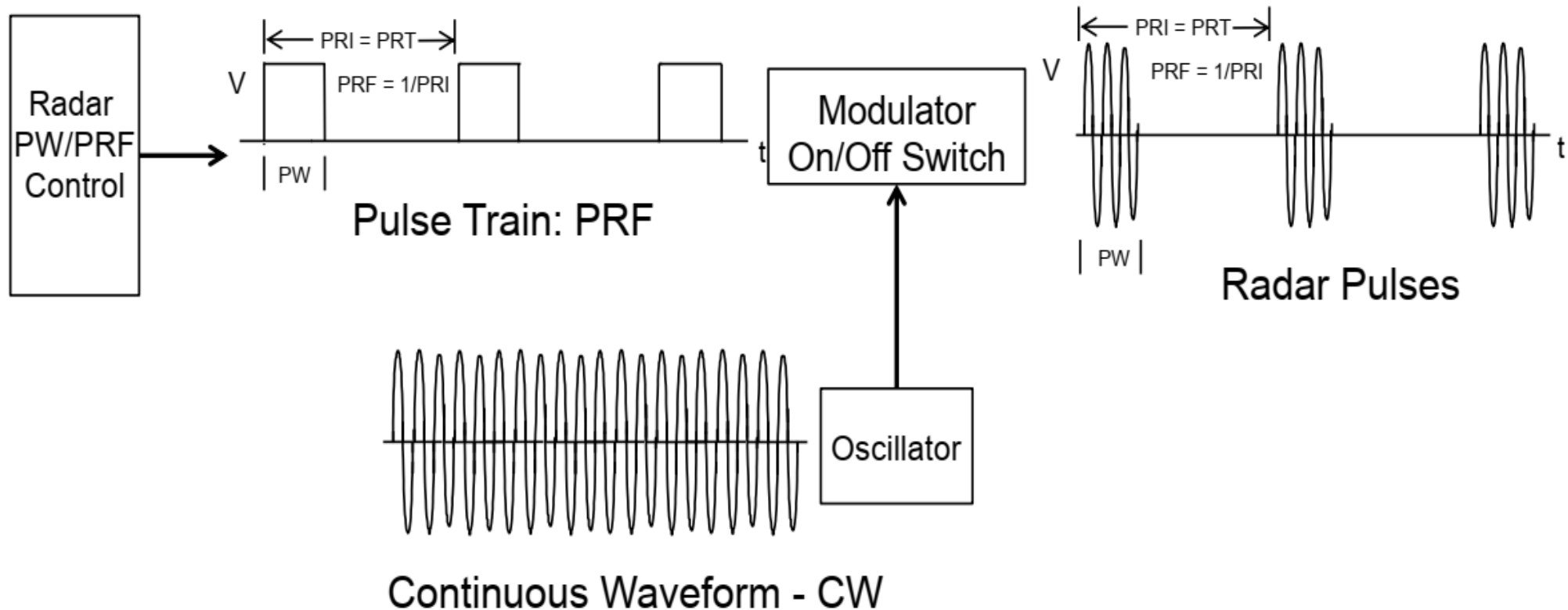
- 100% Amplitude Modulation AM, ON/OFF keying
 - Turns on/off a carrier frequency
- Pulse Width PW amount of time that the radar is on for one pulse
 - Determines the minimum range resolution
- Pulse Repetition Frequency PRF = number of pulses per second
- Pulse Repetition Interval PRI is the time between the start of the pulses
- Pulse Repetition Time PRT = Pulse Repetition Interval PRI = $1/\text{PRF}$
- PRF can determine the radar's maximum detection range

Radar Turns on/off the Carrier Frequency

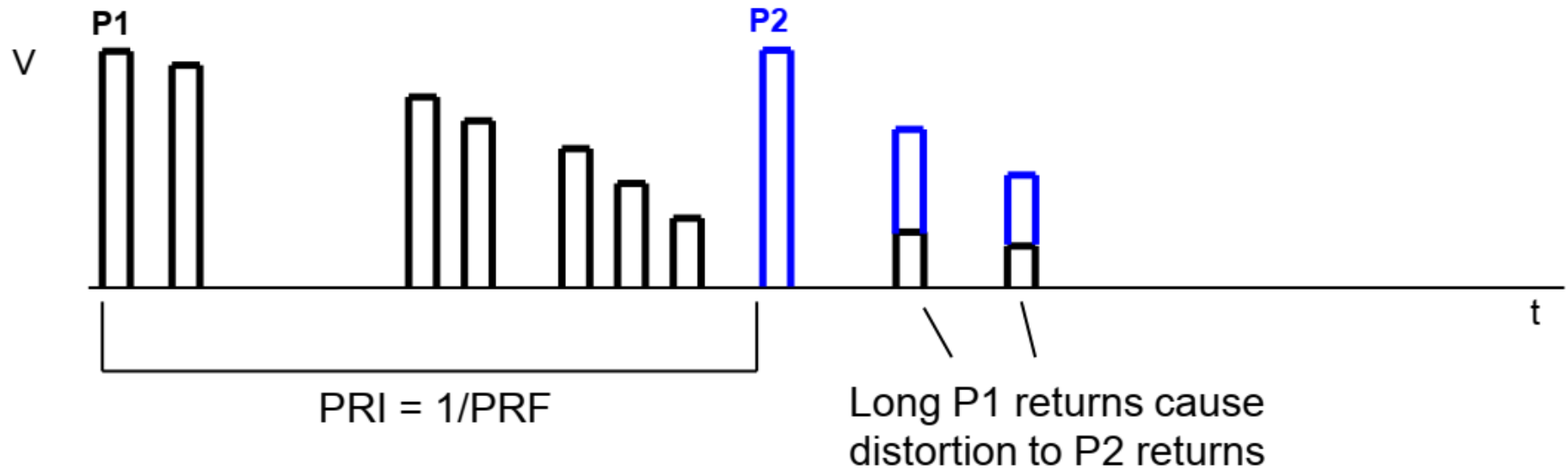


- Burst of Carrier Frequency – Radar burst
- Low duty cycle, high power
- Duty cycle = $\text{PW}/\text{PRI} \times 100 = 1\mu\text{s}/7\mu\text{s} \times 100 = 14\%$

Basic Radar Uses On/Off Keying of a CW Waveform

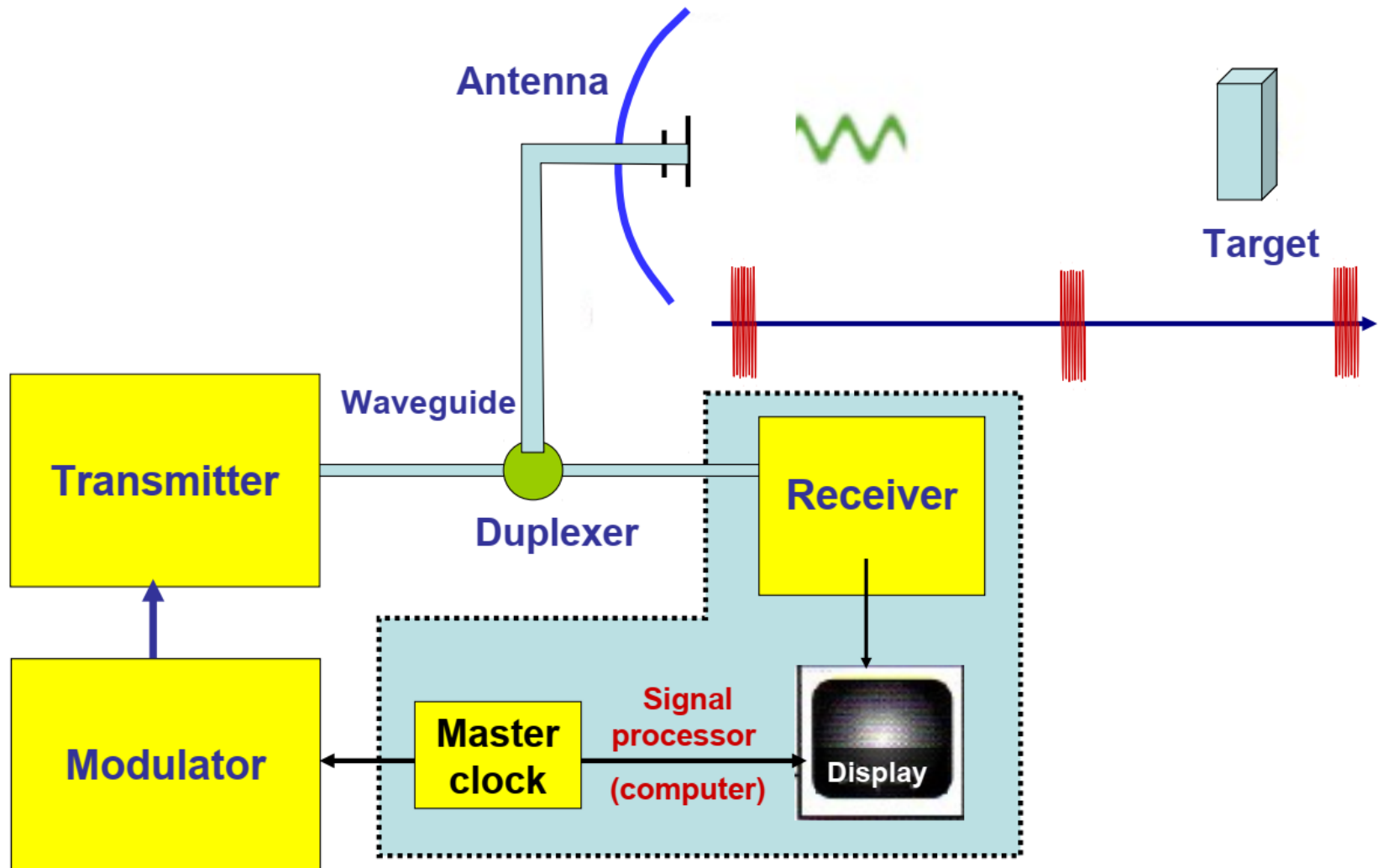


Pulse Distortion



Long returns from P1 causes distortion to the returns of P2

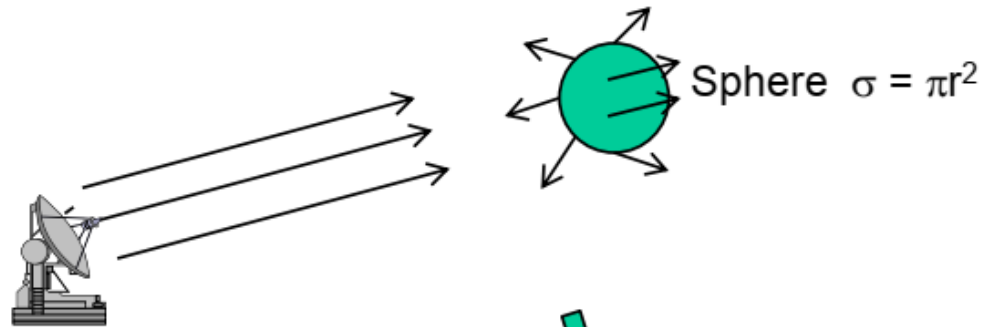
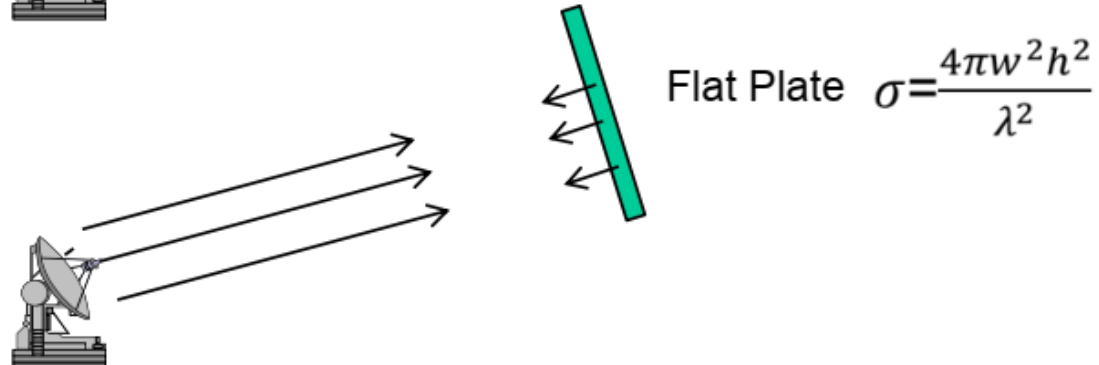
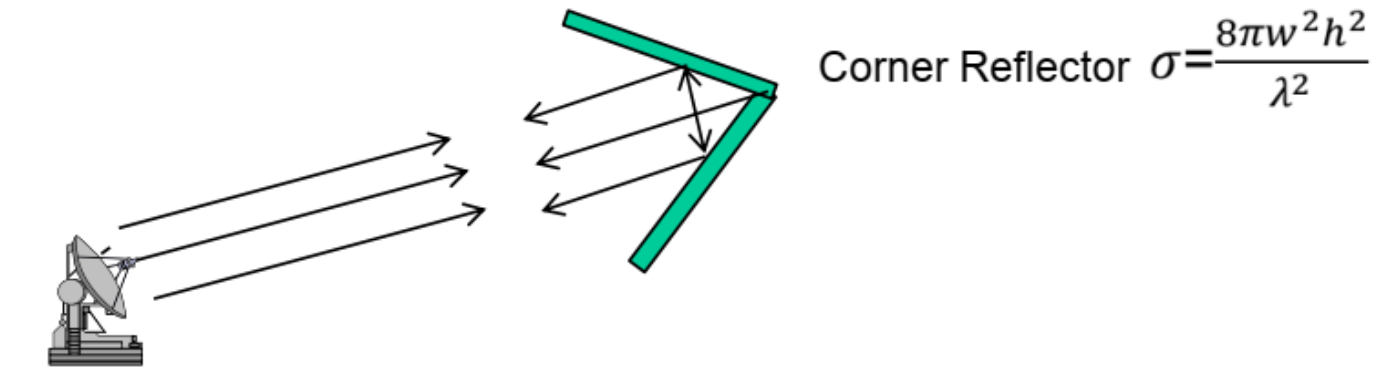
Basic Radar Diagram



Radar Cross Section RCS

- RCS (s) - size and ability of a target to reflect radar energy m^2
- $\text{RCS(s)} = \text{Projected cross section} \times \text{Reflectivity} \times \text{Directivity}$
- The target radar cross sectional area depends on:
 - Target's physical geometry and exterior features
 - Direction of the illuminating radar
 - Transmitted frequency,
 - Material types of the reflecting surface.
- Difficult to estimate
 - Equals the target's cross-sectional area theoretically
 - Not all reflected energy is distributed in all directions
 - Some energy is absorbed
 - Usually measured for accurate results

Radar RCS Patterns



Similar to
Antenna
Gains

RADAR Equation to Assess Radar Performance

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_s}$$

P_r = Radar received power

P_t = Radar transmitted power

G_t = Transmitter antenna gain

G_r = Receiver antenna gain

$G^2 = G_t G_r$ assumes the same antenna at the radar

λ = wavelength

R = slant range

L_s = total two-way additional losses

σ = radar cross section of the target RCS

Radar Range Calculation

- Radar uses electromagnetic energy pulses
- Pulse travel at the speed of light c_0
- Reflects off of a surface and returns an echo back to the radar
- Calculates the two-way distance or slant range
- Slant range = line-of-sight distance from radar to target
- Takes in account the angle from the earth
- Ground range = horizontal distance from radar to target
- Slant range calculated using ground range and elevation
- Radar energy to the target drops proportional to range squared.
- Reflected energy to the radar drops by a factor of range squared
- Received power drops with the fourth power of the range
- Need very large dynamic ranges in the receive signal processing
- Need to detect very small signals in the presence of large interfering signals

Slant Range

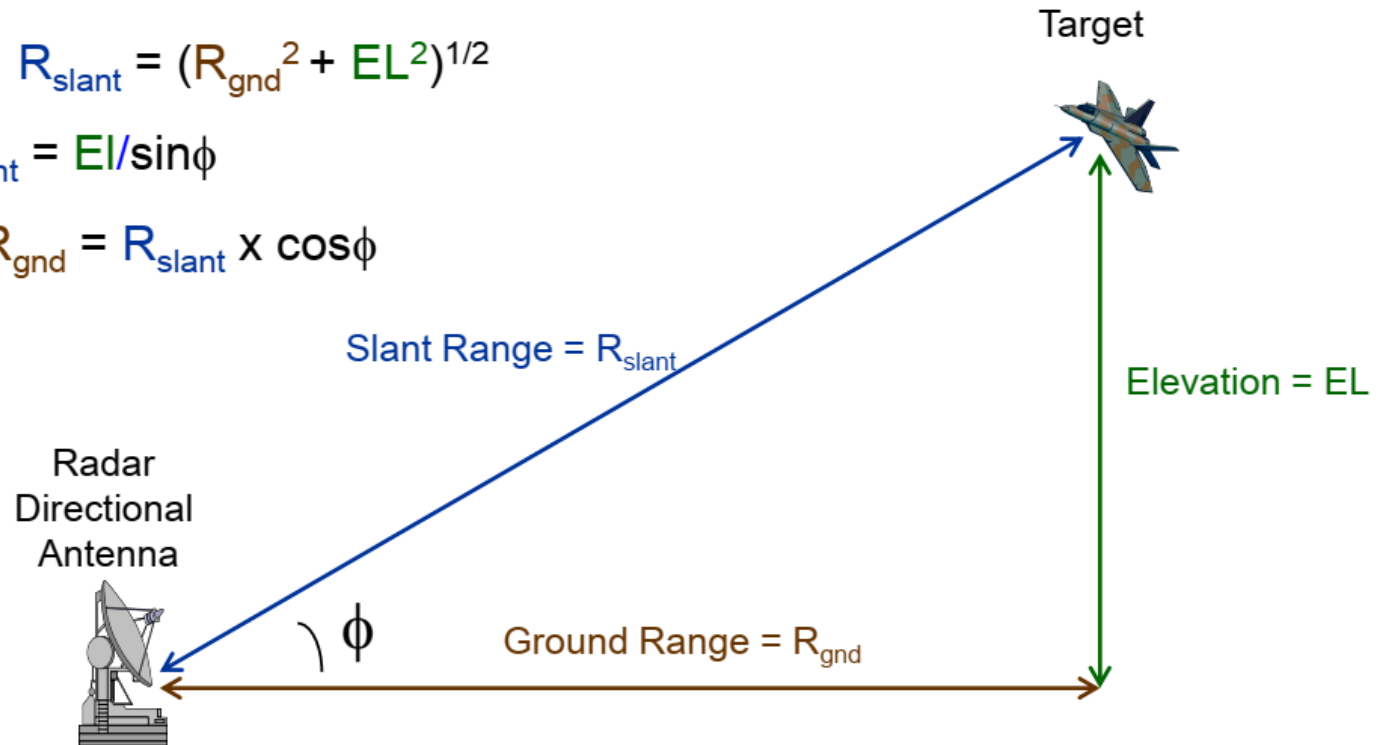
$$R_{\text{slant}}^2 = R_{\text{gnd}}^2 + EL^2: R_{\text{slant}} = (R_{\text{gnd}}^2 + EL^2)^{1/2}$$

$$\sin\phi = EL/R_{\text{slant}}: R_{\text{slant}} = EL/\sin\phi$$

$$\cos\phi = R_{\text{gnd}}/R_{\text{slant}}: R_{\text{gnd}} = R_{\text{slant}} \times \cos\phi$$

Given:
Elevation = 5000 ft
Angle = 30°

Calculate Slant Range =
 $R_{\text{slant}} = EL/\sin\phi = 5000/\sin(30) = 10,000 \text{ ft}$



What is the Ground Range =

$$R_{\text{gnd}} = R_{\text{slant}} \times \cos\phi = 10,000 \times \cos(30) = 8660.25 \text{ ft}$$

$$R_{\text{slant}}^2 = R_{\text{gnd}}^2 + EL^2: R_{\text{gnd}} = (R_{\text{slant}}^2 - EL^2)^{1/2} = (10,000^2 - 5000^2)^{1/2} = 8660.25 \text{ ft}$$

Range Calculation

Electromagnetic energy pulse travels at the speed of light c_0

$$R = \frac{(t_{delay} * c_0)}{2}$$

R = slant range

t_{delay} = two way time delay – Radar-Target-Radar

c_0 = speed of light = 3×10^8 m/s

Given: $t_{delay} = 1\text{ms}$

Calculate Slant Range

$$R = (1\text{ms} \times 10^{-3} \times 10^8 \text{ m/s})/2 = 150\text{km}$$

Range Ambiguity

- Caused by strong targets at a range in excess of the pulse repetition interval or time
- Pulse return from the first pulse comes after the second pulse is sent
- This causes the range to be close instead of far away
- Radar does not know which pulse is being returned
- Large pulse amplitude and higher PRF amplifies the problem
- The maximum unambiguous range for given radar system can be determined by using the formula:

$$R_{max} = (PRI - T) \frac{c_0}{2}$$

PRI = pulse repetition interval

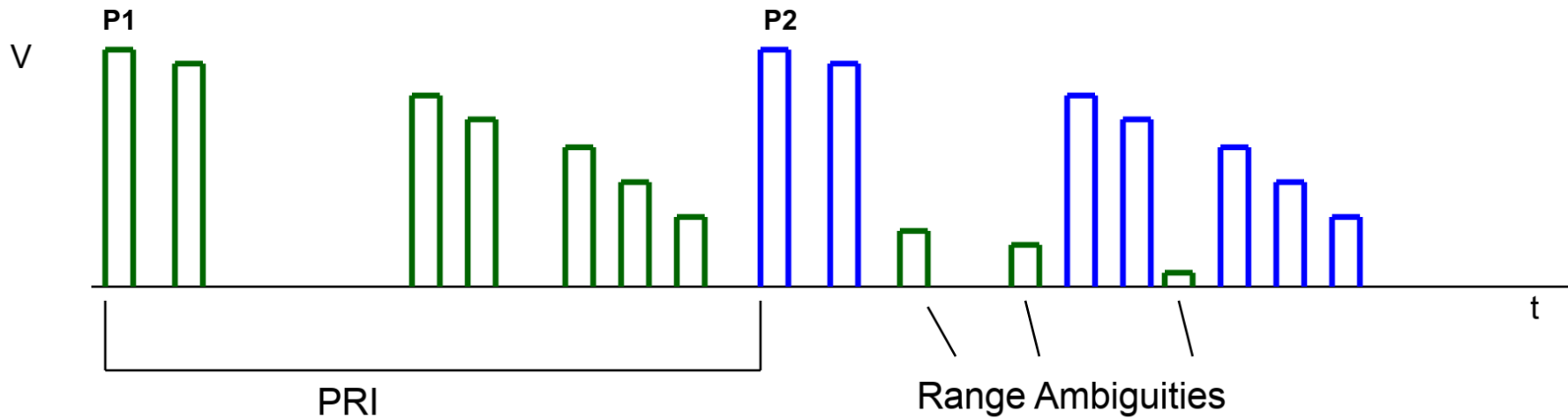
T = pulse width time

c_0 = speed of light

Example: PRI = 1msec, T = 1 μ s

Calculate Max unambiguous Range = $(1\text{ms} - 1\mu\text{s}) \times 3 \times 10^8 / 2 = 149.9\text{km}$

Range Ambiguity



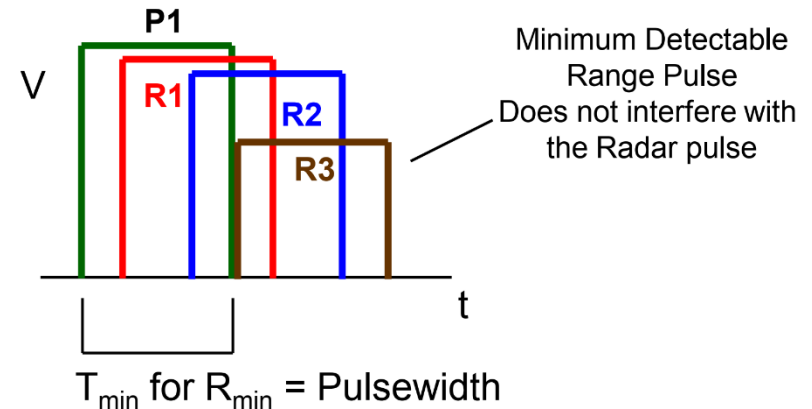
$$R_{max} = (PRI - PW) \frac{c_0}{2}$$

Minimum Detectable Range

- Radar minimum detectable range – return cannot come back during pulse width

$$R_{min} = (T + T_{recovery}) \frac{c_0}{2}$$

T = Pulse width, $T_{recovery}$ = time for pulse to recover



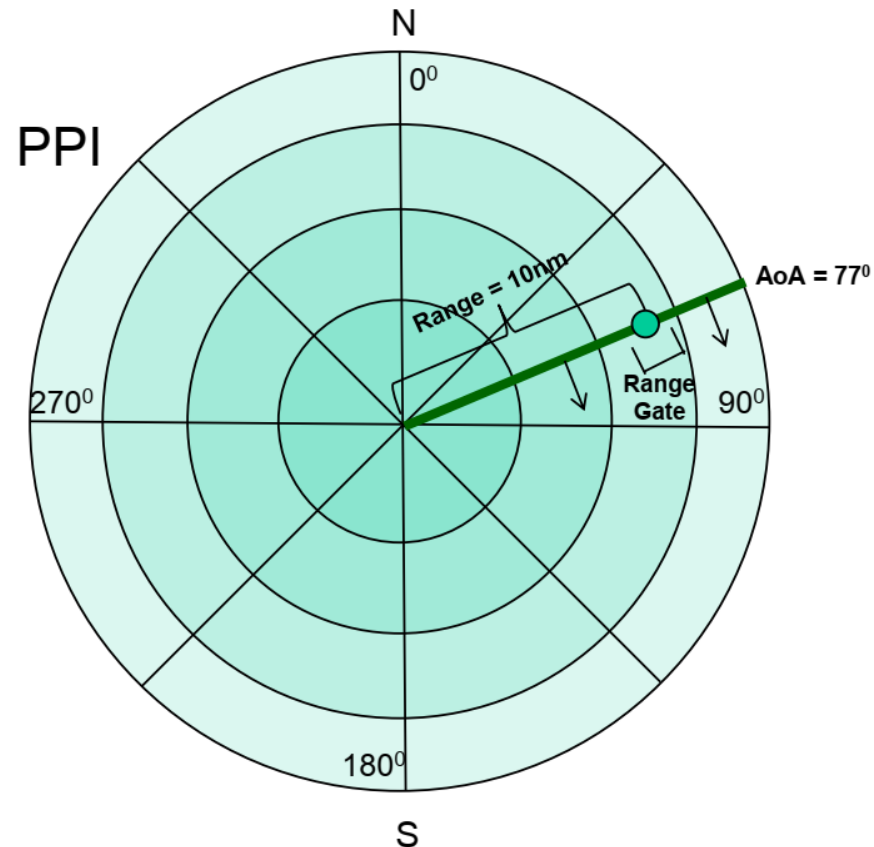
- Very close range targets equivalent to the pulse width not be detected
- Typical value of 1 μ s for the pulse width of short range radar corresponds to a minimum range of about 150 m
- Longer pulse widths have a bigger problem

Range Ambiguity Mitigation

- Decreasing the PRF reduces the range ambiguity
- Transmit different pulses at each PRF interval
- Vary the PRF, depending radar's operational mode

Plan Position Indicator (PPI)

- The return is displayed on a Plan Position Indicator (PPI)
 - Rotating Search Radars illuminates the targets on the PPI according to the angle received
 - Range is displayed according to the distance from the center of the PPI
 - Uses a range gate to lock on the range of the PPI



Example: A radar transmitter has a power of 10 KW and operates at a frequency of 9.5 GHz. Its signal reflect from a target 15 km away with a radar cross section of 10.2 m². The gain of the antenna is 20 dBi. Calculate the received signal power.

Solution: First, since Radar equation requires wavelength, rather than frequency, and antenna gain must be expressed as a power ratio, some preliminary calculations are necessary.

$$\begin{aligned}
 \lambda &= \frac{c}{f} \\
 &= \frac{300 \times 10^6}{9.5 \times 10^9} \\
 &= 0.0316 \text{ m} \\
 G &= \text{antilog} \frac{\text{dB}}{10} \\
 &= \text{antilog} \frac{20}{10} \\
 &= 100
 \end{aligned}$$

$$\begin{aligned}
 P_R &= \frac{\lambda^2 P_T G^2 \sigma}{(4\pi)^3 r^4} \\
 &= \frac{0.0316^2 (10 \times 10^3) (100^2) (10.2)}{(4\pi)^3 (15 \times 10^3)^4} \\
 &= 10.1 \times 10^{-15} \text{ W} \\
 &= 10.1 \text{ fW}
 \end{aligned}$$

Example: A pulse sent to a target returns after 15 μs . How far away is the target?

$$\begin{aligned} R &= \frac{ct}{2} \\ &= \frac{(300 \times 10^6)(15 \times 10^{-6})}{2} \\ &= 2250 \text{ m} \\ &= 2.25 \text{ km} \end{aligned}$$

Example: A pulse radar emits pulses with a duration of $1\text{ }\mu\text{s}$ and a repetition rate of 1KHz . Find the maximum and minimum range for this radar.

$$\begin{aligned} R_{max} &= \frac{c}{2f} \\ &= \frac{300 \times 10^6}{2 \times 1000} \\ &= 150 \times 10^3 \text{ m} \end{aligned}$$

Of course, this range is subject to the signal being able to propagate that far. If this radar were installed on a ship for the purpose of observing objects on the water, the range would actually be limited to the line-of-sight communication distance.

The minimum range is found from Equation (17.25):

$$\begin{aligned} R_{min} &= \frac{cT_P}{2} \\ &= \frac{(300 \times 10^6)(1 \times 10^{-6})}{2} \\ &= 150 \text{ m} \end{aligned}$$

Stealth

There are times when it would be better for an airplane not to appear on radar, for example, if the airplane is military and the radar belongs to an enemy anti-aircraft battery. The techniques for avoiding detection by radar are collectively known as *stealth*, and the details are, of course, kept secret. Still, the general ideas behind stealth are well known and easily understood.

The two basic ways of escaping radar detection are, first, to absorb radar waves rather than reflect them, and, second, to scatter any reflected signals as widely as possible to avoid returning a strong signal to the hostile radar. Achieving the first result involves the use of resistive materials in the body of the aircraft; sharp angles help to achieve the second. Figure 17.53 shows a stealth



Microwave Oven

There is very likely a magnetron in your kitchen, since every microwave oven contains one. The magnetron produces several hundred watts at 2.45 GHz, a frequency that is chosen because water molecules are resonant at that frequency. If subjected to a microwave field at that frequency, water molecules absorb power and become hot, causing any food containing water to cook. The output of the magnetron is coupled to a resonant cavity, the oven itself. The several kilovolts required by the tube are supplied by a step-up transformer and a voltage-doubler rectifier circuit. In variable-power ovens, a thyristor circuit pulses the power so that the magnetron switches rapidly on and off.

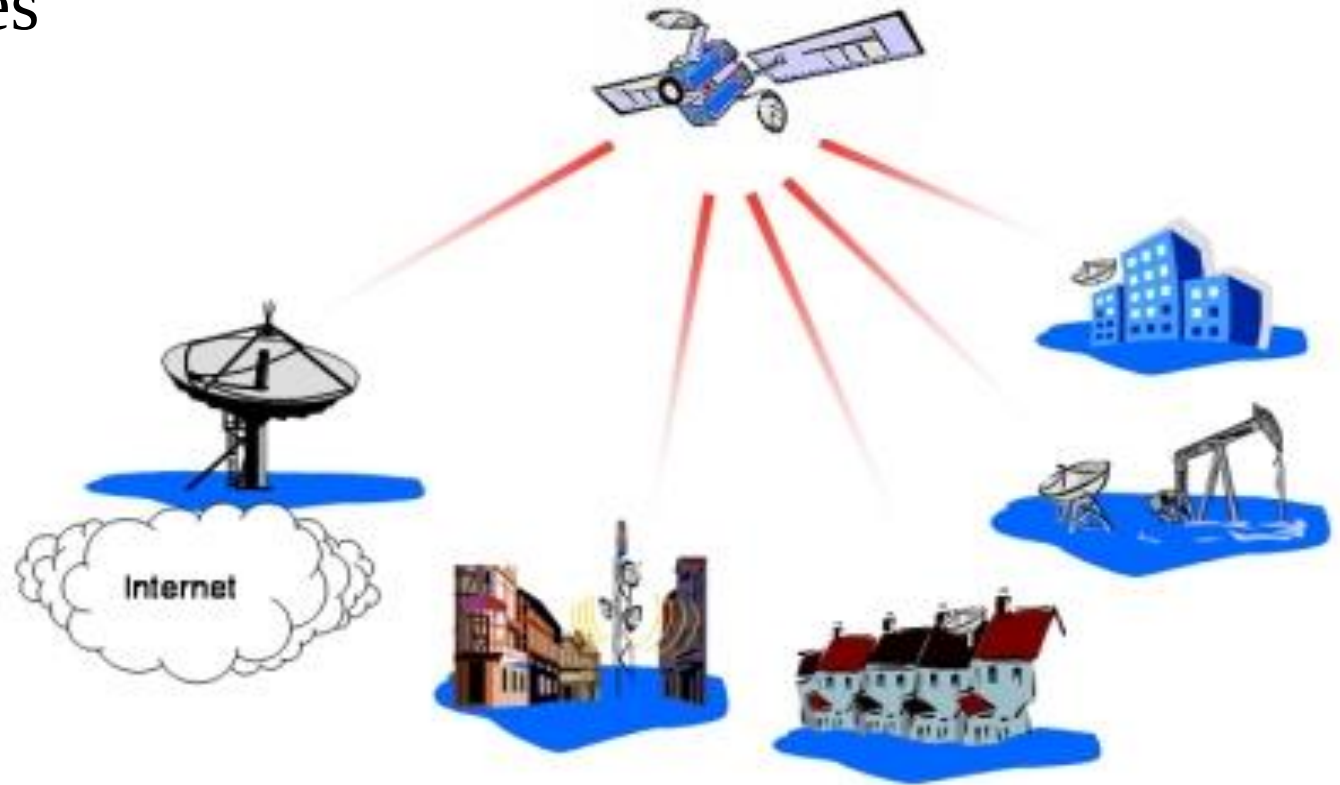
Now that you know something about microwaves, some of the well-known cautions about microwave ovens should be easy to understand. Operating the oven without food is undesirable, since this is equivalent to operating a transmitter without a load—most of the power will be reflected back to the tube. Similarly, the use of metal containers is frowned on because currents will be induced in the metal, heating it and distorting the field in the oven. Some special microwave cookware contains resistive material designed to absorb power from the microwaves and become hot, as an aid to browning certain foods. Some microwaves rotate the food or use a “stirrer” to disturb the fields in the cavity. This is done because the oven, like any resonant cavity, has standing waves, so the electric-field strength and therefore the cooking ability are not evenly distributed.

Lastly, a knowledge of microwaves can be applied to safety concerns. It is important that the door seal properly, and that the interlocks (there are usually two, for backup) disconnect the power when the door is opened. The microwaves that can cook your food can cook you, too, if allowed to escape. (The eyes are especially vulnerable, because they have poor circulation that does not allow heat to be removed quickly by the blood.) But no, the food itself is not “radioactive” in any way. We are dealing with radio waves, at frequencies far below those of ordinary light. Giving radioactivity to substances requires photons with much more energy. “Nuking” food in the microwave is just a figure of speech!

Satellite Communication

Overview

- Basics of Satellites
- Types of Satellites



What is a Satellite ?

- A celestial body –In astronomical term, e.g. moon
- A space vehicle launched by humans and orbits the earth or another celestial body –In aerospace terms
- Communication Satellite –provides communication and other services to variety of consumers
 - It is a microwave repeater in the sky
 - A satellite radio repeater is called a transponder
 - A satellite may have one to many transponders

What is a Satellite Systems ?

A Satellite System may consist of :

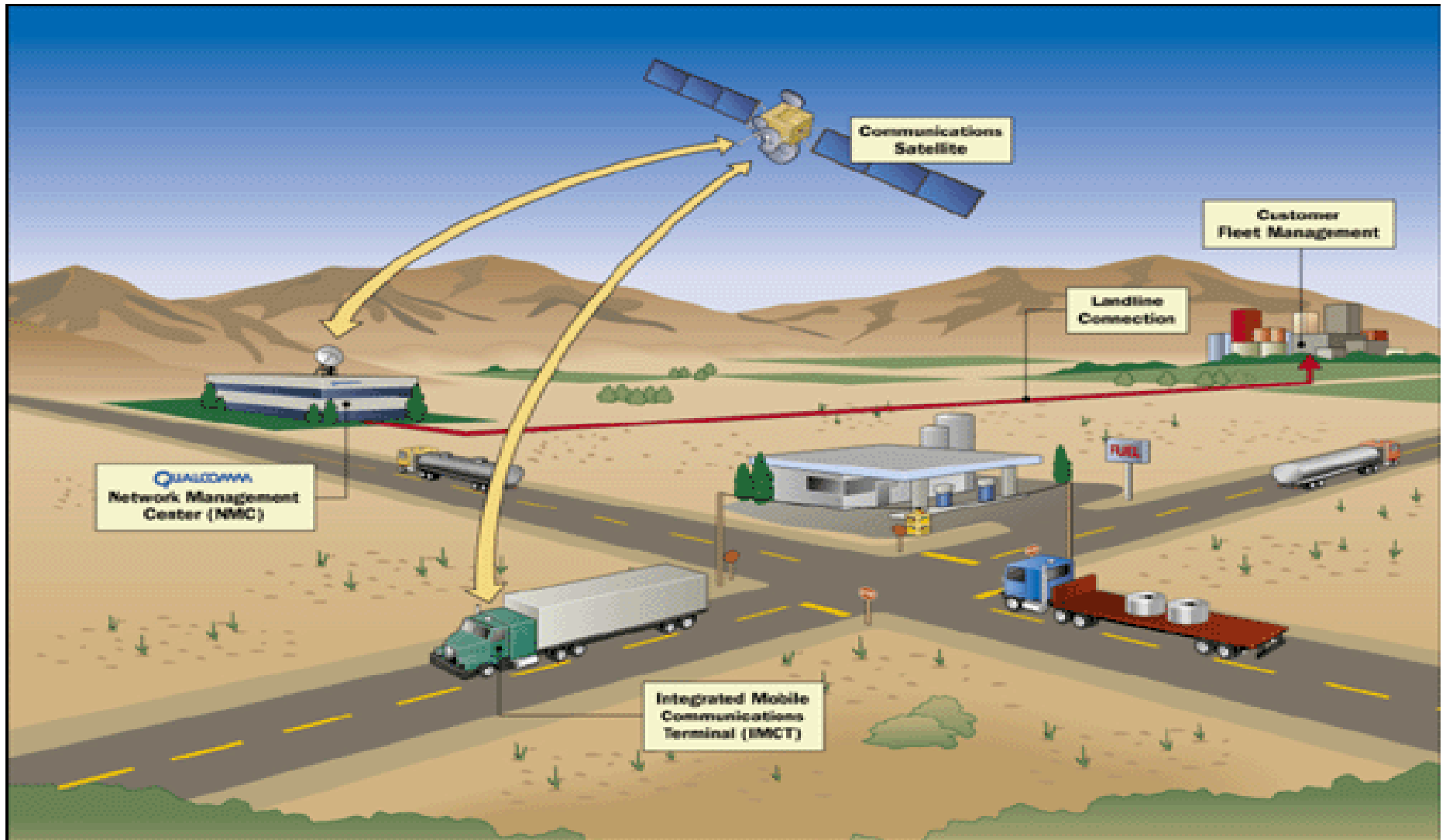
- one or more satellite space vehicles.
- a ground based control earth station.
- and a network of user earth stations that provides the interface facilities for the transmission and reception of terrestrial communications traffic through the satellite systems.
- Transmissions to and from the satellites are categorized as either bus or payload.
- The payload is the actual user information conveyed through the system.
- The bus includes control mechanisms that support the payload operation.

Why Satellite?

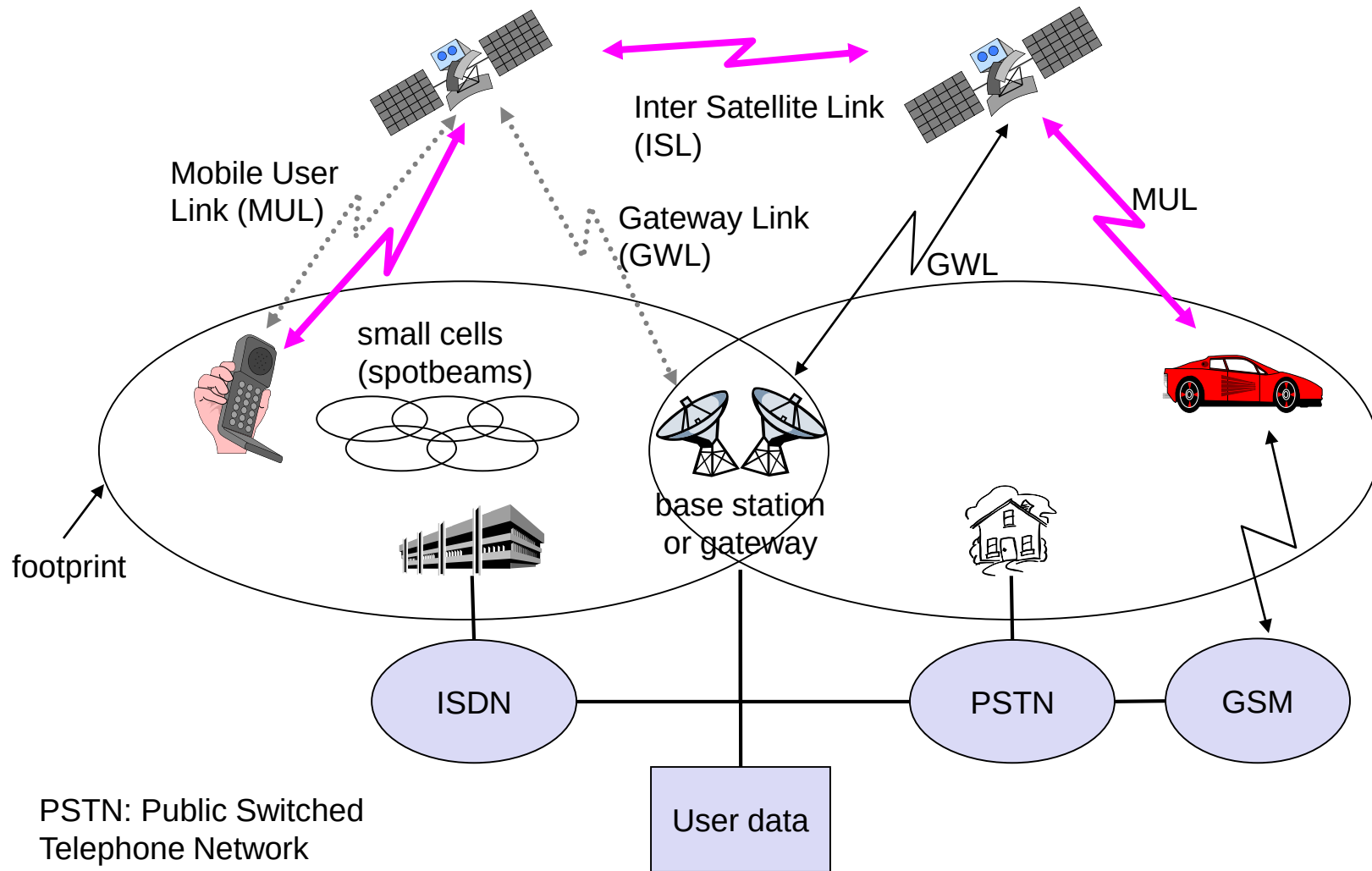
- Through satellite transmission, coverage over geographical area is quite large mainly for sparsely populated areas.
- High bandwidth.
- Wireless and mobile communication applications can be easily established by satellite communication independent of location.
- It is used in wide variety of applications such as global mobile communication, private business networks, Long distance telephone transmission, weather forecasting, radio/TV signal broadcasting, gathering intelligence in military, navigation of ships and air crafts, connecting remote areas, television distribution etc.
- Security in satellite transmission is usually provided by the coding and decoding equipment.

Disadvantages of Satellite

- Design, development, investment and insurance of satellite requires higher cost.
- To reach the satellite from Earth, time can vary between 270 milliseconds and return again to 320 milliseconds. This propagation delay can cause an echo over telephone connections
- Satellites are not easy to repair and maintain.
- Some circumstances like weather or sunspots affect the satellite's signal and can cause interference and make proper operation of the satellite very difficult.
- It requires to be monitored and controlled on regular periods so that it remains in the orbit, once it has been launched.



Classical satellite systems



How do Satellites Work

- Two Stations on Earth want to communicate through radio broadcast but are too far away to use conventional means.
- The two stations can use a satellite as a relay station for their communication
- One **Earth Station** sends a transmission to the satellite. This is called an **Uplink**.
- The satellite **Transponder** converts the signal and sends it down to the second earth station. This is called a **Downlink**.

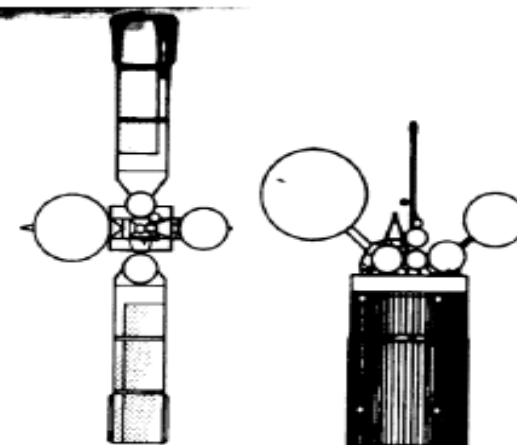
History & Background of Satellites-I

- 1957 –*Sputnik I*(USSR),First active satellite, Transmitted telemetry info for 21 days.
- In same year, *Explorer I*(US),transmitted telemetry info for 5 months
- 1958,NASA's *Score*,first artificial satellite used for relaying terrestrial communications.
- 1960, *Echo-1*(US), a Passive Satellite
- 1962, AT&T *Telstar 1*, LEO satellite, First active satellite to simultaneously transmit and receive radio signals, damaged by radiation
- 1963, *Telstar 2*,electronically similar to *Telstar 1* except more radiation resistant,accomplished first successful video transmission

History & Background of Satellites-II

- 1963,*Syncom I*-First attempt to place a geosynchronous satellite into orbit, lost during orbit injection
- 1963,1964-Successful launches of *Syncom II*, *Syncom III* (linked Japan and USA), *Syncom III* was used to broadcast 1964 Olympic Games from Tokyo
- Meanwhile in 1961,US President defined U.S policy in regard to satellite communications and showed interest to develop a single worldwide system.
- ITU was asked to examine aspects of space communication for which international co-operation is required.
- As a result commercial investment started in an international satellite organization called Intelsat (International Satellite Organization) by 12 interested countries. By 2000, Intelsat had 143 member countries

History of Intelsat Satellites



Designation: Intelsat	I	II	III	IV	IV A	V	V A/V B	VI
Year of first launch	1965	1966	1968	1971	1975	1980	1984/85	1986/87
Prime contractor	Hughes	Hughes	TRW	Hughes	Hughes	Ford Aerospace	Ford Aerospace	Hughes
Width (m)	0.7	1.4	1.4	2.4	2.4	2.0	2.0	3.6
Height (m)	0.6	0.7	1.0	5.3	6.8	6.4	6.4	6.4
Launch vehicles		Thor Delta		Atlas-Centaur		Atlas-Centaur and Ariane	Atlas-Centaur and Ariane	STS and Ariane
Spacecraft mass in transfer orbit (kg)	68	182	293	1385	1489	1946	2140	12,100/3720
Communications payload mass (kg)	13	36	56	185	190	235	280	800
End-of-life (EOL) power of equinox (W)	40	75	134	480	800	1270	1270	2200
Design lifetime (years)	1.5	3	5	7	7	7	7	10
Capacity (number of voice channels)	480	480	2400	8000	12,000	25,000	30,000	80,000
Bandwidth (MHz)	50	130	300	500	800	2137	2480	3520

Basics

Satellites in circular orbits

- attractive force $F_g = m g (R/r)^2$
- centrifugal force $F_c = m r \omega^2$
- m : mass of the satellite
- R : radius of the earth ($R = 6370$ km)
- r : distance to the center of the earth
- g : acceleration of gravity ($g = 9.81$ m/s²)
- ω : angular velocity ($\omega = 2 \pi f$, f : rotation frequency)

Stable orbit

- $F_g = F_c$

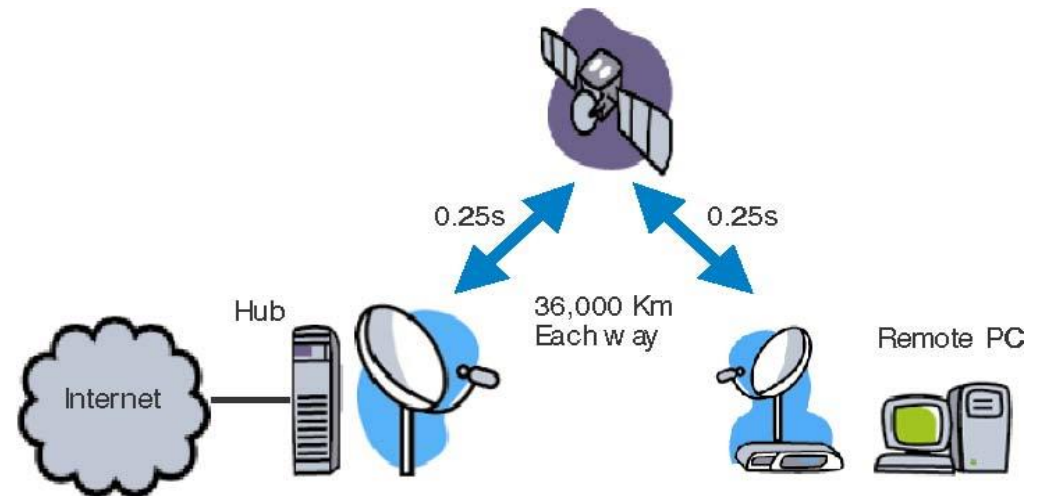
$$r = \sqrt[3]{\frac{gR^2}{(2\pi f)^2}}$$

Advantages of Satellites

- The advantages of satellite communication over terrestrial communication are:
 - The coverage area of a satellite greatly exceeds that of a terrestrial system.
 - Transmission cost of a satellite is independent of the distance from the center of the coverage area.
 - Satellite to Satellite communication is very precise.
 - Higher Bandwidths are available for use.

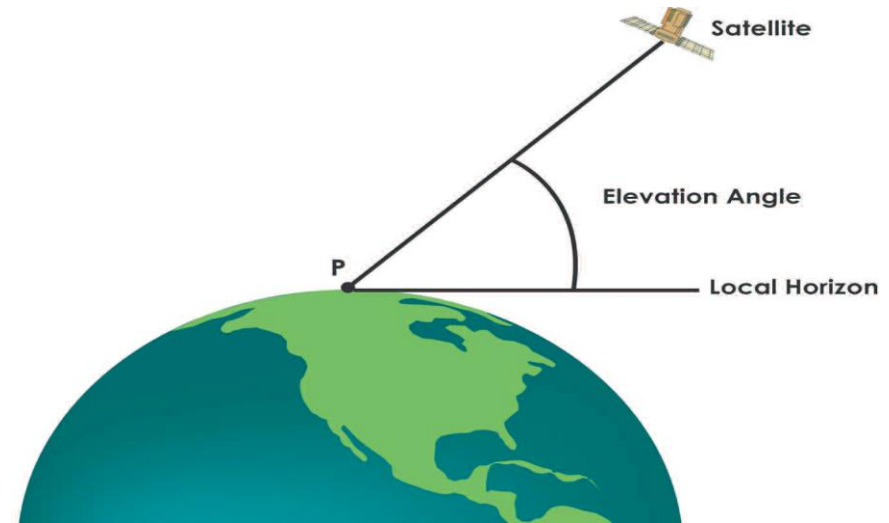
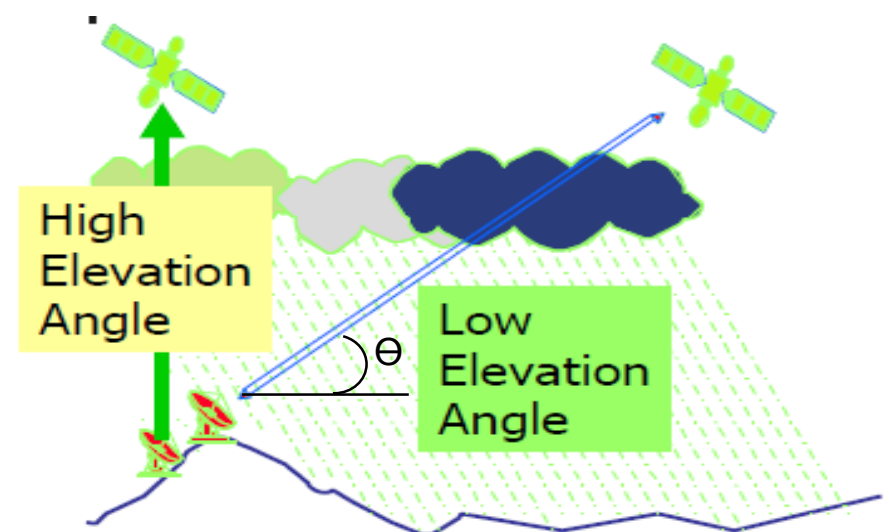
Disadvantages of Satellites

- The disadvantages of satellite communication:
 - Launching satellites into orbit is costly.
 - Satellite bandwidth is gradually becoming used up.
 - There is a larger propagation delay in satellite communication than in terrestrial communication.



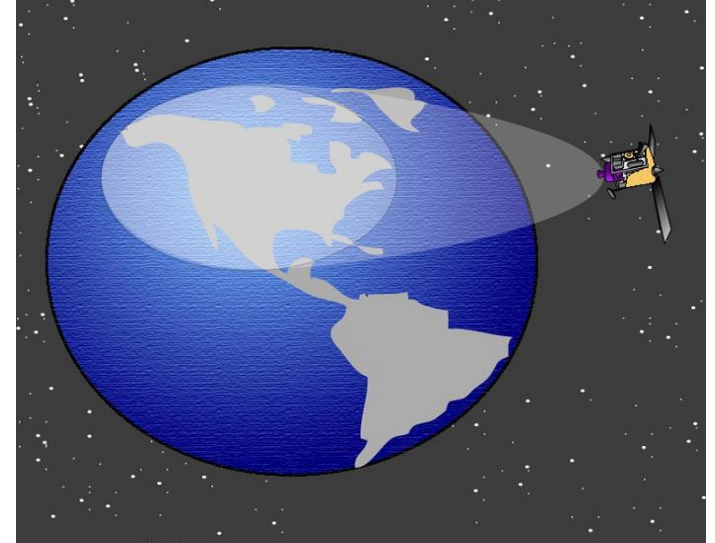
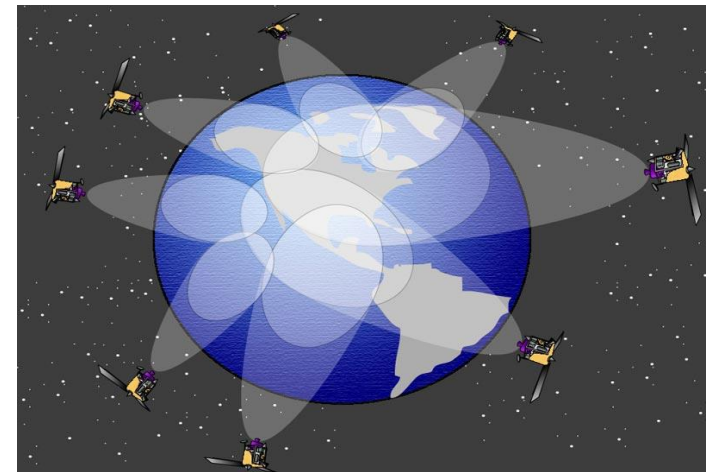
Factors in satellite communication

- Elevation Angle: The angle of the horizontal of the earth surface to the center line of the satellite transmission beam.
 - This effects the satellites coverage area. Ideally, you want an elevation angle of 0 degrees, so the transmission beam reaches the horizon visible to the satellite in all directions.
 - However, because of environmental factors like objects blocking the transmission, atmospheric attenuation, and the earth electrical background noise, there is a minimum elevation angle of earth stations.

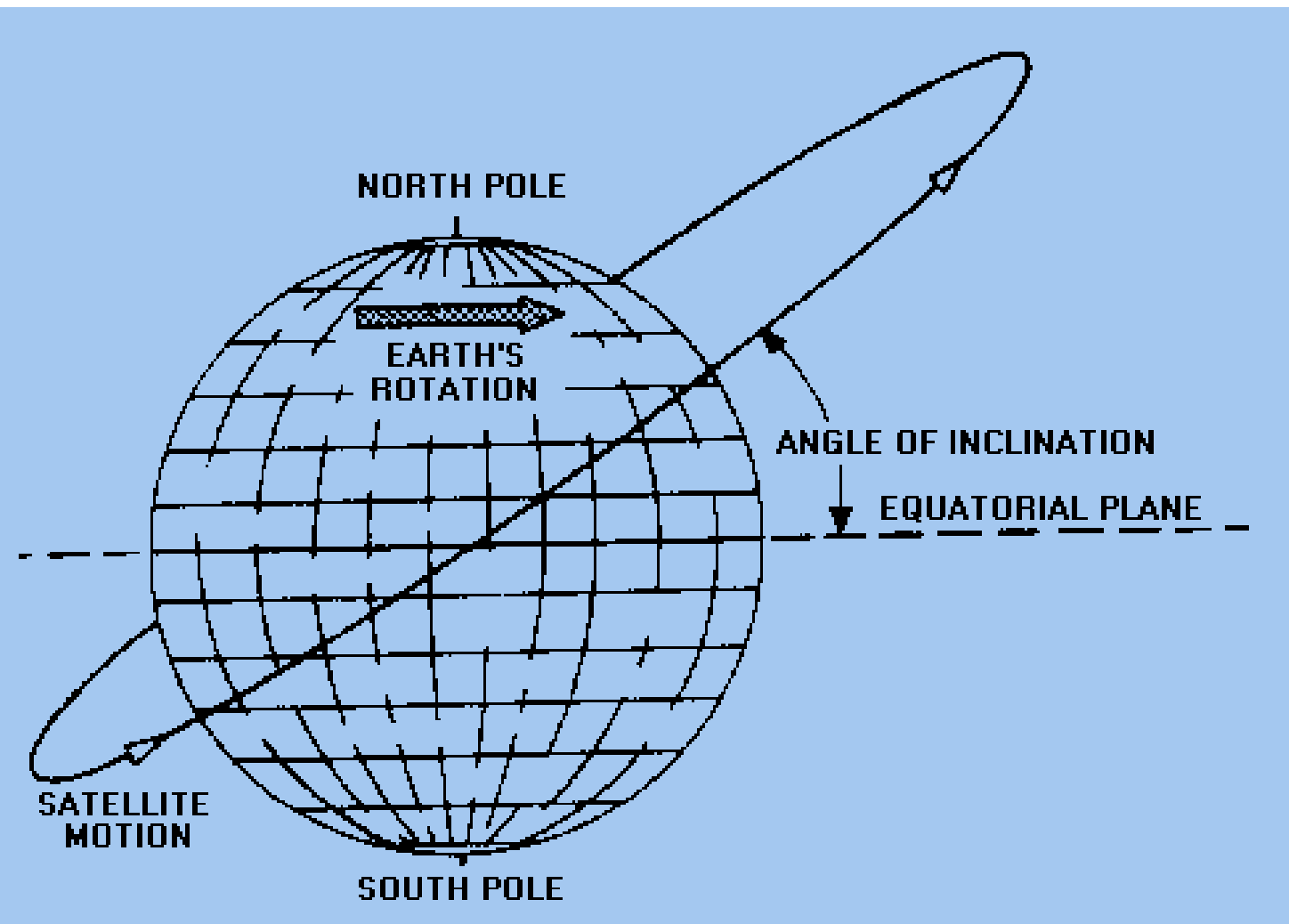


Factors in satellite communication (cont.)

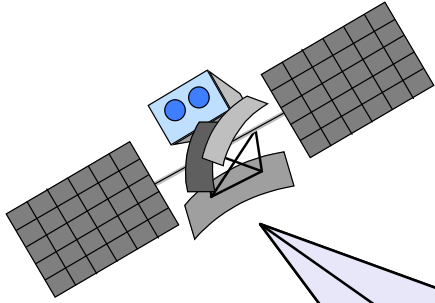
- Other impairments to satellite communication:
 - The distance between an earth station and a satellite (free space loss).
 - Satellite Footprint: The satellite transmission's strength is strongest in the center of the transmission, and decreases farther from the center as free space loss increases.
 - Atmospheric Attenuation caused by air and water can impair the transmission. It is particularly bad during rain and fog.



Footprint of Satellite



Elevation

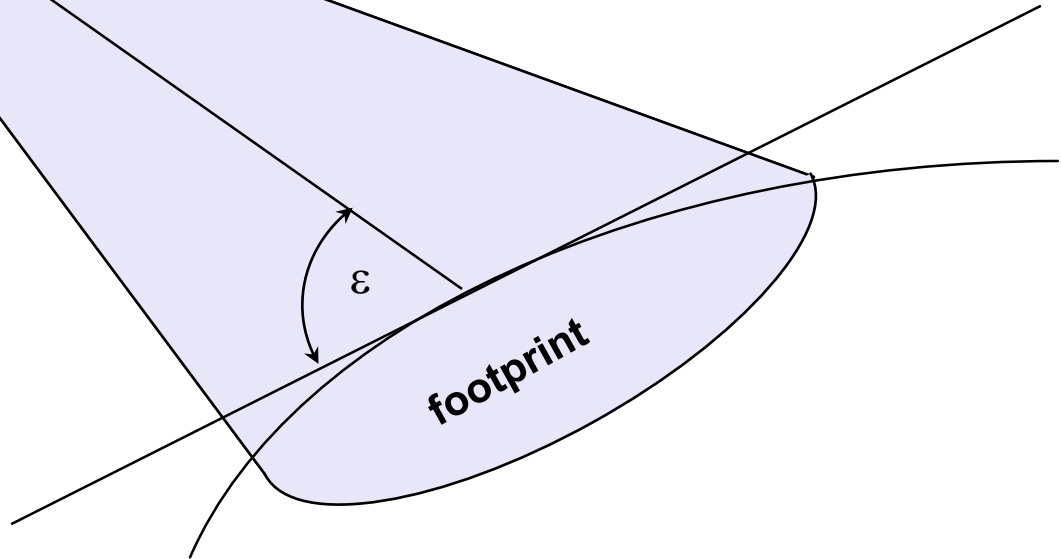


Elevation:

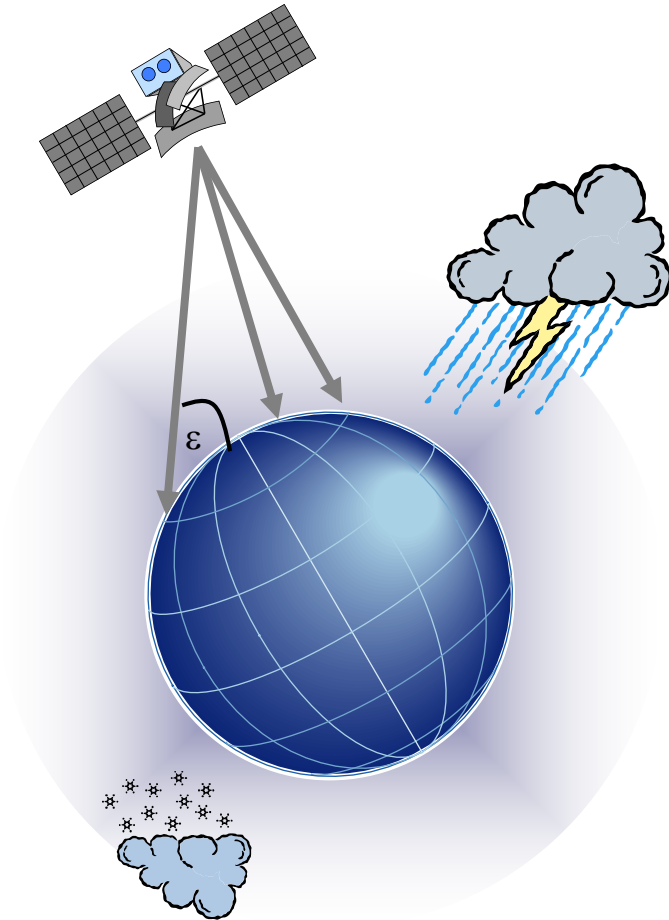
angle ε between center of satellite beam
and surface

minimal elevation:

elevation needed at least
to communicate with the satellite

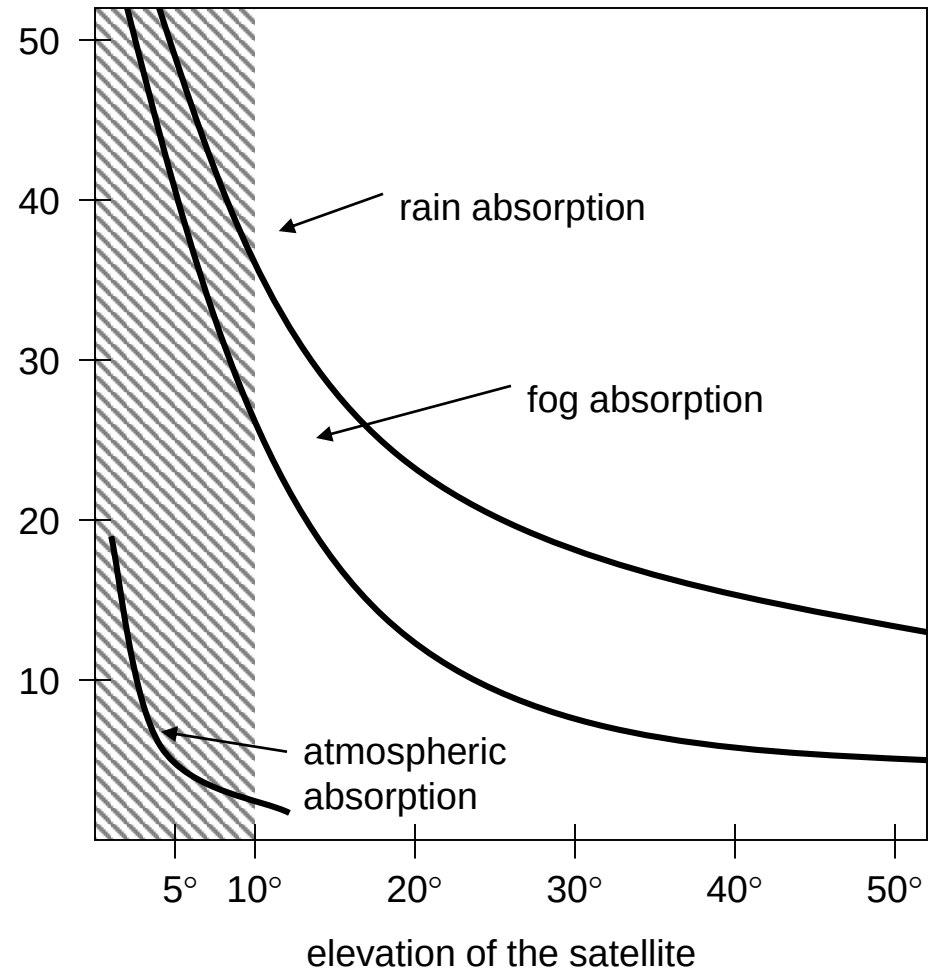


Atmospheric attenuation



Attenuation of
the signal in %

Example: satellite systems at 4-6 GHz



How Satellites are used

- Service Types
 - Fixed Service Satellites (FSS)
 - Example: Point to Point Communication
 - Broadcast Service Satellites (BSS)
 - Example: Satellite Television/Radio
 - Also called Direct Broadcast Service (DBS).
 - Mobile Service Satellites (MSS)
 - Example: Satellite Phones

Passive and Active Satellites

- Passive Satellite

- Simplest type of satellite is a *passive reflector*
- It simply “bounces” signals from one place to another.
- It reflects signals back to earth as there are no gain devices on board to amplify or modify the signals
- Moon became the first passive satellite in 1954 when the U.S Navy successfully transmitted the first message over an Earth-to-moon-to-Earth communication system.
- But moon proved to be unreliable communication satellite as it is above the horizon only half of the time and its position relative to earth is constantly changing.

Passive and Active Satellites

- Advantage of Passive Satellite

- No sophisticated electronic equipment on board.
- Radio beacon transmitters are required for tracking and ranging purposes.
- A beacon is a continuously transmitted un-modulated carrier that an earth station can lock on to and use to determine the exact location of a satellite so the earth station can align its antennas.

- Disadvantage of Passive Satellite

- Inefficient use of transmitted power
- As little as 1 part in every 10^{18} of an earth station's transmitted power is actually returned to earth station receiving antennas

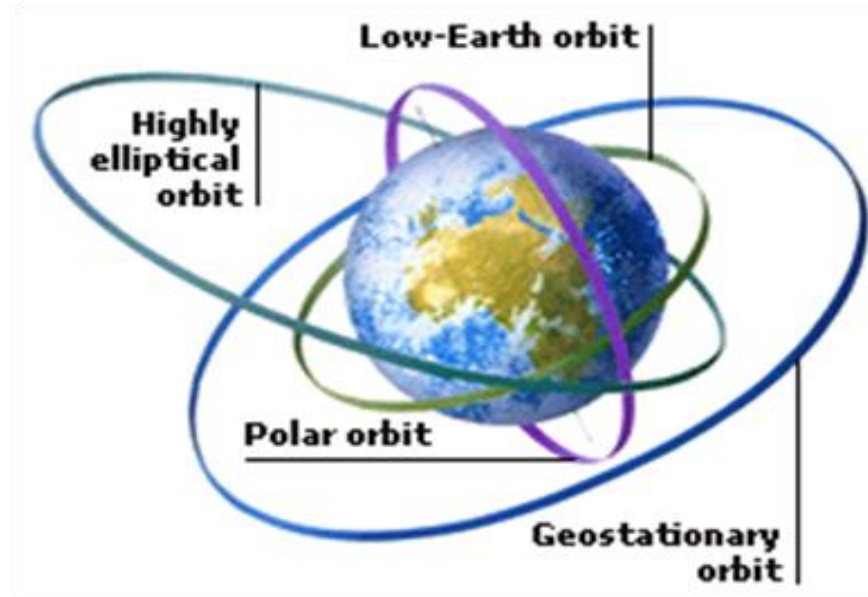
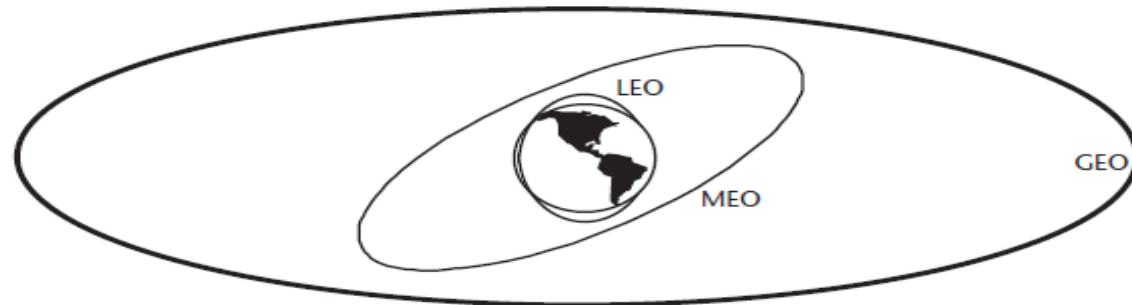
Passive and Active Satellites

- Active Satellite

- It is capable of receiving, amplifying, reshaping, regenerating and retransmitting the information
- Has sophisticated electronic equipment on-board.

Types of Satellites

- Satellite Orbits
 - GEO
 - LEO
 - MEO



GEO (GEOSTATIONARY ORBIT)

- In the equatorial plane
- Orbital Period = 23 h 56 min. 4.091 s
= one ***Sidereal Day*** (defined as one complete rotation relative to the fixed stars)
- Satellite appears to be **stationary** over a point on the equator to an observer
- Radius of orbit, r , = 42,164.57 km

NOTE: Radius = orbital height + radius of the earth

Average radius of earth = 6,378.14 km

Characteristic of Communication Satellite on the GEO

- Synchronize to the earth's rotation period.
 - $T=23\text{h } 56\text{min } 4.091\text{s}$
- Orbit altitude
 - $H=36,000\text{km}$
- One satellite can cover 40% of the earth
 - All the surface of the earth can be covered by three satellites.
- Fixed propagation delay
 - $D=250\text{msec}\sim 270\text{ms}$

Current GEO Satellite Applications

- **Broadcasting** - mainly TV at present
 - DirecTV, PrimeStar, etc.
- **Point to Multi-point** communications
 - VSAT, Video distribution for Cable TV
- **Mobile Services**
 - Motient (former American Mobile Satellite), INMARSAT, etc.

GEO (cont.)

- Advantages
 - A GEO satellite's distance from earth gives it a large coverage area, almost a fourth of the earth's surface.
 - GEO satellites have a 24 hour view of a particular area.
 - These factors make it ideal for satellite broadcast and other multipoint applications.

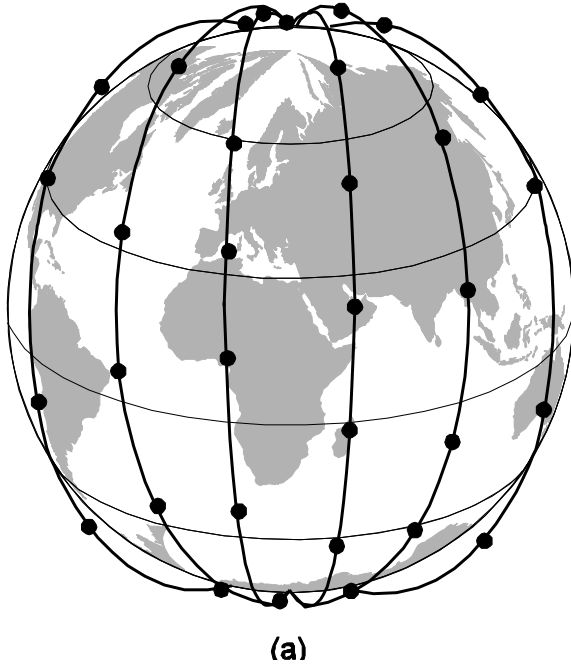
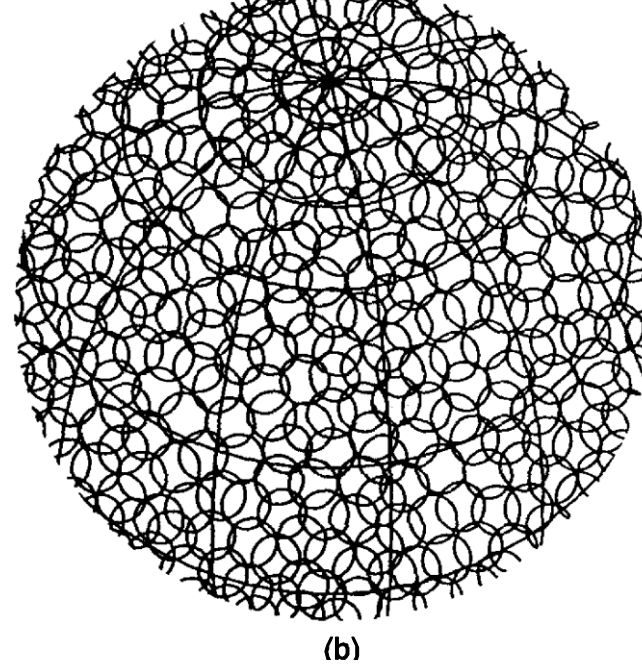
GEO (cont.)

- Disadvantages
 - A GEO satellite's distance also cause it to have both a comparatively weak signal and a time delay in the signal, which is bad for point to point communication.
 - GEO satellites, centered above the equator, have difficulty broadcasting signals to near polar regions

LEO Satellites in year 2000

- Several new systems are just starting service
 - Circular or inclined orbit with < 1400 km altitude
 - Satellite travels across sky from horizon to horizon in 5 - 15 minutes
 - Earth stations must track satellite or have omni-directional antennas
 - Constellation of satellites is needed for continuous communication.
 - Handoff needed.

LEO (Low-Earth Orbit) Satellites Iridium



- (a) The Iridium satellites from six necklaces around the earth.
- (b) 1628 moving cells cover the earth.

LEO (cont.)

- Advantages
 - A LEO satellite's proximity to earth compared to a GEO satellite gives it a better signal strength and less of a time delay, which makes it better for point to point communication.
 - A LEO satellite's smaller area of coverage is less of a waste of bandwidth.

LEO (cont.)

- Disadvantages
 - A network of LEO satellites is needed, which can be costly
 - LEO satellites have to compensate for Doppler shifts caused by their relative movement.
 - Atmospheric drag affects LEO satellites, causing gradual orbital deterioration.

Medium Earth Orbit (MEO)

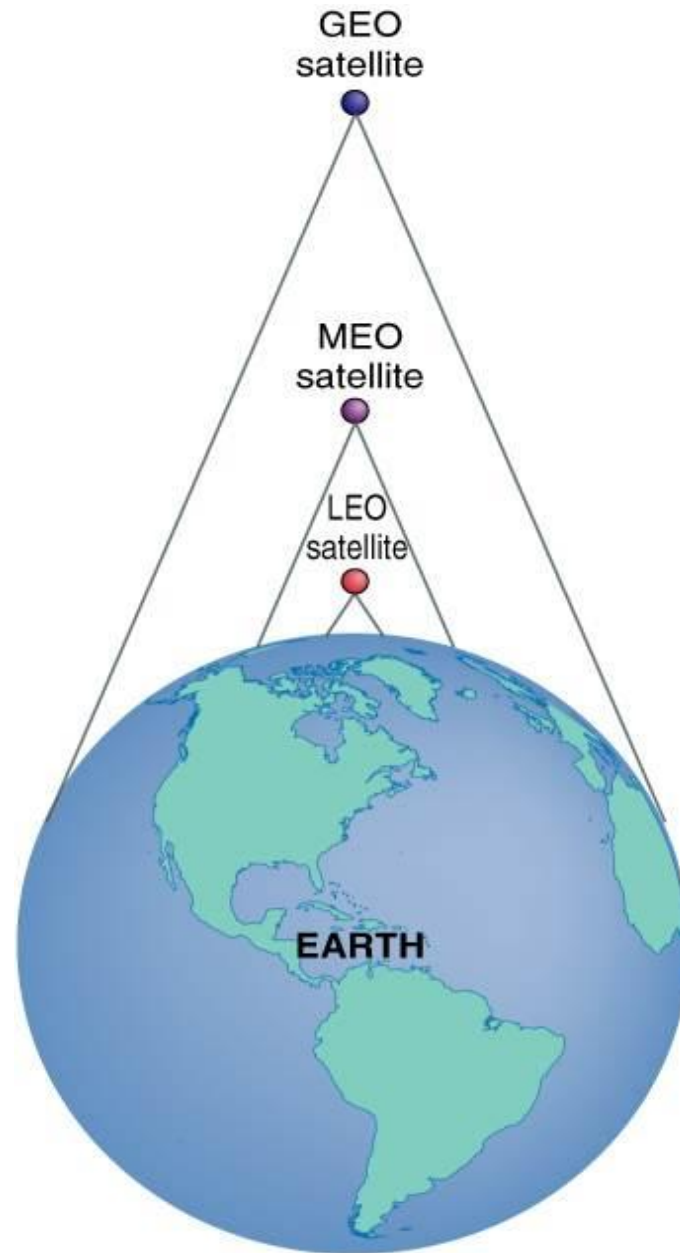
- A MEO satellite is in orbit somewhere between 8,000 km and 18,000 km above the earth's surface.
- MEO satellites are similar to LEO satellites in functionality.
- MEO satellites are visible for much longer periods of time than LEO satellites, usually between 2 to 8 hours.
- MEO satellites have a larger coverage area than LEO satellites.

MEO (cont.)

- Advantage
 - A MEO satellite's longer duration of visibility and wider footprint means fewer satellites are needed in a MEO network than a LEO network.
- Disadvantage
 - A MEO satellite's distance gives it a longer time delay and weaker signal than a LEO satellite, though not as bad as a GEO satellite.

Satellite Navigation: GPS by MEO Satellite System

- **GPS** is a medium earth orbit (MEO) satellite system
 - GPS satellites broadcast pulse trains with very accurate time signals
 - A receiver able to “see” four GPS satellites can calculate its position within 30 m anywhere in world
- “You never need be lost again”
 - Every automobile and cellular phone will eventually have a GPS location read-out



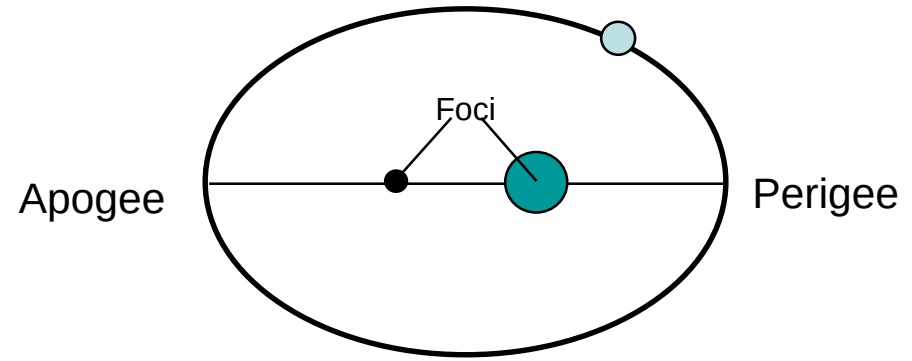
Lecture-12-

Kepler's Laws

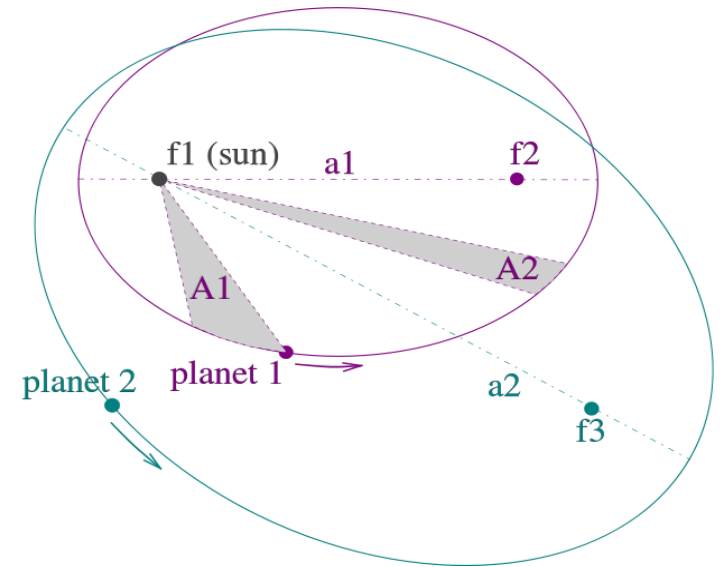
Kepler's laws

- First Law: Planets orbit the sun in ellipses with the sun at one focus.
- Second Law: Each planet moves in so that an imaginary line drawn from the sun to any planet sweeps out equal areas of space in equal intervals of time.
- Third Law: The square of the orbital period (T) of a planet is directly proportional to the cube of the average distance of the planet from the sun (r), or alternatively:

$$\frac{r^3}{T^2} = k$$



First Kepler's laws



Second Kepler's laws

Physics for Satellite Orbit

When a body moving in a circle, from Newton's 2nd law there must be a force acting on it to cause the acceleration. This force will also be directed toward the centre and is called the centripetal force.

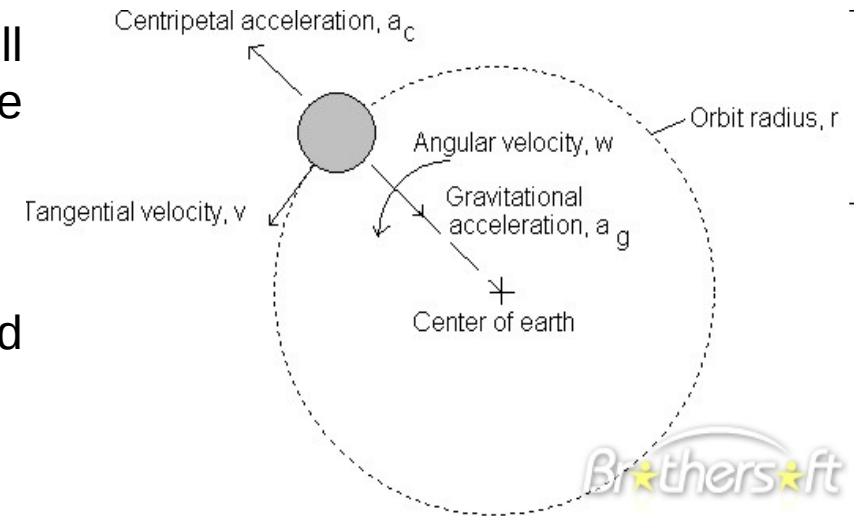
$$F_1 = mac = mv^2/r = mr\omega^2$$

Where m is the mass of the body and v is the speed in the circular path of radius r .

Newton's 2nd law

$$F_2 = ma_g, a_g = GM/r^2$$

$$F = \frac{GMm}{r^2}, \omega = 2\pi/T$$



Period of orbit

Period of orbit

$$T^2 = \frac{4\pi^2}{GM_e} r^3$$

Gravitational constant **Mass of the Earth** **Radius of the orbit**

- Valid only for circular orbits (but a good approximation for most satellites).
- Radius is measured from the center of the Earth (satellite altitude+Earth's radius).
- Accurate periods of elliptical orbits can be determined with Kepler's Equation.
- We can find the tangential velocity of a planet or satellite where m is orbiting M.

Set:

$$\begin{array}{lcl} \text{Centripetal Force} & = & \text{Force of Gravity} \\ F = \frac{mv^2}{r} & = & \frac{GmM}{r^2} \end{array}$$

Solve for v:

$$v = \sqrt{\frac{GM}{r}}$$

Example: A satellite is placed into a circular orbit 1000 km above the surface of the earth ($r = 1000 \text{ km} + 6400 \text{ km} = 7400 \text{ km}$). Determine:

a) The time period (T) of the satellite.

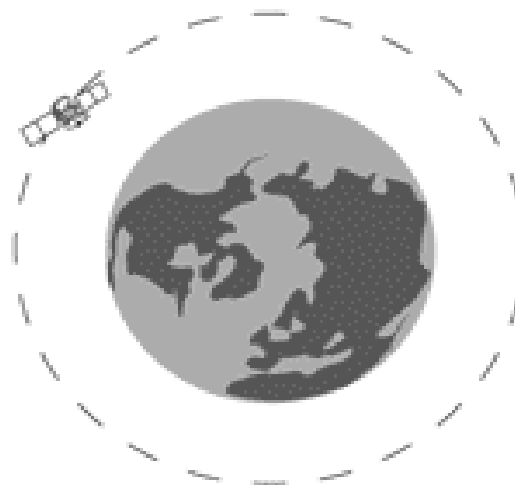
b) The speed (v) of the satellite.

Example: What is the speed of orbit for a satellite orbiting Saturn if the radius of orbit is $6.43 \times 10^7 \text{ m}$?

answer: $2.43 \times 10^4 \text{ m/s}$

Question:

Which of the following factors must one take into account when determining the necessary orbital speed for a satellite in circular orbit around the earth (discounting any friction forces in the orbit path)?



- a. both satellite mass and height of orbit
- b. only satellite mass
- c. only radius of orbit
- d. orbit radius is the same for all satellites orbiting the earth

Example: An artificial satellite in orbit around the Earth has a speed of 7.6×10^3 m/s. How far above the Earth's surface is the satellite orbiting?

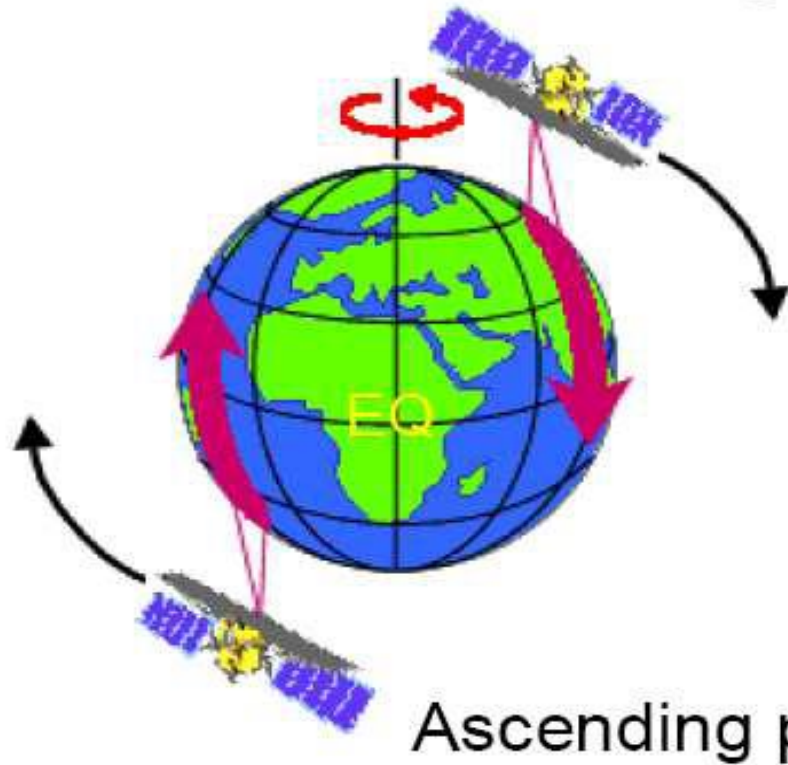
Answer: 5.3×10^5 m

Example: The average distance from the centre of the Earth to the centre of the Moon is 3.85×10^8 m? What is the period of orbit of the Moon around the Earth?

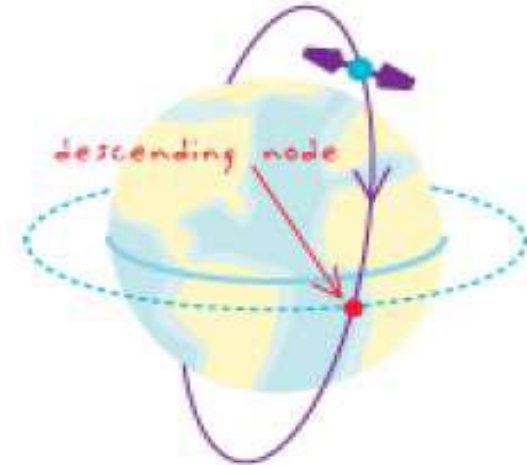
Answer: 27.5 days

Ascending and Descending

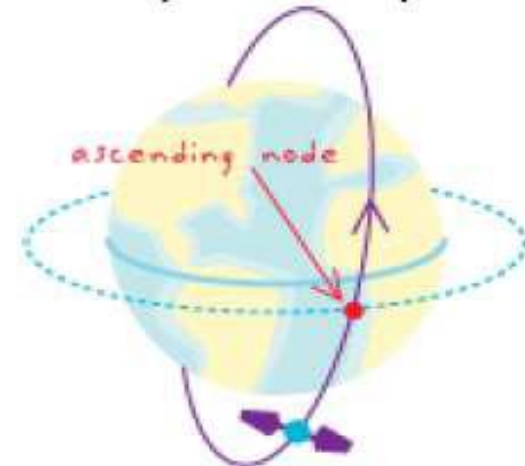
Descending pass



Ascending pass



Node = point that satellite crosses equatorial plane.



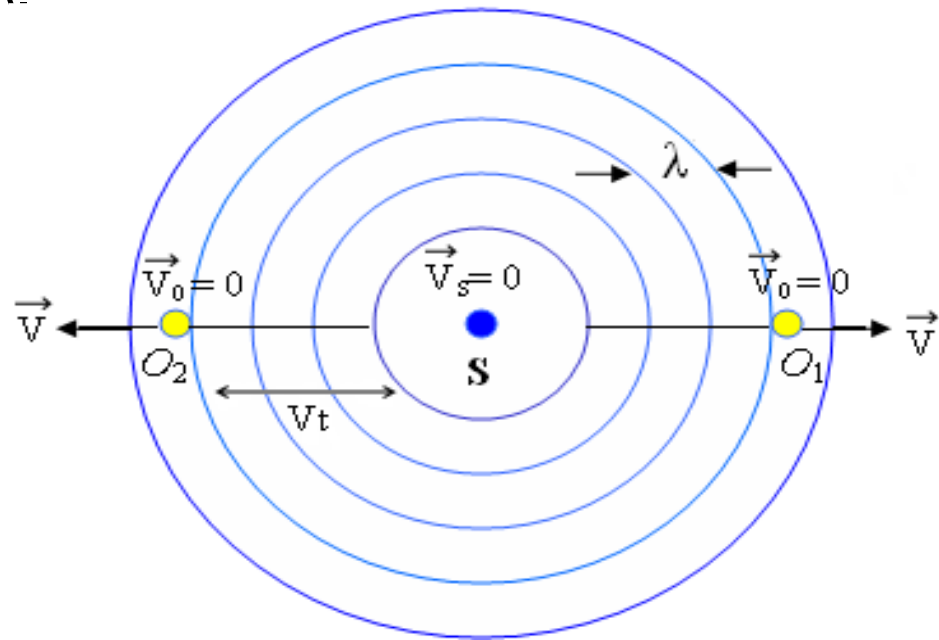
Lecture-13-

Doppler Effect

- One might wonder why the siren on a moving ambulance seems to produce sound with a higher pitch when it passes an observer and decreases when it recede the observer.
- Is this simply because of the relative distance between the observer and the ambulance (sound)?
- Or is it because of the loudness of the sound produced by the siren?
- Doppler Effect is the change in the frequency (or wavelength) of any emitted waves, such as a wave of light or sound as the source of the wave approaches or moves away from an observer.
- This effect was named from the Austrian physicist, Christian Johann Doppler, who first stated the physical principle in 1842.
- Doppler's principle explains why, if the source of waves and the observer are approaching each other, the sound heard by the observer becomes higher in pitch, whereas if the source and observer are moving apart the pitch becomes lower.
- For the sound waves to propagate it requires a medium such as air, where it serves as a frame of reference with respect to which motion of source and observer are measured.

Situation 1: Stationary Source And Observers (No doppler effect)

- A stationary sound source S emits a spherical wavefronts of one λ apart spread out at speed v relative to the medium air.
- In time t , the wavefronts move a distance vt toward the observers, O_1 & O_2 .
- The number of wavelengths detected by the observer in front and behind the source are the same and equal to vt/λ .



Figure(1)

Thus, the frequency f heard by both stationary observers is given by,

$$f = \frac{vt/\lambda}{t} = \frac{v}{\lambda} \quad (1)$$

f - frequency of sound source

v - speed of sound waves

t - time

λ - wavelength

What if both of the observers in figure 1 are moving, is there any change in the frequency and wavelength of the source?

Situation 2: Stationary Source; Moving Observers

- Observer 1 moves a distance $v_o t$ toward the source at speed v_o
- We had known earlier that wavefronts also move at speed v towards O_1 in time t at distance vt . The distance traveled by the wavefronts with respect to O_1 becomes $vt + v_o t$.
- The number of wavelengths intercepted by O_1 at this distance is $(vt + v_o t) / \lambda$.

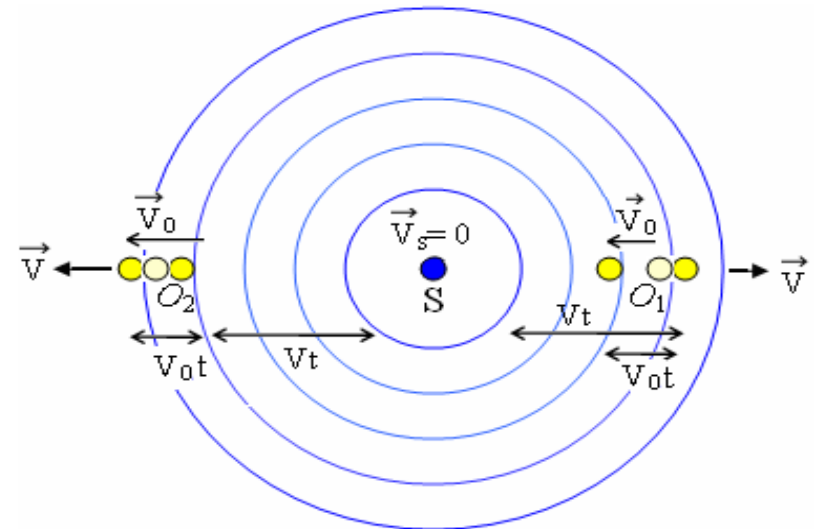


Figure (2)

This shows that there is an increase in the frequency f' heard by O_1 as it goes nearer to the sound source as given by,

$$f' = \frac{(vt + v_0 t)/\lambda}{t} = \frac{v + v_0}{\lambda} \quad (2)$$

From equation (1), we have $\lambda = v/f$, f' becomes:

$$f' = f \left(\frac{v + v_0}{v} \right) \quad (3)$$

- If observer 2 moves away from the sound source, the distance traveled by the wavefronts with respect to O_2 in time t , is $vt - v_o t$.
- Consequently, there would be a decrease in the frequency heard by O_2 as given by:

$$f' = f \left(\frac{v - v_o}{v} \right) \quad (4)$$

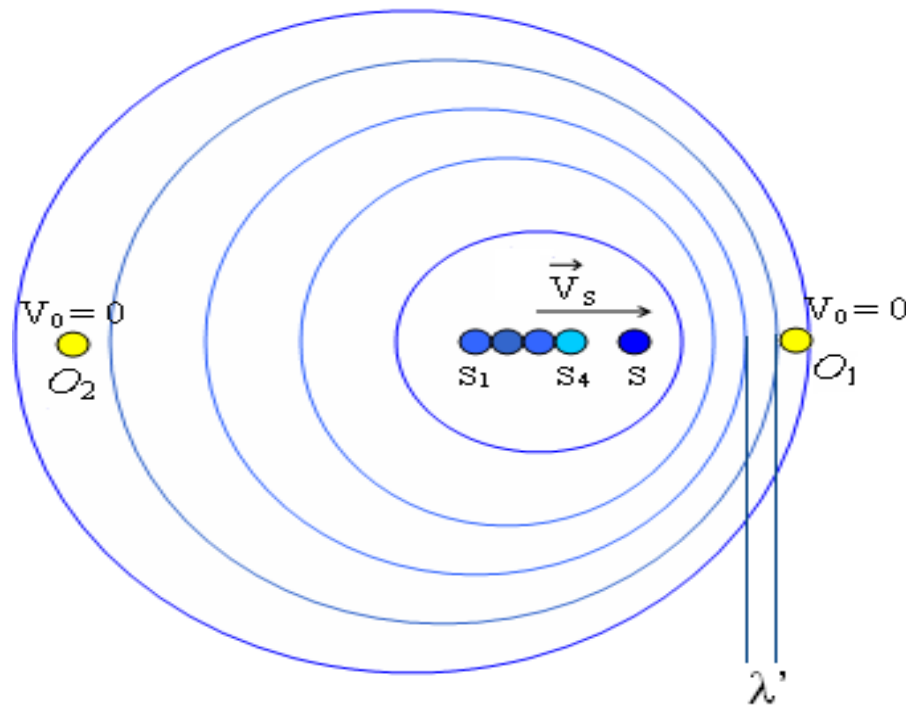
Combining Equations (3) and (4), we have

$$f' = f \left(\frac{v \pm v_o}{v} \right) \quad (5)$$

(STATIONARY SOURCE; MOVING OBSERVER)

- In these situations only the frequency heard by the observers changes due to their motion relative to the source.
- However the wavelength of sound remains constant.

Situation 3: Moving Source; Stationary Observers



- As the source moves a distance $v_s T$ ($T = 1/f$ period of wave) toward O_1 there is a decrease in the wavelength of sound by a quantity of $v_s T$.
- The shortened wavelength λ' becomes:

$$\lambda' = \lambda - v_s T$$

The frequency f' of sound wave heard by O_1 increases as given by:

$$f' = \frac{v}{\lambda'} = \frac{v}{\lambda - v_s T}$$

$$= \frac{v}{v/f - v_s f}$$

$$f' = f \left(\frac{v}{v - v_s} \right) \quad (6)$$

- With respect to observer 2, the wavelength of sound increases, where λ' becomes:

$$\lambda + v_s T$$

- The frequency f' of sound wave heard by O_2 decreases as given by:

$$f' = f \left(\frac{v}{v + v_s} \right) \quad (7)$$

Combining Equations (6) and (7), we have:

$$f' = f \left(\frac{v}{v \pm v_s} \right) \quad (8)$$

(MOVING SOURCE; STATIONARY OBSERVER)

SITUATION 4: Moving Source and Observer

From the equations (5) and (8), we can now derive the equation of general Doppler Effect by replacing f in equation (5) with f' of equation (8). This result to,

$$f' = f \left(\frac{v \pm v_o}{v \pm v_s} \right) \quad (9)$$

(MOVING SOURCE AND OBSERVER)

$$f' = f \left(\frac{v \pm v_0}{v \pm v_s} \right) \quad (9)$$

The $\pm$ signs correspond to the direction of the source or observer when they are moving relative to the other. These would determine whether there is an increase or decrease on the frequency heard by the observer during the motion.

$$f' = f \left(\frac{v + v_0}{v + v_s} \right)$$

(APPROACHING OBSERVER; RECEDING SOURCE)

- If $v_0 > v_s$, increase in observed frequency
- If $v_0 < v_s$, decrease in observed frequency

$$f' = f \left(\frac{v - v_0}{v + v_s} \right)$$

(RECEEDING OBSERVER; RECEDING SOURCE)

- Decrease in observed frequency

$$f' = f \left(\frac{v + v_o}{v - v_s} \right)$$

(APPROACHING OBSERVER; APPROACHING SOURCE)

- Increase in observed frequency

$$f' = f \left(\frac{v - v_o}{v - v_s} \right)$$

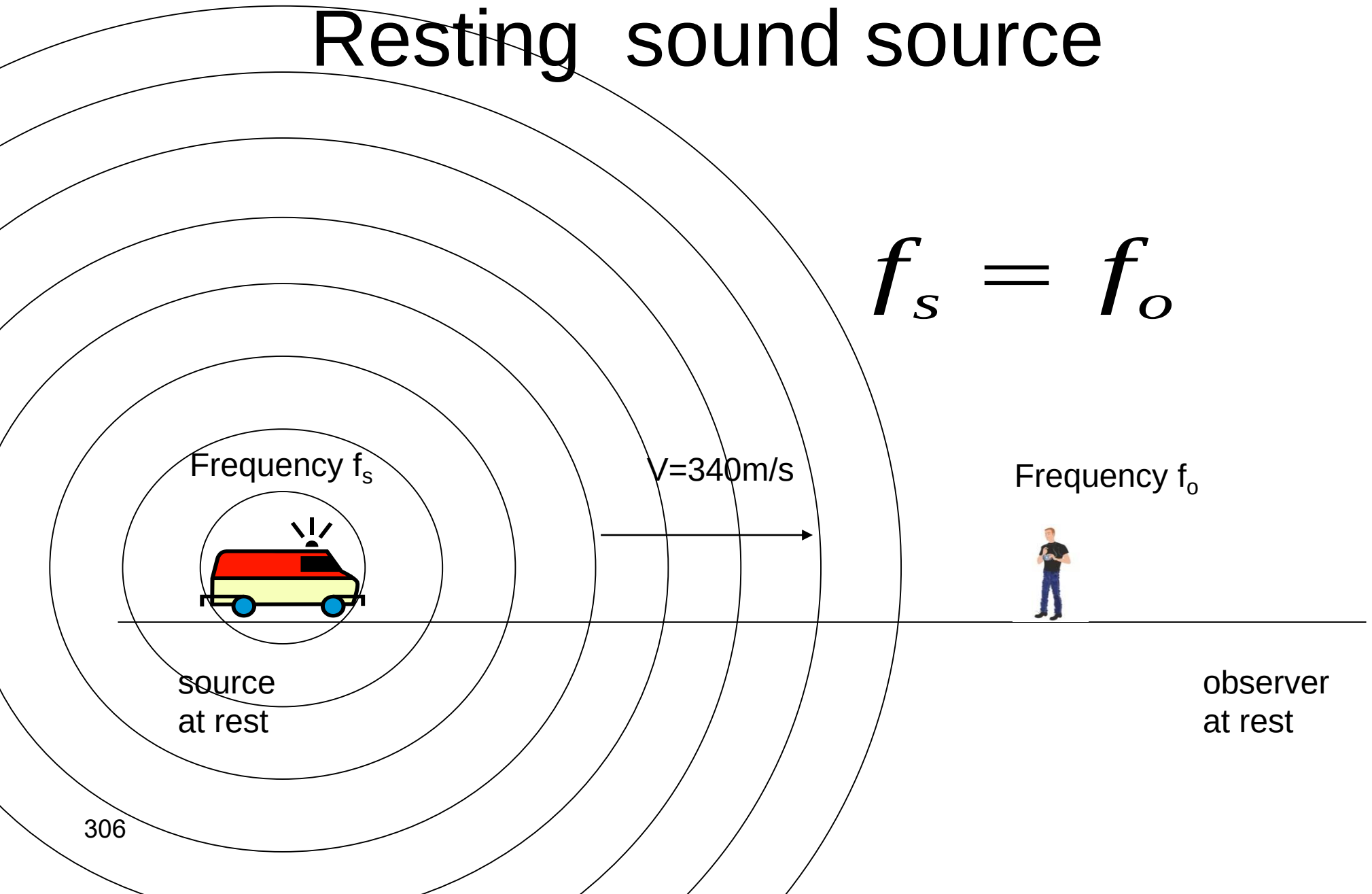
(RECEDING OBSERVER; APPROACHING SOURCE)

- If $v_o > v_s$, decrease in observed frequency

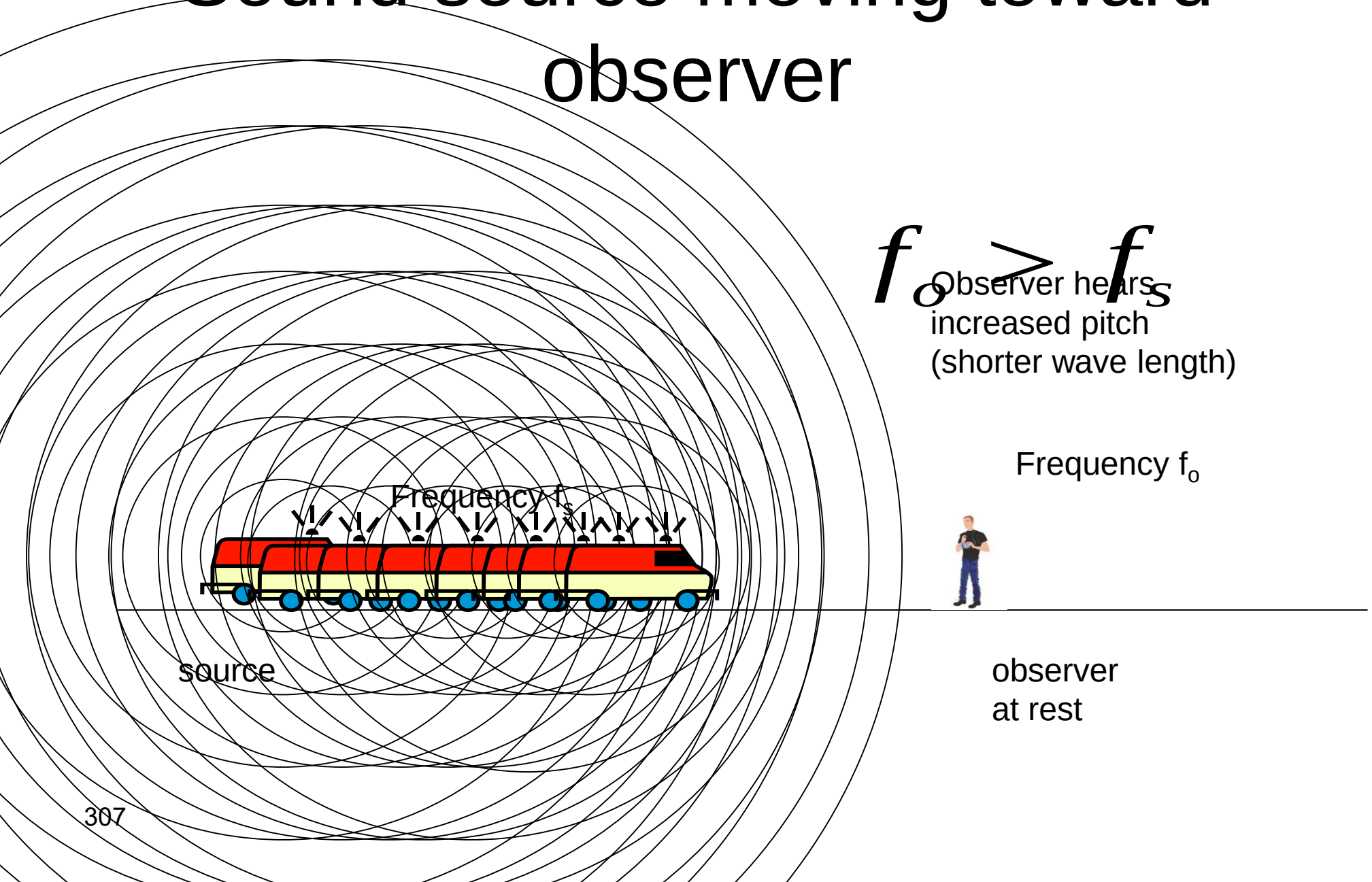
If $v_o < v_s$, increase in observed frequency

Resting sound source

$$f_s = f_o$$



Sound source moving toward observer



$f_o > f_s$
Observer hears
increased pitch
(shorter wave length)

Frequency f_o



observer
at rest

Sound source moving away from observer

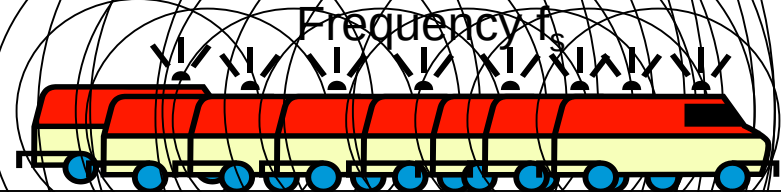
$$f_o < f_s$$

Observer hears
decreased pitch
(longer wave length)

Frequency f_o



observer
at rest



Frequency f_s

source

Frequency heard by observer

**Source moving toward
observer.**

Perceived wavelength: $\lambda_o = \lambda_s - v_s \tau = \lambda_s - \frac{v_s}{f_s}$
With $v = \lambda_s f_s = \lambda_o f_o$

$$\frac{v}{f_o} = \frac{v}{f_s} - \frac{v_s}{f_s}$$

Observer:
$$f_o = \frac{v}{v - v_s} f_s$$

Observed frequency

- Source toward observer:

– Increased frequency $f_o = \frac{v}{v - v_s} f_s$

- Source away from observer:

– Decreased frequency $f_o = \frac{v}{v + v_s} f_s$

Summary

$$f = f_o \frac{(v + v_o)}{(v - v_s)}$$

In order for this equation to work properly, there is a standard convention to which you must adhere whenever solving Doppler exercises.

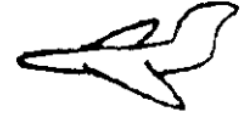
v_o is (+) if the observer moves toward the source.

v_o is (−) if the observer moves away from the source.

v_s is (+) if the source moves toward the observer.

v_s is (−) if the source moves away from the observer.

Example 1: Sitting on the beach at Coney Island one afternoon, Sunny finds herself beneath the flight path of the airplanes leaving Kennedy Airport. What frequency will Sunny hear as a jet, whose engines emit sound at a frequency of 1000. Hz, flies toward her at a speed of 100.0 m/s?



Solution: Notice in the calculation below that Sunny is sitting at rest and the plane is approaching. Therefore, the source is moving toward the observer. The observer remains stationary.

$$\begin{aligned}\text{Given: } f_o &= 1000. \text{ Hz} \\ v_o &= 0 \text{ m/s} \\ v &= 340.0 \text{ m/s} \\ v_s &= 100.0 \text{ m/s}\end{aligned}$$

$$\begin{aligned}\text{Unknown: } f &= ? \\ \text{Original equation: } f &= f_o \frac{(v + v_o)}{(v - v_s)}\end{aligned}$$

$$\text{Solve: } f = f_o \frac{(v + v_o)}{(v - v_s)} = 1000. \text{ Hz} \frac{(340.0 \text{ m/s} + 0 \text{ m/s})}{(340.0 \text{ m/s} - 100.0 \text{ m/s})} = \mathbf{1417 \text{ Hz}}$$

Example 2: In the previous example, what frequency will Sunny observe as the jet travels away from her at the same speed?



Solution: Solution: Again, draw a diagram of the situation. This time, the source is moving away from the observer, so the value for v_s must be negative.



Given: $f_o = 1000. \text{ Hz}$
 $v_o = 0 \text{ m/s}$
 $v = 340.0 \text{ m/s}$
 $v_s = -100.0 \text{ m/s}$

Unknown: $f = ?$
Original equation: $f = f_o \frac{v + v_o}{v - v_s}$

Solve: $f = f_o \frac{(v + v_o)}{(v - v_s)} = 1000. \text{ Hz} \frac{(340.0 \text{ m/s} + 0 \text{ m/s})}{(340.0 \text{ m/s} - [-100.0 \text{ m/s}])} = 772.7 \text{ Hz}$

Example 3: A sparrow chases a crow with a speed of 4.0 m/s, while chirping at a frequency of 850.0 Hz. What frequency of sound does the crow hear as he flies away from the sparrow with a speed of 3.0 m/s?

Solution:

$$\begin{aligned}\text{Given: } f_o &= 850.0 \text{ Hz} \\ v_o &= -3.0 \text{ m/s} \\ v &= 340.0 \text{ m/s} \\ v_s &= 4.0 \text{ m/s}\end{aligned}$$

$$\begin{aligned}\text{Unknown: } f &= ? \\ \text{Original equation: } f &= f_o \frac{(v + v_o)}{(v - v_s)}\end{aligned}$$

$$\text{Solve: } f = f_o \frac{(v + v_o)}{(v - v_s)} = 850.0 \text{ Hz} \frac{(340.0 \text{ m/s} + [-3.0 \text{ m/s}])}{(340.0 \text{ m/s} - 4.0 \text{ m/s})} = 852.5 \text{ Hz}$$

Lecture-14-

Introduction to Antennas

HISTORY

- The first antennas were built in 1888 by German physicist Heinrich Hertz in his pioneering experiments to prove the existence of electromagnetic waves predicted by the theory of James Clerk Maxwell.
- Hertz placed dipole antennas at the focal point of parabolic reflectors for both transmitting and receiving. He published his work in *Annalen der Physik und Chemie* (vol. 36, 1889).

INTRODUCTION

- An antenna is an electrical device which converts electric currents into radio waves, and vice versa. It is usually used with a radio transmitter or radio receiver.
- In transmission, a radio transmitter applies an oscillating radio frequency electric current to the antenna's terminals, and the antenna radiates the energy from the current as electromagnetic waves (radio waves).

- **Transmitting Antenna:** Any structure designed to efficiently radiate electromagnetic radiation in a preferred direction is called a *transmitting antenna*.
- In reception, an antenna intercepts some of the power of an electromagnetic wave in order to produce a tiny voltage at its terminals, that is applied to a receiver to be amplified. An antenna can be used for both transmitting and receiving.
- **Receiving Antenna:** Any structure designed to efficiently receive electromagnetic radiation is called a receiving antenna

BASIC STRUCTURE

- It is a metallic conductor system capable of radiating and receiving em waves.
- Typically an antenna consists of an arrangement of metallic conductors (“elements”), electrically connected (often through a transmission line) to the receiver or transmitter.
- An oscillating current of electrons forced through the antenna by a transmitter will create an oscillating magnetic field around the antenna elements, while the charge of the electrons also creates an oscillating electric field along the elements.
- These time-varying fields radiate away from the antenna into space as a moving electromagnetic field wave.
- Conversely, during reception, the oscillating electric and magnetic fields of an incoming radio wave exert force on the electrons in the antenna elements, causing them to move back and forth, creating oscillating currents in the antenna.
- Antenna reciprocity : can be used as transmitter and receiver. In two way communication same antenna can be used as transmitter and receiver.
- Antennas may also contain reflective or directive elements or surfaces not connected to the transmitter or receiver, such as parasitic elements, parabolic reflectors or horns, which serve to direct the radio waves into a beam or other desired radiation pattern.
- Antennas can be designed to transmit or receive radio waves in all directions equally (omnidirectional antennas), or transmit them in a beam in a particular direction, and receive from that one direction only (directional or high gain antennas).

WHY ANTENNAS ?

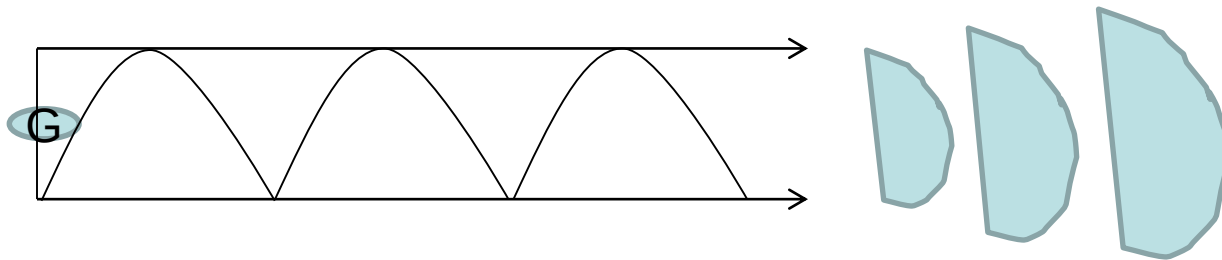
- Need of antenna arisen when two person wanted to communicate between them when separated by some distance and wired communication is not possible.
- Antennas are required by any radio receiver or transmitter to couple its electrical connection to the electromagnetic field.
- Radio waves are electromagnetic waves which carry signals through the air (or through space) at the speed of light with almost no transmission loss.
- Radio transmitters and receivers are used to convey signals (information) in systems including broadcast (audio) radio, television, mobile telephones , point-to-point communications links (telephone, data networks), satellite links.
- Radio waves are also used directly for measurements in technologies including Radar, GPS, and radio astronomy.
- In each and every case, the transmitters and receivers involved require antennas, although these are sometimes hidden (such as the antenna inside an AM radio or inside a laptop computer equipped with wi-fi).

WHERE USED?

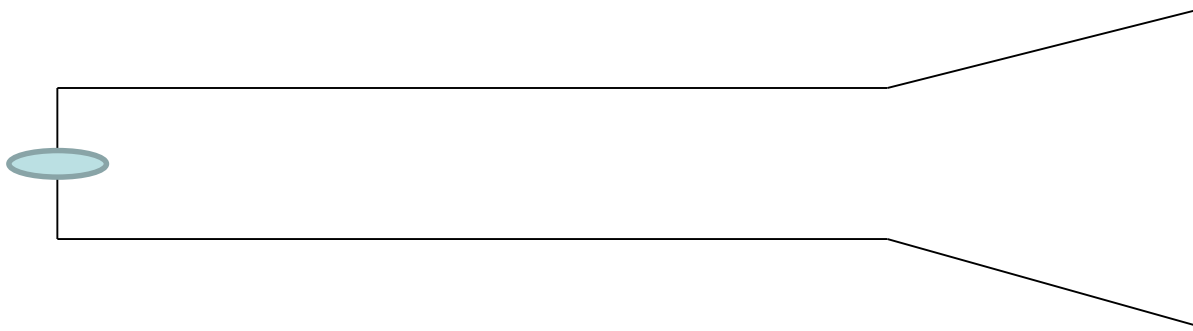
- Antennas are used in systems such as radio and television broadcasting, point to point radio communication, wireless LAN, radar and space exploration
- Antennas are most utilized in air or outer space
- But can also be operated under water or even through soil and rock at certain frequencies for short distances

RADIATION MECHANISM

- Ideally all incident energy must be reflected back when open circuit. But practically a small portion of electromagnetic energy escapes from the system that is it gets radiated.
- This occurs because the line of force don't undergo complete phase reversal and some of them escapes.
- The amount of escaped energy is very small due to mismatch between transmission line and surrounding space.
- Also because two wires are too close to each other, radiation from one tip will cancel radiation from other tip.(as they are of opposite polarities and distance between them is too small as compared to wavelength)



- To increase amount of radiated power open circuit must be enlarged , by spreading the two wires.
- Due to this arrangement, coupling between transmission line and free space is improved.
- Also amount of cancellation has reduced.
- The radiation efficiency will increase further if two conductors of transmission line are bent so as to bring them in same line.

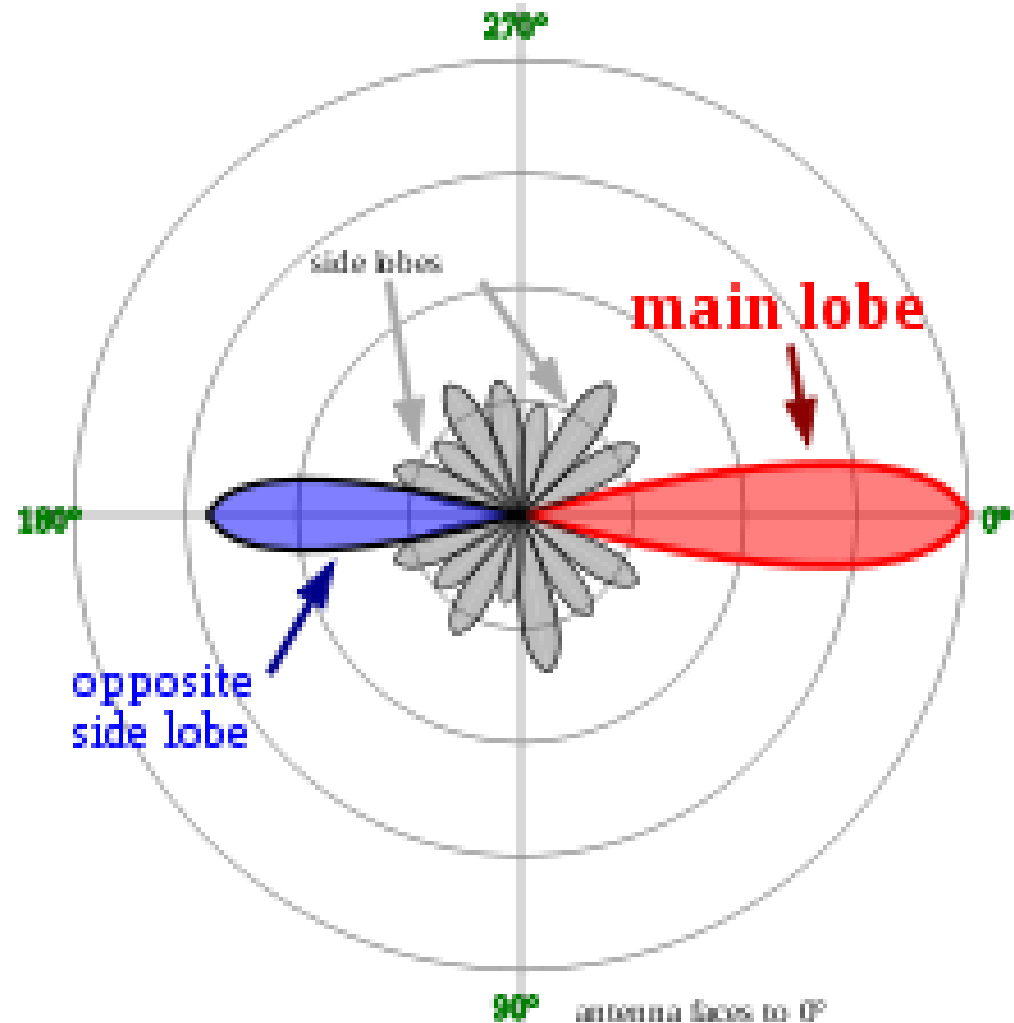


TYPES OF ANTENNAS

- According to their applications and technology available, antennas generally fall in one of two categories:
 1. Omnidirectional or only weakly directional antennas which receive or radiate more or less in all directions. These are employed when the relative position of the other station is unknown or arbitrary. They are also used at lower frequencies where a directional antenna would be too large, or simply to cut costs in applications where a directional antenna isn't required.
 2. Directional or *beam* antennas which are intended to preferentially radiate or receive in a particular direction or directional pattern.

- According to length of transmission lines available, antennas generally fall in one of two categories:
 1. Resonant Antennas – is a transmission line, the length of which is exactly equal to multiples of half wavelength and it is open at both ends.
 2. Non-resonant Antennas – the length of these antennas is not equal to exact multiples of half wavelength. In these antennas standing waves are not present as antennas are terminated in correct impedance which avoid reflections. The waves travel only in forward direction .Non-resonant antenna is a unidirectional antenna.

RADIATION PATTERN



- The radiation pattern of an antenna is a plot of the relative field strength of the radio waves emitted by the antenna at different angles.
- It is typically represented by a three dimensional graph, or polar plots of the horizontal and vertical cross sections. It is a plot of field strength in V/m versus the angle in degrees.
- The pattern of an ideal isotropic antenna , which radiates equally in all directions, would look like a sphere.
- Many non-directional antennas, such as dipoles, emit equal power in all horizontal directions, with the power dropping off at higher and lower angles; this is called an omni directional pattern and when plotted looks like a donut.

- The radiation of many antennas shows a pattern of maxima or "*lobes*" at various angles, separated by "*nulls*", angles where the radiation falls to zero.
- This is because the radio waves emitted by different parts of the antenna typically interfere, causing maxima at angles where the radio waves arrive at distant points in phase, and zero radiation at other angles where the radio waves arrive out of phase.
- In a directional antenna designed to project radio waves in a particular direction, the lobe in that direction is designed larger than the others and is called the "*main lobe*".
- The other lobes usually represent unwanted radiation and are called "*sidelobes*". The axis through the main lobe is called the "*principle axis*" or "*boresight axis*".

ANTENNA GAIN

- Gain is a parameter which measures the degree of directivity of the antenna's radiation pattern. A high-gain antenna will preferentially radiate in a particular direction.
- Specifically, the *antenna gain*, or *power gain* of an antenna is defined as the ratio of the intensity (power per unit surface) radiated by the antenna in the direction of its maximum output, at an arbitrary distance, divided by the intensity radiated at the same distance by a hypothetical isotropic antenna.
- The gain of an antenna is a passive phenomenon - power is not added by the antenna, but simply redistributed to provide more radiated power in a certain direction than would be transmitted by an isotropic antenna.
- High-gain antennas have the advantage of longer range and better signal quality, but must be aimed carefully in a particular direction.
- Low-gain antennas have shorter range, but the orientation of the antenna is relatively inconsequential.

- For example, a dish antenna on a spacecraft is a high-gain device that must be pointed at the planet to be effective, whereas a typical Wi-Fi antenna in a laptop computer is low-gain, and as long as the base station is within range, the antenna can be in any orientation in space.
- In practice, the half-wave dipole is taken as a reference instead of the isotropic radiator. The gain is then given in **dBd** (decibels over **dipole**)

ANTENNA EFFICIENCY

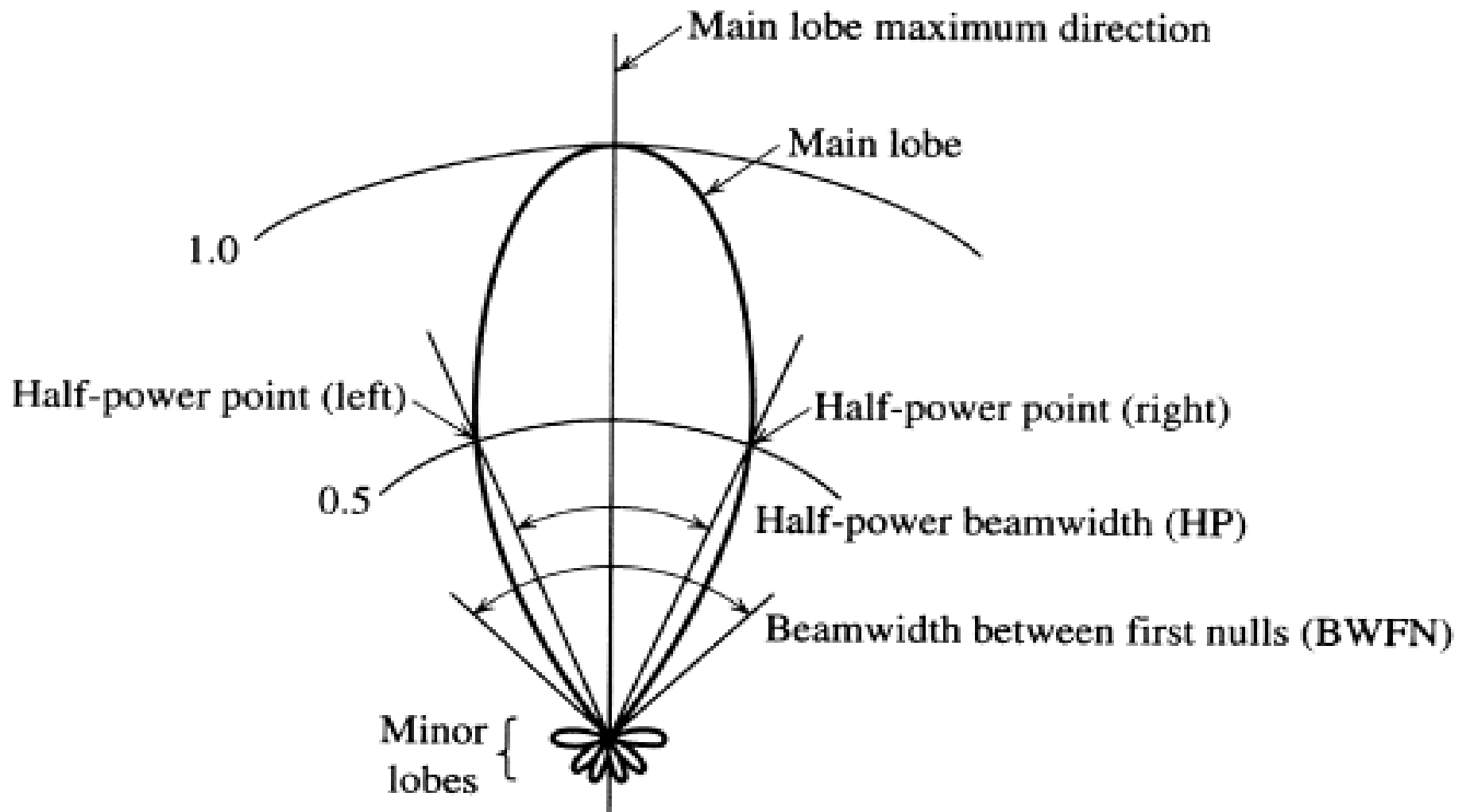
- Efficiency of a transmitting antenna is the ratio of power actually radiated (in all directions) to the power absorbed by the antenna terminals.
- The power supplied to the antenna terminals which is not radiated is converted into heat. This is usually through loss resistance in the antenna's conductors, but can also be due to dielectric or magnetic core losses in antennas (or antenna systems) using such components.

POLARIZATION

- The polarization of an antenna is the orientation of the electric field (E-plane) of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna and by its orientation.
- A simple straight wire antenna will have one polarization when mounted vertically, and a different polarization when mounted horizontally.
- Reflections generally affect polarization. For radio waves the most important reflector is the ionosphere - signals which reflect from it will have their polarization changed
- LF,VLF and MF antennas are vertically polarized

BEAM-WIDTH

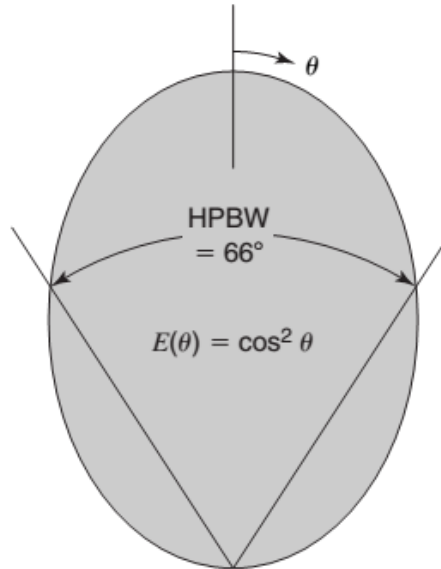
- Beam-width of an antenna is defined as angular separation between the two half power points on power density radiation pattern OR
- Angular separation between two 3dB down points on the field strength of radiation pattern
- It is expressed in degrees



An antenna has a field pattern given by:

$$E(\theta) = \cos^2(\theta) \text{ for } 0^\circ \leq \theta \leq 90^\circ$$

Find the half-power beamwidth (HPBW).



Solution

$E(\theta)$ at half power = 0.707. Thus $0.707 = \cos^2 \theta$ so $\cos \theta = \sqrt{0.707}$ and $\theta = 33^\circ$

$$\text{HPBW} = 2\theta = 66^\circ$$

An antenna has a field pattern given by $E(\theta) = \cos \theta \cos 2\theta$ for $0^\circ \leq \theta \leq 90^\circ$. Find (a) the half-power beamwidth (HPBW) and (b) the beamwidth between first nulls (FNBW).

■ **Solution**

(a) $E(\theta)$ at half power = 0.707. Thus $0.707 = \cos \theta \cos 2\theta = 1/\sqrt{2}$.

$$\cos 2\theta = \frac{1}{\sqrt{2} \cos \theta} \quad 2\theta = \cos^{-1} \left(\frac{1}{\sqrt{2} \cos \theta} \right) \quad \text{and}$$

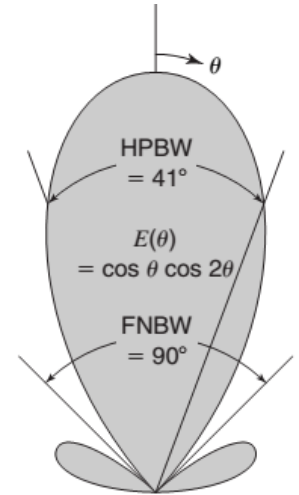
$$\theta = \frac{1}{2} \cos^{-1} \left(\frac{1}{\sqrt{2} \cos \theta'} \right)$$

Iterating with $\theta' = 0$ as a first guess, $\theta = 22.5^\circ$. Setting $\theta' = 22.5^\circ$, $\theta = 20.03^\circ$, etc., until after next iteration $\theta = \theta' = 20.47^\circ \cong 20.5^\circ$ and

$$\text{HPBW} = 2\theta = 41^\circ \quad \text{Ans. (a)}$$

(b) $0 = \cos \theta \cos 2\theta$, so $\theta = 45^\circ$ and

$$\text{FNBW} = 2\theta = 90^\circ \quad \text{Ans. (b)}$$

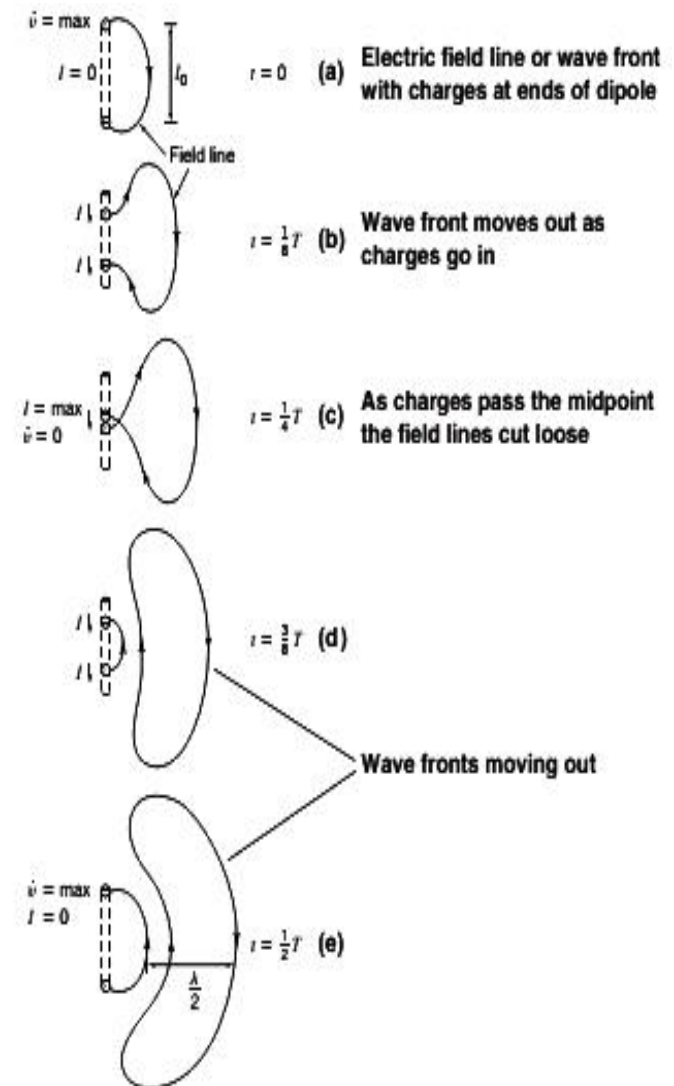


FIELDS FROM OSCILLATING DIPOLE

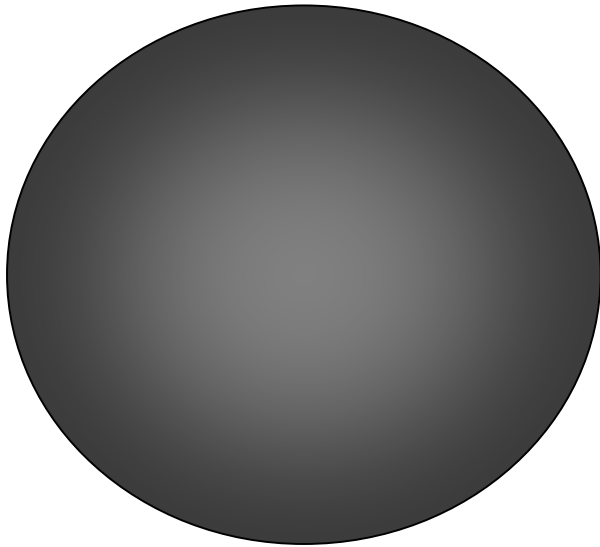
Although a charge moving with uniform velocity along a straight conductor does not radiate, a charge moving back and forth in simple harmonic motion along the conductor is subject to acceleration (and deceleration) and radiates.

To illustrate radiation from a dipole antenna, let us consider that the dipole of figure below has two equal charges of opposite sign oscillating up and down in harmonic motion with instantaneous separation l (maximum separation l_0) while focusing attention on the electric field. For clarity only a single electric field line is shown.

At time $t = 0$ the charges are at maximum separation and undergo maximum acceleration (v') as they reverse direction. At this instant the current (I) is zero. At an $1/8$ -period later, the charges are moving toward each other and at a $1/4$ -period they pass at the midpoint. As this happens, the field lines detach and new ones of opposite sign are formed. At this time the equivalent current (I) is a maximum and the charge acceleration is zero. As time progresses to a $1/2$ -period, the fields continue to move out as in figure *d* and *e*.



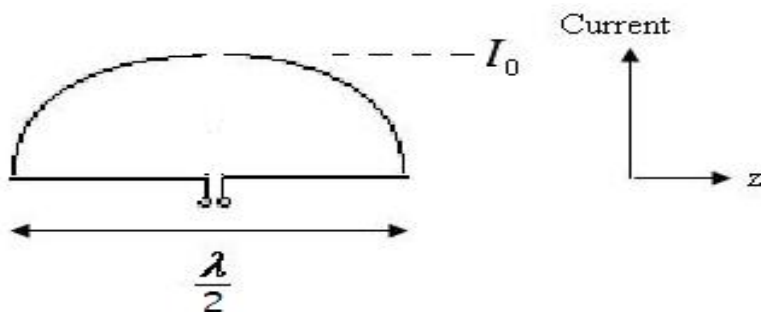
ISOTROPIC ANTENNA



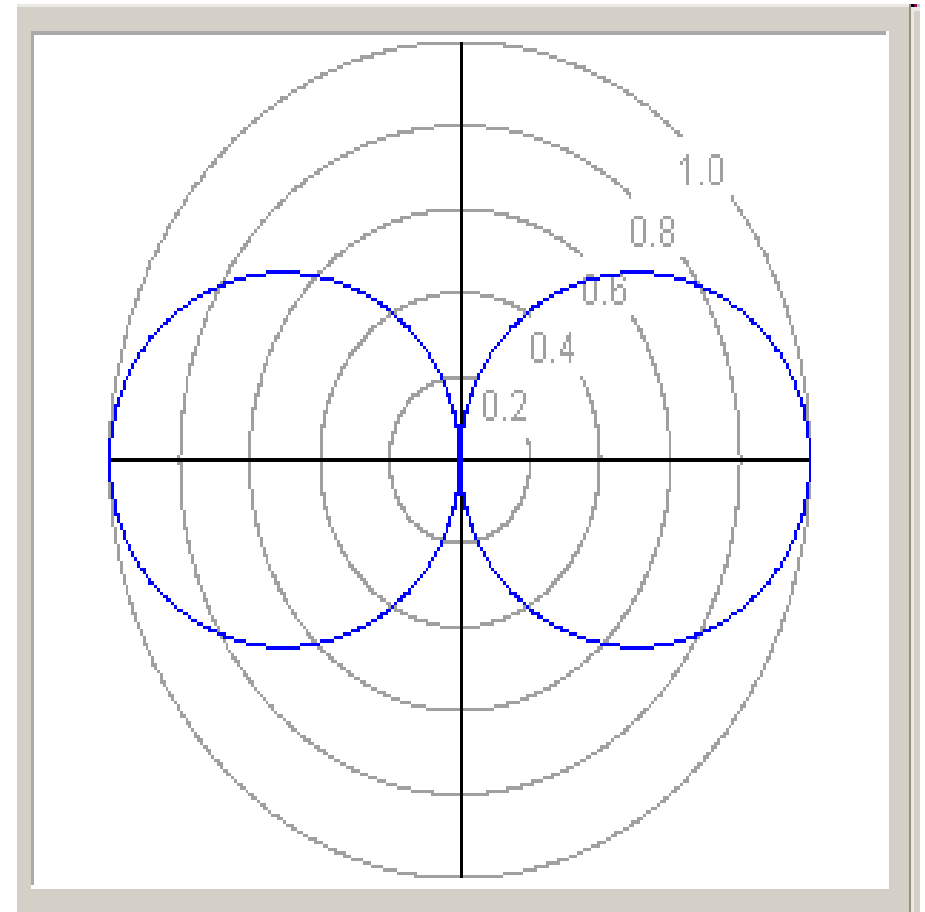
- *Isotropic antenna or isotropic radiator* is a hypothetical (not physically realizable) concept, used as a useful reference to describe real antennas.
- Isotropic antenna radiates equally in all directions.
 - Its radiation pattern is represented by a sphere whose center coincides with the location of the isotropic radiator.
- It is considered to be a point in space with no dimensions and no mass. This antenna cannot physically exist, but is useful as a theoretical model for comparison with all other antennas.
- Most antennas' gains are measured with reference to an isotropic radiator, and are rated in dBi (decibels with respect to an isotropic radiator).

HALF WAVE DIPOLE ANTENNA

- The **half-wave dipole antenna** is just a special case of the dipole antenna.
- Half-wave term means that the length of this dipole antenna is equal to a half-wavelength at the frequency of operation.
- The dipole antenna, is the basis for most antenna designs, is a balanced component, with equal but opposite voltages and currents applied at its two terminals through a balanced transmission line.
- To make it crystal clear, if the antenna is to radiate at 600 MHz, what size should the half-wavelength dipole be?
- One wavelength at 600 MHz is $\lambda = c / f = 0.5$ meters. Hence, the half-wavelength dipole antenna's length is 0.25 meters.
- The half-wave dipole antenna is as you may expect, a simple half-wavelength wire fed at the center as shown in Figure



- Dipoles have an radiation pattern, doughnut symmetrical about the axis of the dipole. The radiation is maximum at right angles to the dipole, dropping off to zero on the antenna's axis.



FOLDED DIPOLE

- Folded antenna is a single antenna but it consists of two elements.
- First element is fed directly while second one is coupled inductively at its end.
- Radiation pattern of folded dipole is same as that of dipole antenna i.e figure of eight (8).



Advantages

- Input impedance of folded dipole is four times higher than that of straight dipole.
- Typically the input impedance of half wavelength folded dipole antenna is 288 ohm.
- Bandwidth of folded dipole is higher than that of straight dipole.

HERTZ ANTENNA

- The Hertzian dipole is a theoretical short dipole (significantly smaller than the wavelength) with a uniform current along its length.
- A true Hertzian dipole cannot physically exist, since the assumed current distribution implies an infinite charge density at its ends, and significant radiation requires a very high current over its very short length.

LOOP ANTENNA

- A **loop antenna** is a radio antenna consisting of a loop of wire with its ends connected to a balanced transmission line
- It is a single turn coil carrying RF current through it.
- The dimensions of coil are smaller than the wavelength hence current flowing through the coil has same phase.
- Small loops have a poor efficiency and are mainly used as receiving antennas at low frequencies. Except for car radios, almost every AM broadcast receiver sold has such an antenna built inside of it or directly attached to it.
- A technically small loop, also known as a magnetic loop, should have a circumference of one tenth of a wavelength or less. This is necessary to ensure a constant current distribution round the loop.
- As the frequency or the size are increased, a standing wave starts to develop in the current, and the antenna starts to have some of the characteristics of a folded dipole antenna or a self-resonant loop.
- Self-resonant loop antennas are larger. They are typically used at higher frequencies, especially VHF and UHF, where their size is manageable. They can be viewed as a form of folded dipole and have somewhat similar characteristics. The radiation efficiency is also high and similar to that of a dipole.

- Radiation pattern of loop antenna is a doughnut pattern.
- Can be circular or square loop
- No radiation is received normal to the plane of loop and null is obtained in this direction.
- Application: Used for direction finding applications



Lecture-15-

Antennas Radiation Pattern

Antenna Characterization

- (i) radiation field pattern.
- (ii) gain.
- (iii) lobes, beamwidth, nulls.
- (iv) directivity.

Antennas generate **EM field pattern**:

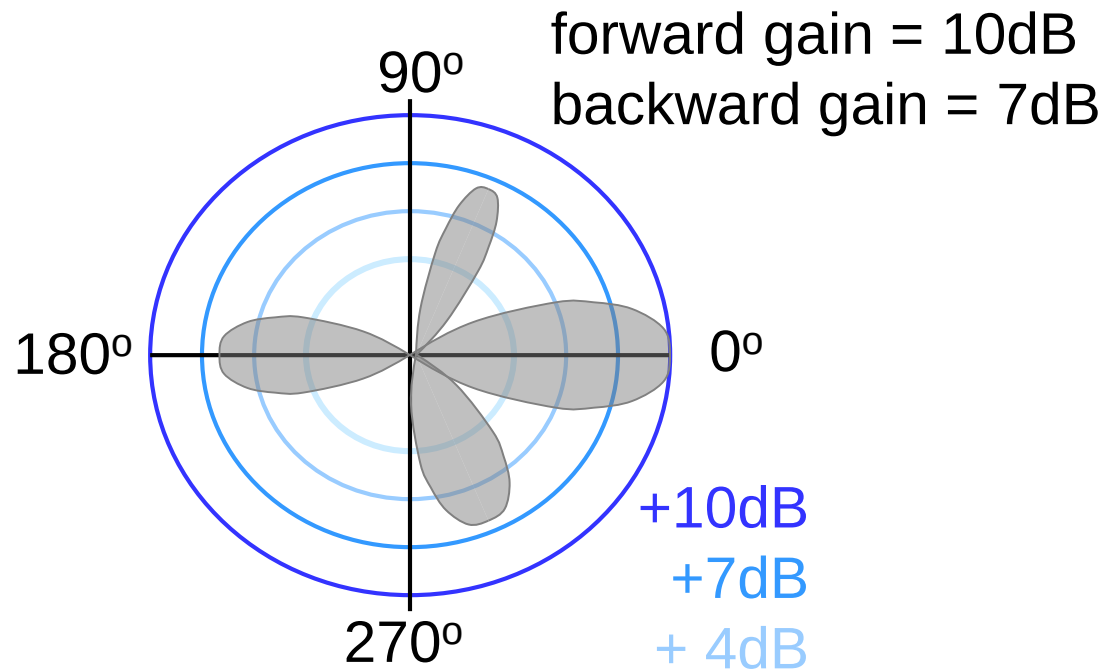
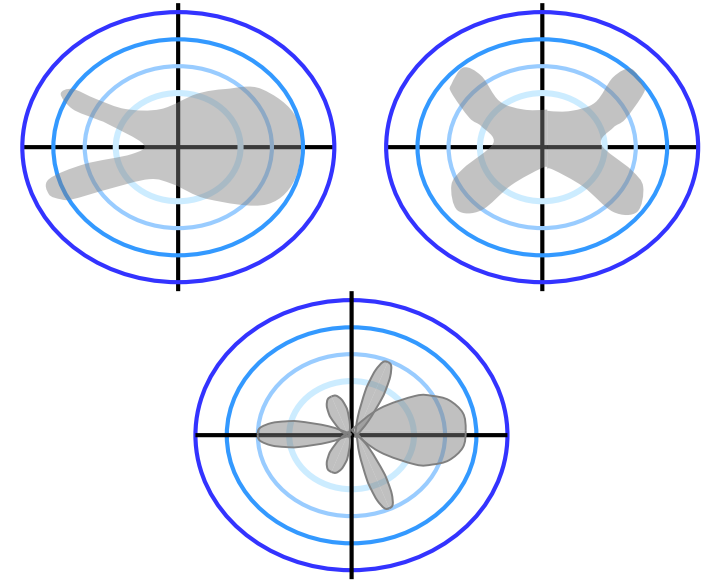
- not always possible to model mathematically
- difficult to account for obstacles.
- antennas are studied in EM **isolated rooms** to extract key performance characteristics

absolute value of **signal intensity** varies for given antenna design:

- at the transmitter this is related to power applied at transmitter.
- at the receiver this is related to power in surrounding space.

Polar Plot of relative signal strength of radiated field:

- shows how field strength is shaped.
- generally 0° aligned with major physical axis of antenna.
- most plots are relative scale (dB).
 - maximum signal strength location is 0 dB reference.
 - closer to center represents weaker signals.



(i) antenna field pattern = general shape of signal intensity in *far-field*

far-field measurements measured many wavelengths away from antenna.

near-field measurement involves complex interactions of decaying electrical and magnetic fields.

Measuring Antenna Field Pattern

Field strength meter used to measure field pattern:

- indicates amplitude of received signal
- calibrated to receiving antenna
- relationship between meter and receive antenna known
 - measured strength in $\mu\text{V}/\text{meter}$
 - received power is in $\mu\text{W}/\text{meter}$
- directly indicates EM field strength

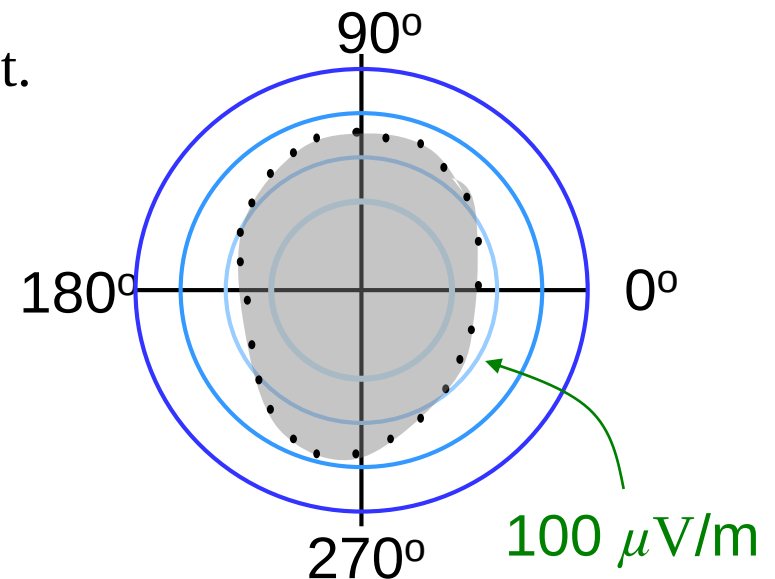
Determination of overall Antenna Field Pattern

Form Radiation Polar Plot Pattern:

- use nominal field strength value (e.g. $100\mu\text{V/m}$).
- measure points for 360° around antenna.
- record distance & angle from antenna.
- connect points of equal field strength.

Practically:

- distance between meter & antenna kept constant.
- antenna is rotated.
- plot of **field strength** versus **angle** is made.



Why Shape the Antenna Field Pattern ?

Transmit antennas: produce higher effective power in **direction** of intended receiver.

- receive antennas: concentrate **energy collecting** ability in direction of transmitter

- **reduced noise** levels - receiver only picks up intended signal

- avoid unwanted receivers (multiple access interference = **MAI**):

- security

- multi-access systems

- **locate** target direction & distance – e.g. radar

not always necessary to shape field pattern, standard broadcast is often omnidirectional - 360°.

(ii) Antenna Gain

Gain is Measured Specific to a **Reference Antenna**:

- **isotropic antenna** often used.
 - isotropic antenna – radiates power ideally in all directions.
 - gain measured in **dBi**.
 - test antenna's field strength relative to reference isotropic antenna
 - at same *power*, *distance*, and *angle*.
 - isotropic antenna cannot be practically realized.
- **½ wave dipole** often used as reference antenna because:
 - easy to build.
 - simple field pattern.

Antenna Gain $\neq$ Amplifier Gain

- antenna power output = power input – transmission line loss.
- antenna shapes radiated field pattern.
- **power measured** at a point is greater/less than that using **reference antenna**
- total power output doesn't increase.
- power output in given direction increases/decreases relative to reference antenna.

e.g.

a lamp is similar to an isotropic antenna

a lens is similar to a directional antenna

- provides a gain/loss of visible light in a specific direction.
- doesn't change actual power radiated by lamp.

- **transmit antenna** with 6dB gain in specific direction over isotropic antenna $\rightarrow$ 4 $\times$ transmit power in that direction
- **receive antenna** with 3dB gain in some direction receives 2 $\times$ as much power than reference antenna

Antenna Gain

often a cost effective means to

- (i) increase effective transmit power
- (ii) effectively improve receiver sensitivity

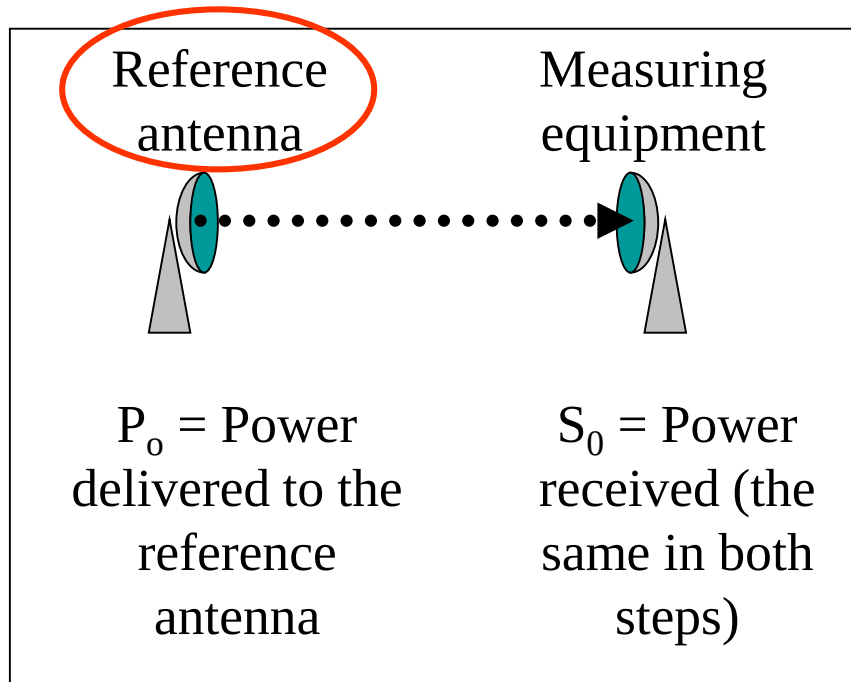
may be only technically viable means

- more power may not be available (batteries)
- front end noise determines maximum receiver sensitivity

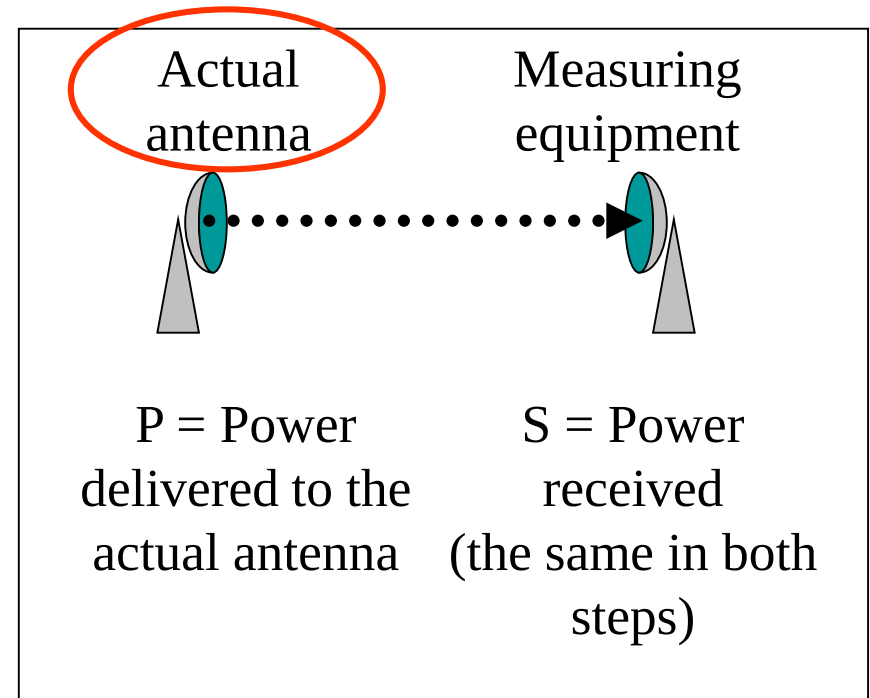
Rotational Antennas can vary direction of antenna gain

Directional Antennas focus antenna gain in primary direction

Antenna gain measurement in practice



Step 1: reference



Step 2: substitution

$$\text{Antenna Gain} = (P/P_o)_{S=S_o}$$

(iii) Beamwidth, Lobes & Nulls

Lobe: area of high signal strength

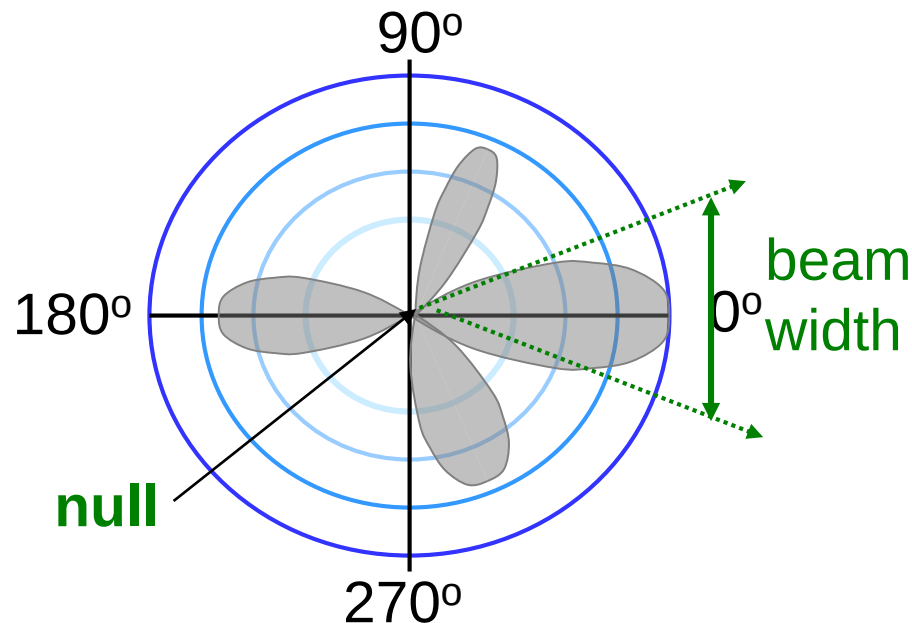
- main lobe
- secondary lobes

Nulls: area of very low signal strength

Beamwidth: total angle where relative signal power is 3dB below peak value of main lobe

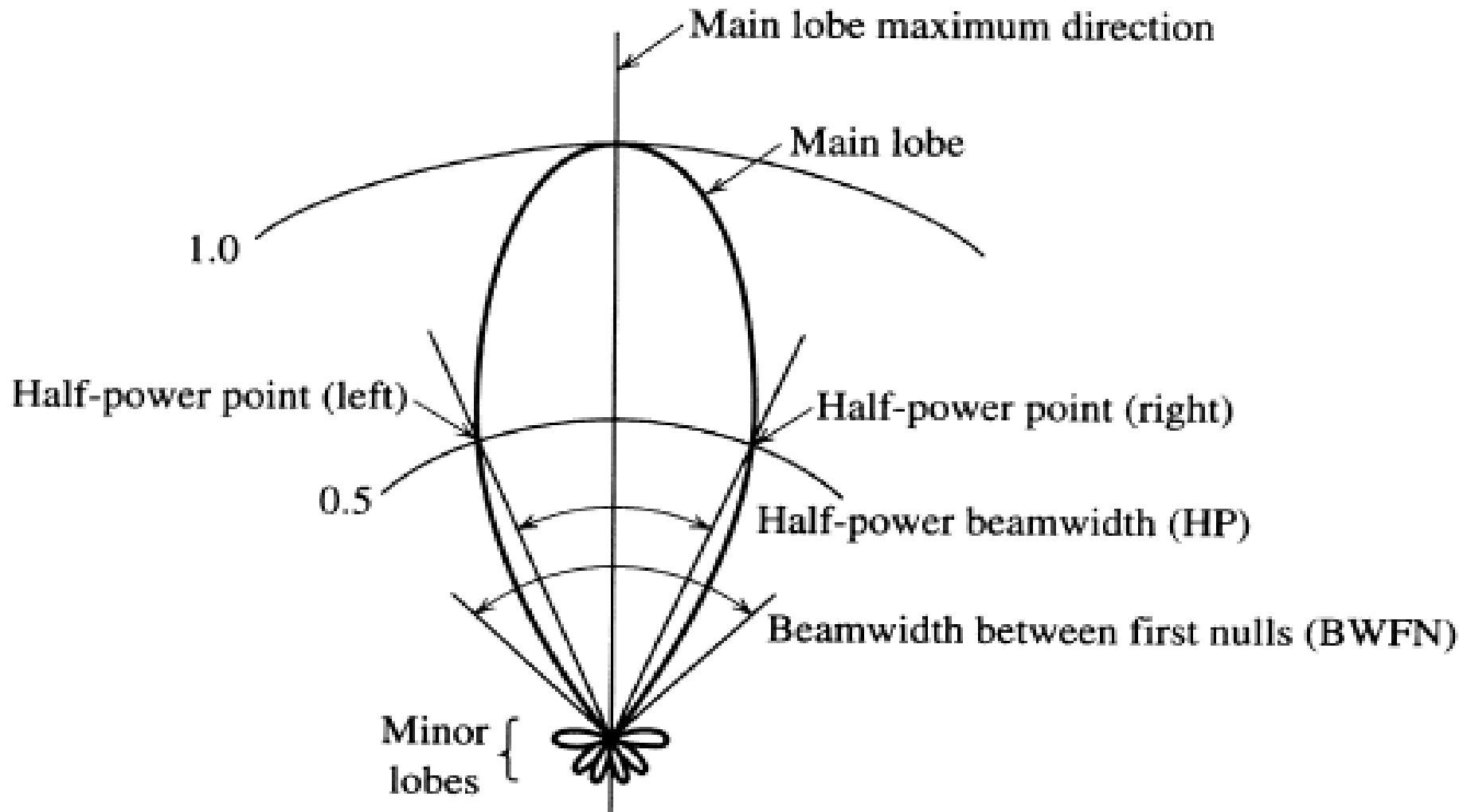
- can range from 1° to 360° .

Beamwidth & Lobes indicate sharpness of pattern focus.



- ***Half-power beamwidth*** (HPBW) is the angle between two vectors from the pattern's origin to the points of the major lobe where the radiation intensity is half its maximum.
 - Often used to describe the antenna resolution properties
 - » Important in radar technology, radioastronomy, etc.
- ***First-null beamwidth*** (FNBW) is the angle between two vectors, originating at the pattern's origin and tangent to the main beam at its base.
 - » Often $\text{FNBW} \approx 2 \times \text{HPBW}$

Example



Lecture-16-

Antennas Characteristics (2)

Directivity:

The directivity of the antenna has been defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged overall directions.

Gain, Directive gain, Power gain:

Is the ratio of the intensity (power per unit surface) radiated by the antenna in a given direction at an arbitrary distance divided by the intensity radiated at the same distance by a hypothetical isotropic lossless antenna.

Antenna Efficiency

Antenna efficiency or radiation efficiency is the measure of the antenna's ability to transmit the input power into radiation. Antenna efficiency is the ratio between the radiated powers to the input power:

$$e = \frac{P_r}{P_{in}}$$

Efficiency is ultimately a ratio, giving a number between 0 and 1. Efficiency is very often quoted in terms of a percentage; for example, an efficiency of 0.5 is the same as 50%. Antenna efficiency is also frequently quoted in decible (dB); an efficiency of 0.1 is 10% or (-10 dB), and an efficiency of 0.5 or 50% is -3 dB. If an antenna could be made to be a totally ideal electrical component, it would transform all of the power fed to its terminals to a radiating electromagnetic energy that propagates into the surrounding space. This is possible only in theory, and thus in real life some of the power fed to the antenna terminals is always lost. For example, the mismatch between the antenna element and the feeding network causes power losses. Also the actual antenna material loses energy just by its nature and creates unintended heat. All together these losses lead to situations where the antenna radiated efficiency in actual operation is always below 100% (equals 0 dB). The antenna efficiency is measured in an anechoic chamber by feeding some power to the antenna feed pads and measuring the strength of the radiated electromagnetic field in the surrounding space. A good antenna, in general, radiates 50 – 60 % of the energy fed to it (-3 to -2.2dB).

Intermodulation

Generally, an antenna is considered a passive linear device. However, when such a device is excited by high enough power, it acts slightly as a nonlinear device. The nonlinearity is normally caused by metal-to-metal joints and nonlinear materials in the antenna structure. Therefore, when signals with multiple frequencies are fed into nonlinear devices, intermodulation product terms whose frequencies are different to those of the input signal are generated. A typical passive intermodulation signal level is from -180 to -120 dBc (dBc relative to carrier power).

An antenna's intermodulation degrades a wireless system's performance if the system has the following features:

- High transmitted power is adopted.
- The system is equipped with high receiver sensitivity.
- One antenna is used for both transmitting and receiving.
- Signals at more than one frequency are transmitted.

Base stations normally have this entire feature set. Base stations, therefore, suffer from passive intermodulation (**PIM**). High-power signals excite the antenna of the base station, and intermodulation components cause back reflection to the receiver due to the antenna's PIM. Since the receiver is highly sensitive and is able to sense very weak signals, the intermodulation signals cause interference. The problem becomes worse if the intermodulation term falls inside the receiving band because the interference cannot be removed by filtering. For example, for the **P-GSM-900** system whose downlink band is from **935 MHz to 960 MHz** and whose uplink band is from **890 MHz to 915 MHz**, the 3rd order intermodulation term at the base station side may be $2 \times 935 - 960 = 910 \text{ MHz}$, which falls inside the uplink band.

On the other hand, the PIM problem is not that serious at a client terminal, such as a cell phone, a personal digital assistant (PDA), or a laptop with wireless capability, and is normally ignored. On the client side, the transmitted power is not that high due to limited battery capacity and for electromagnetic safety reasons, and thus the PIM reflected to the receiver is weaker than that at the base station. The relatively low-power transmission does not reduce the quality of uplink as the base station is equipped with a highly sensitive receiver. In addition, the receiver sensitivity is not high at a client terminal, and the reflected PIM level is thus lower than the noise level. Similarly, the relatively lower receiver sensitivity does not degrade the downlink performance as a high-power signal is transmitted from the base station.

Lecture-17-

Patch Antennas, Parabolic Dish Antennas

Introduction

- Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc...
- The telemetry and communication antennas on missiles need to be thin and conformal and are often Microstrip patch antennas. Another area where they have been used successfully is in Satellite communication.

Microstrip/Patch Antennas

- In its most basic form, a Microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other.
- The patch is generally made of conducting material such as copper or gold and can take any possible shape.
- The radiating patch and the feed lines are usually photo etched on the dielectric substrate.
- Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation.

Some of their principal advantages

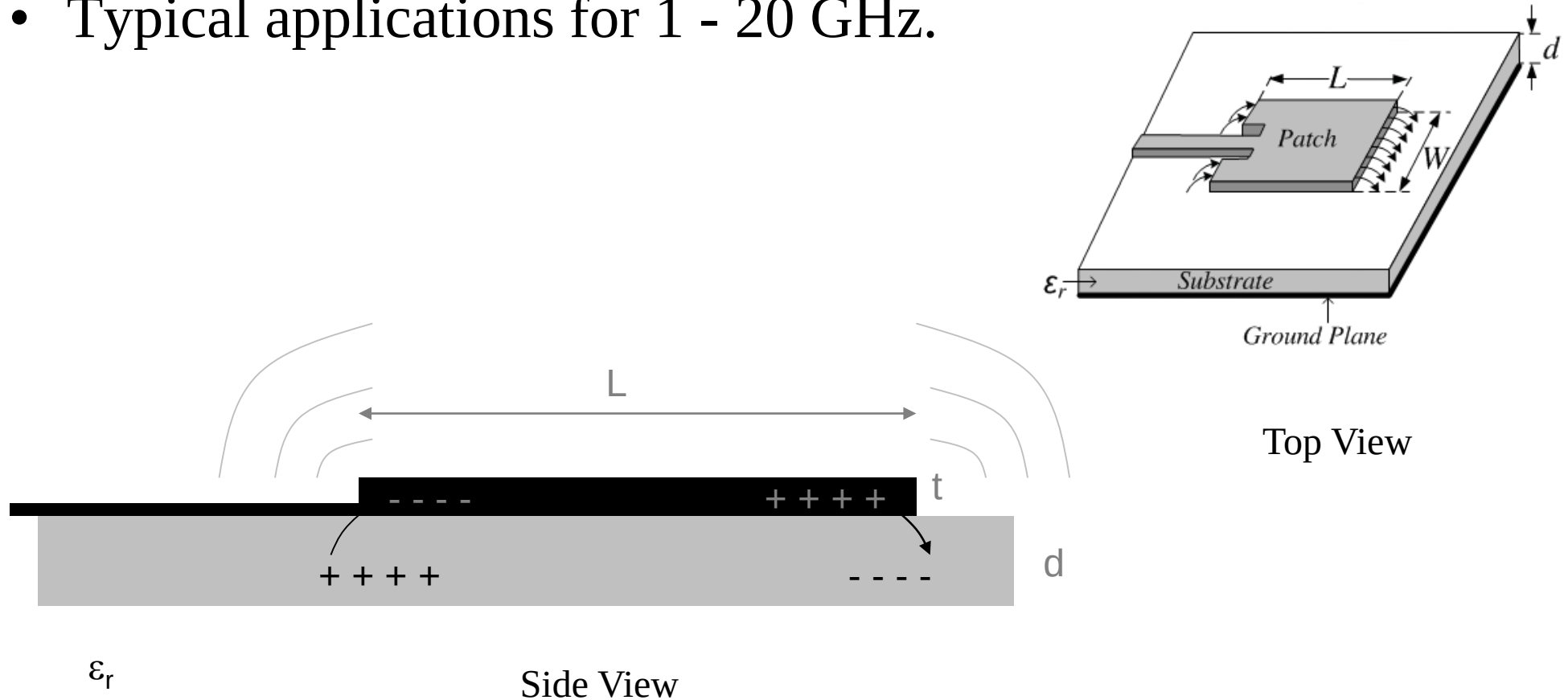
- Light weight and low volume.
- Low profile planar configuration which can be easily made conformal to host surface.
- Low fabrication cost, hence can be manufactured in large quantities.
- Supports both, linear as well as circular polarization.
- Can be easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.
- Mechanically robust when mounted on rigid surfaces.

Microstrip patch antennas suffer from a number of disadvantages as compared to conventional antennas.

- Narrow bandwidth.
- Low efficiency.
- Low Gain.
- Extraneous radiation from feeds and junctions.
- Poor end fire radiator except tapered slot antennas.
- Low power handling capacity.
- Surface wave excitation.

Microstrip/Patch Antennas

- Ease of construction and integration, relatively low cost, compact low profile configuration and good flexibility.
- Typical applications for 1 - 20 GHz.



Patch Shapes

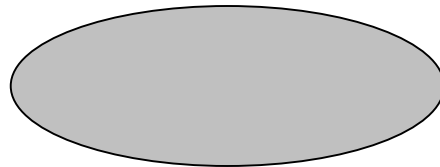
Rectangular



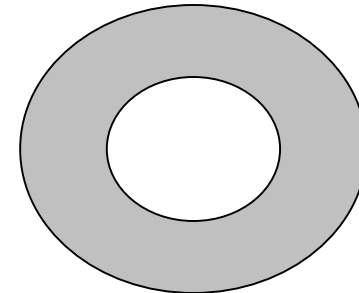
Dipole



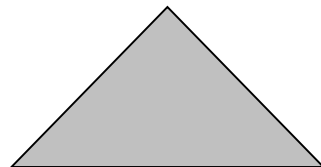
Elliptical



Circular Ring



Triangular



Application & Performance

1. It is applied where small antennas are required:
→ aircrafts, mobiles, etc.
2. Due to shape variations they are versatile in polarisation, pattern, impedance, etc.
3. They have a low efficiency, spurious feed radiation and a narrow bandwidth.
4. They usually operate in broadside regime.
5. $\lambda/3 < L < \lambda/2$ and $2 < \epsilon_r < 12$

Operational principles

- To be a resonant antenna, the length L should be around half of the wavelength. In this case, the antenna can be considered as a $(\lambda/2)$ *transmission line resonant cavity with two open ends where the fringing fields from the patch to the ground are exposed to the upper half space ($z > 0$) and are responsible for the radiation.*
- This radiation mechanism is the same as the slot line, thus there are two radiating slots on a patch antenna.
- As a resonant cavity, there are many possible modes (as waveguides), thus a patch antenna is multi-mode and may have many resonant frequencies.

Microstrip\ Patch Antenna Design

Effective Dielectric Constant:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2}$$

Effective Patch Length:

$$L_{\text{eff}} = L + 2\Delta L$$

Actual Patch Length:

$$L = \frac{1}{2f_r \sqrt{\epsilon_{\text{reff}}} \sqrt{\mu_0 \epsilon_0}} - 2\Delta L$$

Patch Width:

$$W = \frac{1}{2f_r \sqrt{\mu_0 \epsilon_0}} \sqrt{\frac{2}{\epsilon_r + 1}} = \frac{v_0}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}}$$

Extension Of the Length:

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{W}{h} + 0.8 \right)}$$

Example: Design a rectangular microstrip antenna using a substrate (RT/duroid 5880) with dielectric constant of 2.2, $h = 0.1588$ cm so as to resonate at 10 GHz.

Solution:

$$W = \frac{30}{2(10)} \sqrt{\frac{2}{2.2 + 1}} = 1.186 \text{ cm}$$

$$\epsilon_{\text{reff}} = \frac{2.2 + 1}{2} + \frac{2.2 - 1}{2} \left(1 + 12 \frac{0.1588}{1.186} \right)^{-1/2} = 1.972$$

$$\begin{aligned} \Delta L &= 0.1588(0.412) \frac{(1.972 + 0.3) \left(\frac{1.186}{0.1588} + 0.264 \right)}{(1.972 - 0.258) \left(\frac{1.186}{0.1588} + 0.8 \right)} \\ &= 0.081 \text{ cm} \end{aligned}$$

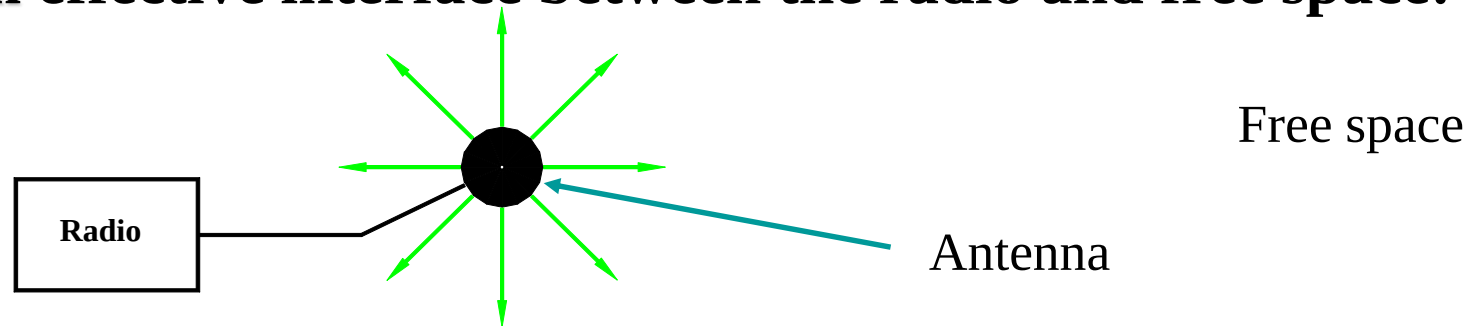
$$L = \frac{\lambda}{2} - 2\Delta L = \frac{30}{2(10)\sqrt{1.972}} - 2(0.081) = 0.906 \text{ cm}$$

$$L_e = L + 2\Delta L = \frac{\lambda}{2} = 1.068 \text{ cm}$$

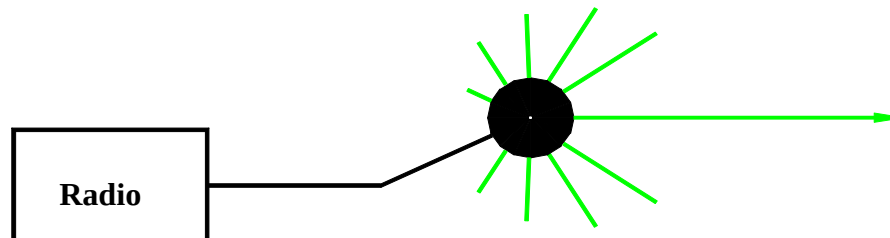
Parabolic Dish Antennas

An Antenna is :

An effective interface between the radio and free space:



For Terrestrial Communications, antennas must be directional:



Terrestrial Microwave Antennas for Point-To-Point Communication

- Terrestrial antennas generate a beam of RF signal to communicate between two locations.
- Point-To-Point communication depends upon a clear line of sight between two antennas.
- Obstructions, such as buildings, trees or terrain interfere with the signal.
- Depending upon the location, usage and frequency, different types can be utilized.
- We will address the basic characteristics of these various types...

Basic Parabolic Antenna Types



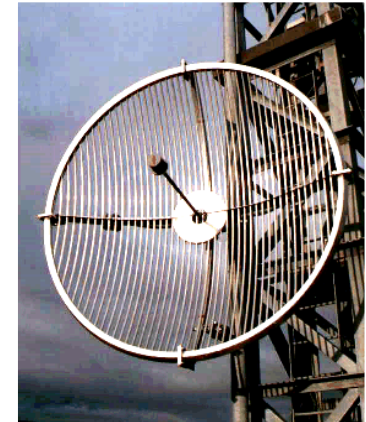
**Standard
Parabolic
Antenna**



**Shielded
(Radomes)
Antenna**



**Focal Plane
Antenna**



**GRIDPAK®
Antenna**

Standard Parabolic Antenna



- **Basic Antenna**
- **Comprised of**
 - **Reflector**
 - **Feed Assembly**
 - **Mount**



Shielded Antenna

- Absorber-Lined Shield
- Improved Feed System
- Protection Against Ice, Snow and Dirt
- Better against the wind

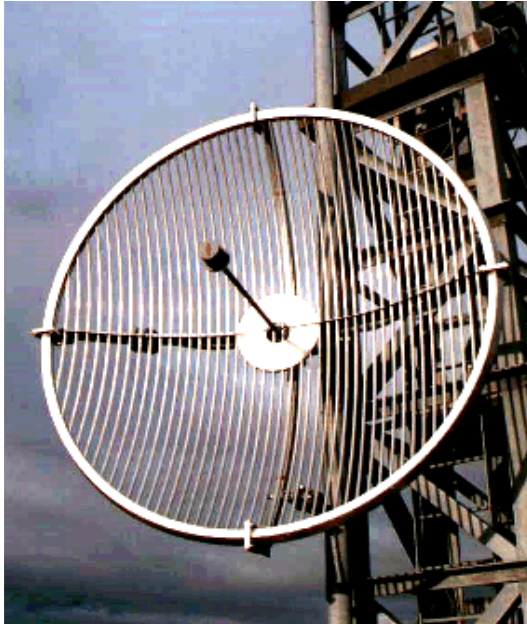


Focal Plane Antenna



- **Deeper Reflector**
- **Edge Geometry**
- **Slightly Lower Gain**

GRIDPAK[®] Antenna



- **Grid Reflector**
- **Low Wind load**
- **Below 2.7GHz**

Antenna Efficiency

**Well-designed antennas
have efficiency ratings of
45 - 65%**

Efficiency Factor Affected By :

- **Signal Strength,**
- **Blockage & Obstructions**
- **Reflector Surface**

Efficiency can never be 100%



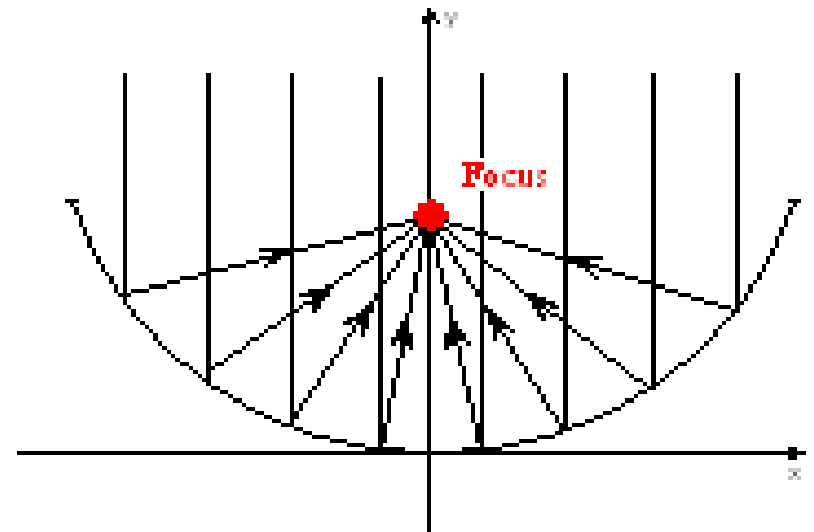
Calculating the Focal Point

- In order to determine the optimal location for the antenna feed, or receiver, you must calculate the focal point.
- Using the following formula:
 - » **$F = D^2 / 16d$**
 - Where
 - F = focal point
 - D = Diameter of the dish
 - d = depth of dish

Focal Point

The point at which the RF signals meet after reflecting off of the parabolic curve of the antenna.

Parabola Shape



Calculating the Focal Point

- If you have a Parabolic Dish antenna that is 12" in diameter and 3" deep where would the focal point be located?
- Use the formula: **$F = D^2 / 16d$**
 - 12" squared = 144",
 - 144" divided by (16 x 3") or 48"
 - 144/48"=3"
 - The focal point is 3".

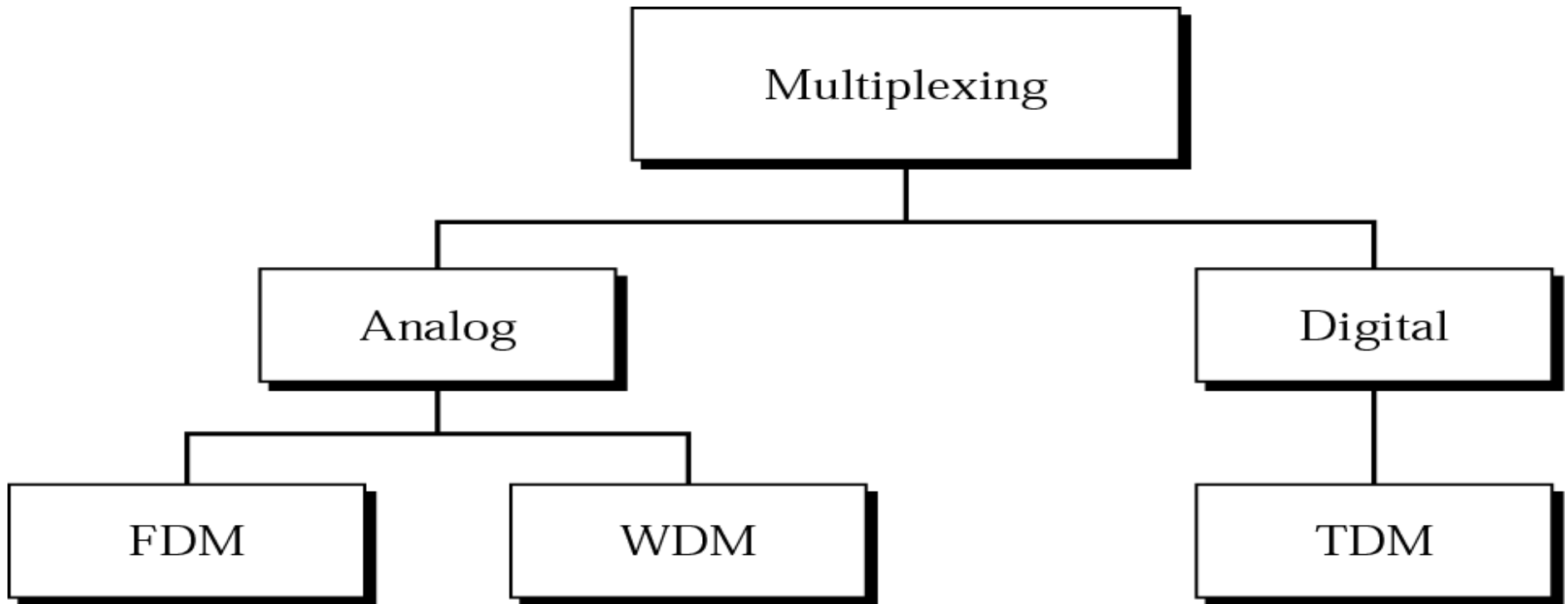
Lecture-18-

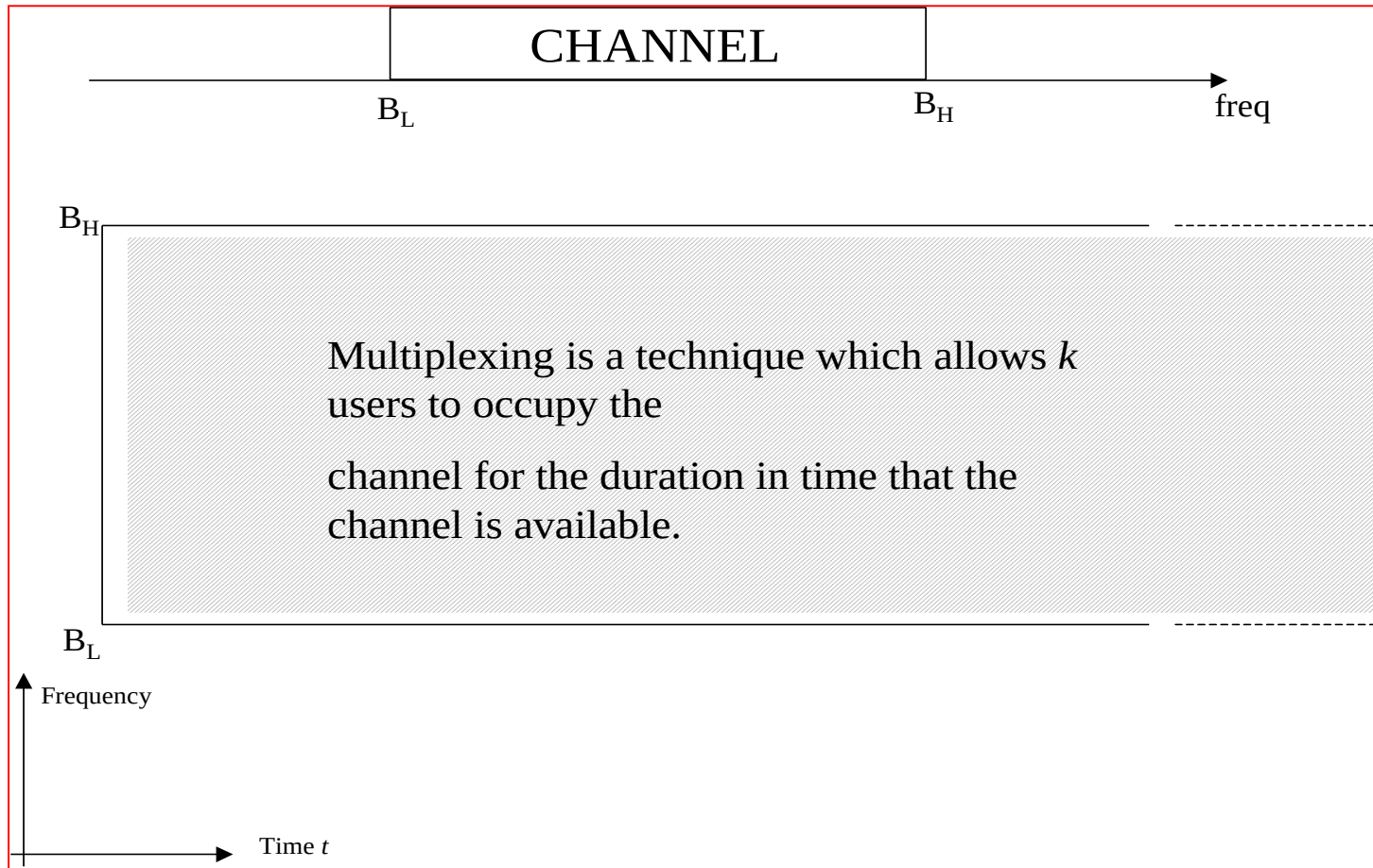
Multiplexing : FDM, TDM

Multiplexing

- Multiplexing is the name given to techniques, which allow more than one message to be transferred via the same communication channel. The channel in this context could be a transmission line, *e.g.* a twisted pair or co-axial cable, a radio system or a fibre optic system *etc.*
- A channel will offer a specified bandwidth, which is available for a time t , where t may $\rightarrow \infty$. Thus, with reference to the channel there are 2 ‘degrees of freedom’, *i.e.* bandwidth or frequency and time.

CATEGORIES OF MULTIPLEXING





Now consider a signal $v_s(t) = A \cos(\omega t + \phi)$

The signal is characterised by amplitude, frequency, phase and time.

- Various multiplexing methods are possible in terms of the channel bandwidth and time, and the signal, in particular the frequency, phase or time. The two basic methods are:

1) Frequency Division Multiplexing FDM

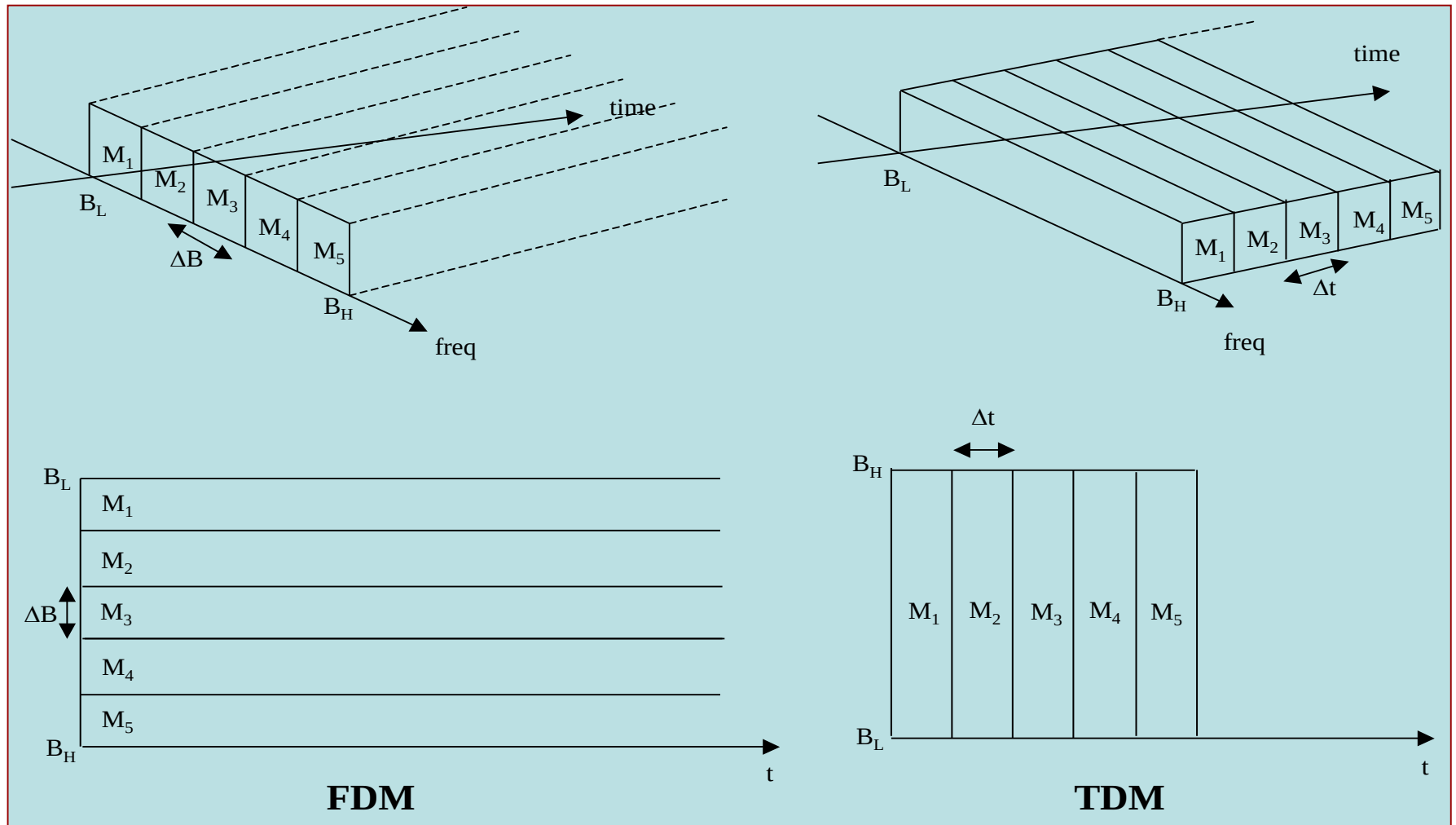
FDM is derived from AM techniques in which the signals occupy the same physical ‘line’ but in different frequency bands. Each signal occupies its own specific band of frequencies all the time, *i.e.* the messages share the channel **bandwidth**.

2) Time Division Multiplexing TDM

TDM is derived from sampling techniques in which messages occupy all the channel bandwidth but for short time intervals of time, *i.e.* the messages share the channel **time**.

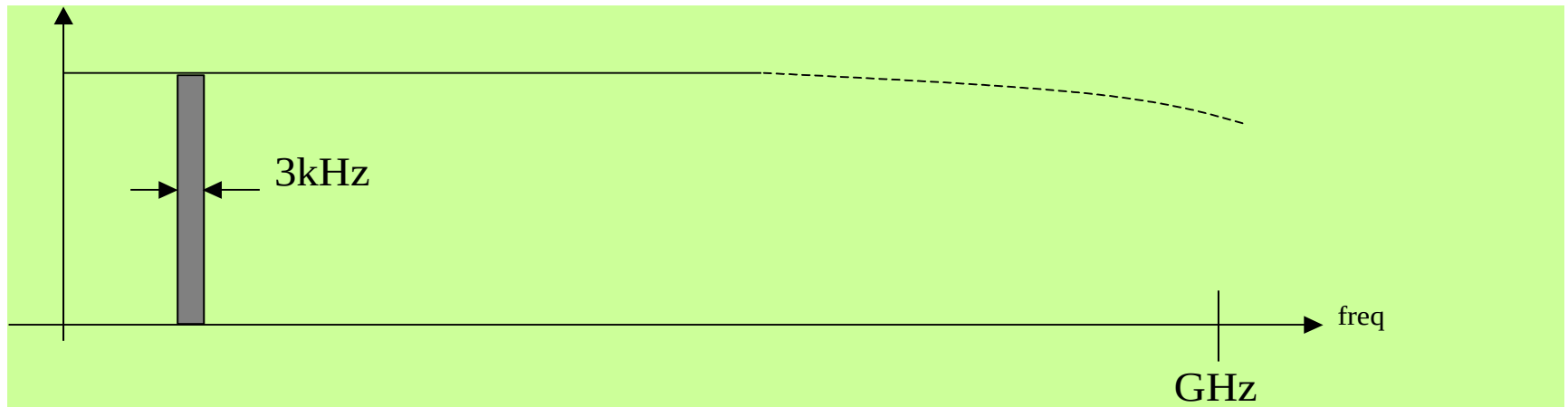
- FDM – messages occupy **narrow** bandwidth – all the time.
- TDM – messages occupy **wide** bandwidth – for short intervals of time.

These two basic methods are illustrated below:

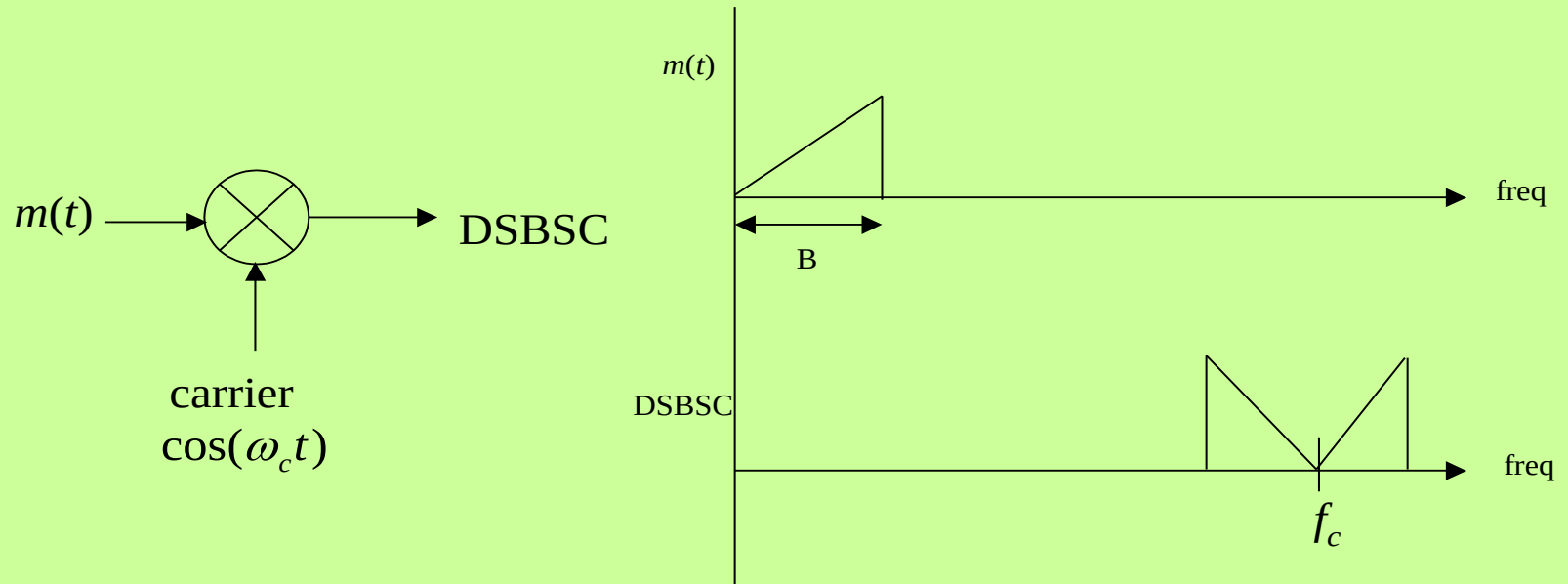


Frequency Division Multiplexing FDM

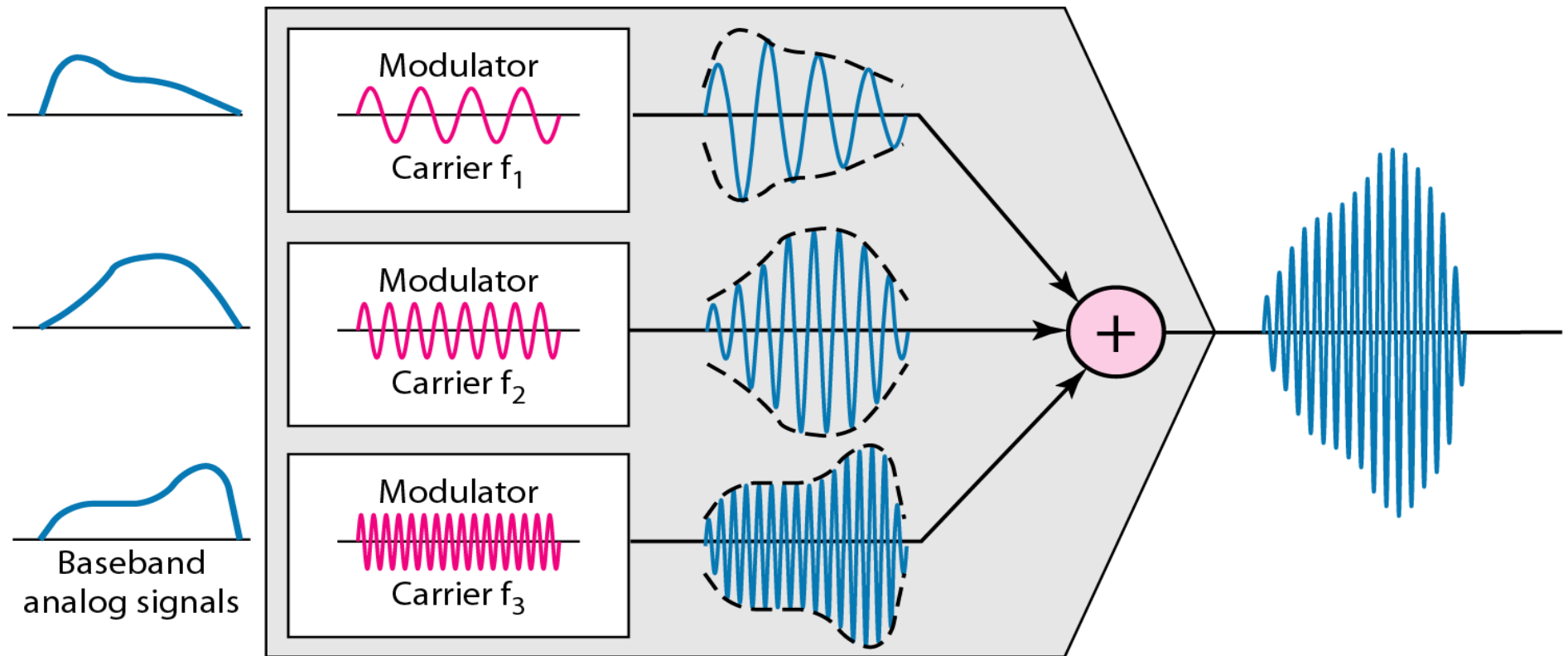
- FDM is widely used in radio and television systems (*e.g.* broadcast radio and TV) and was widely used in multichannel telephony (now being superseded by digital techniques and TDM).
- The multichannel telephone system illustrates some important aspects and is considered below. For speech, a bandwidth of $\approx 3\text{kHz}$ is satisfactory.
- The physical line, *e.g.* a co-axial cable will have a bandwidth compared to speech as shown next



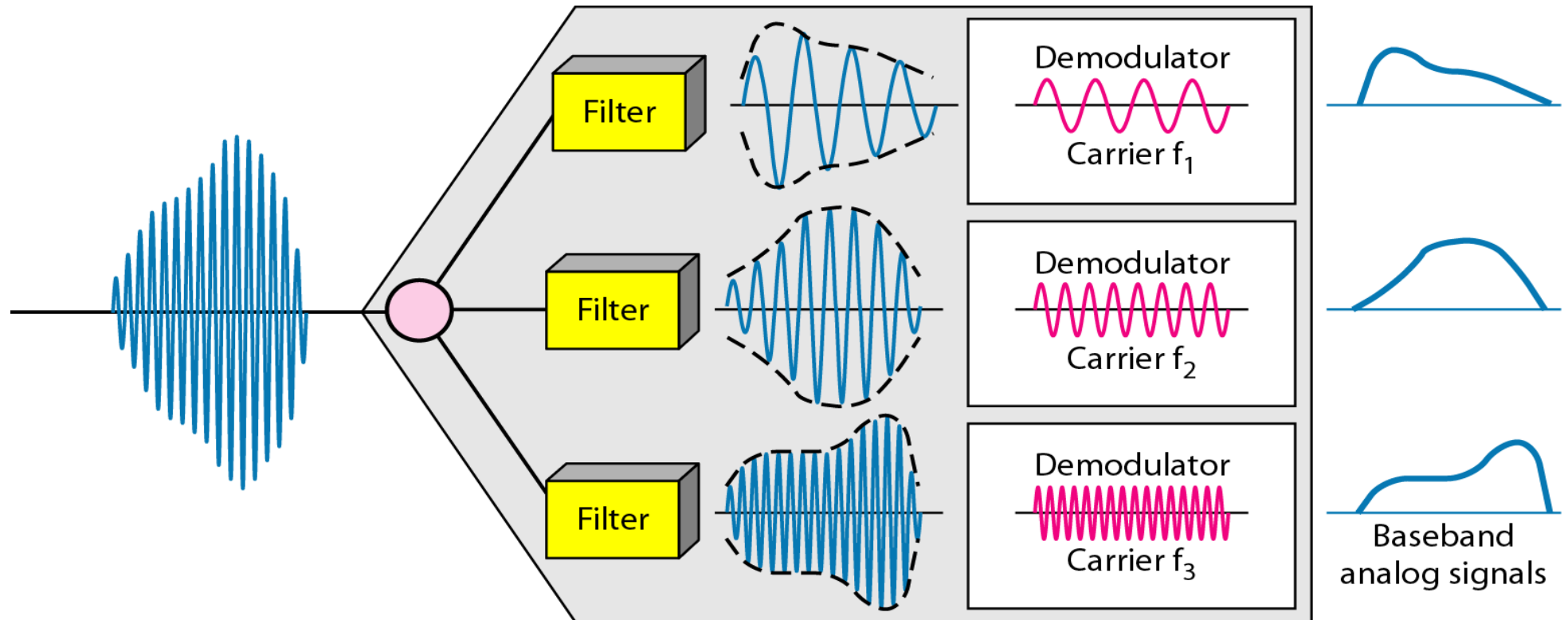
From AM we have noted:



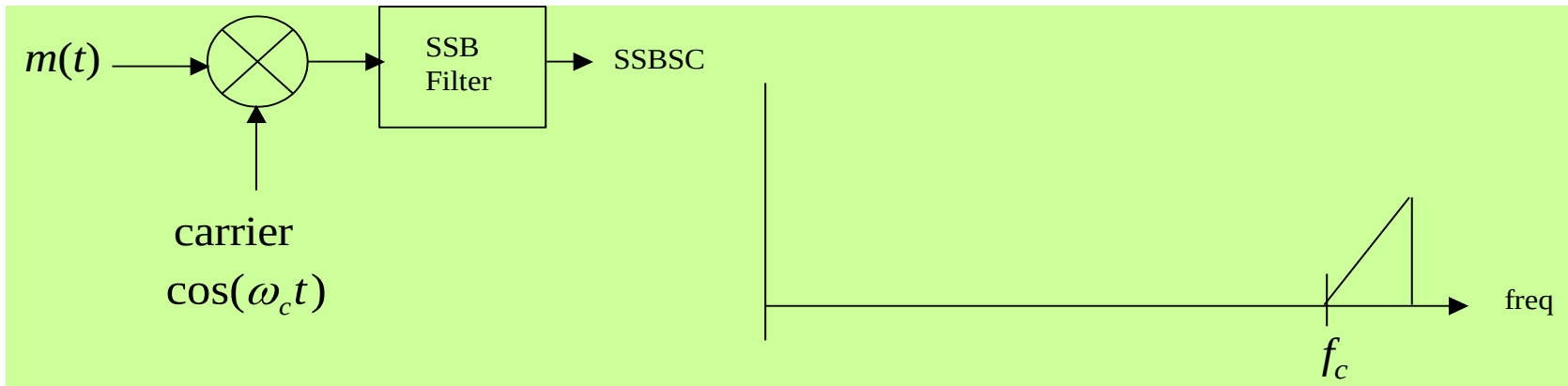
FDM process



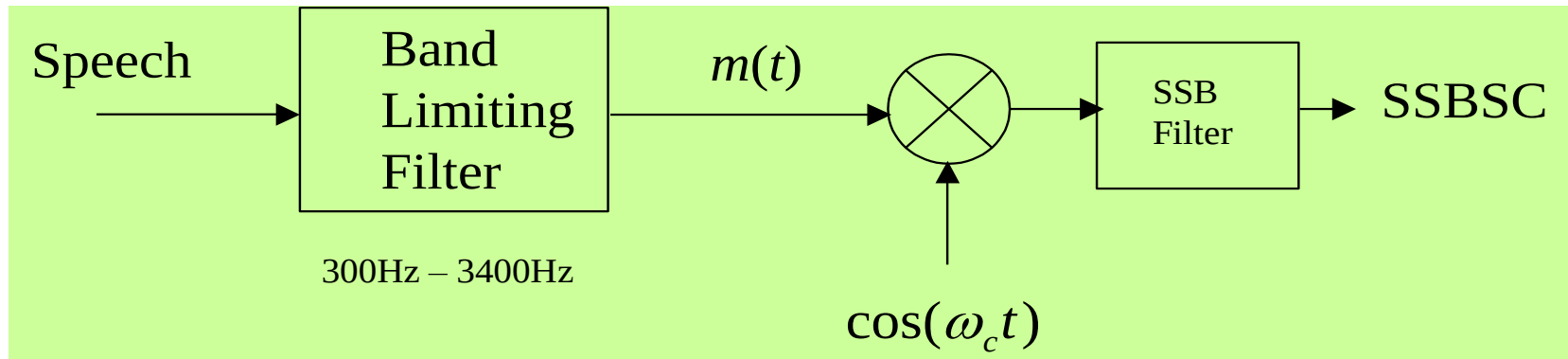
FDM demultiplexing example



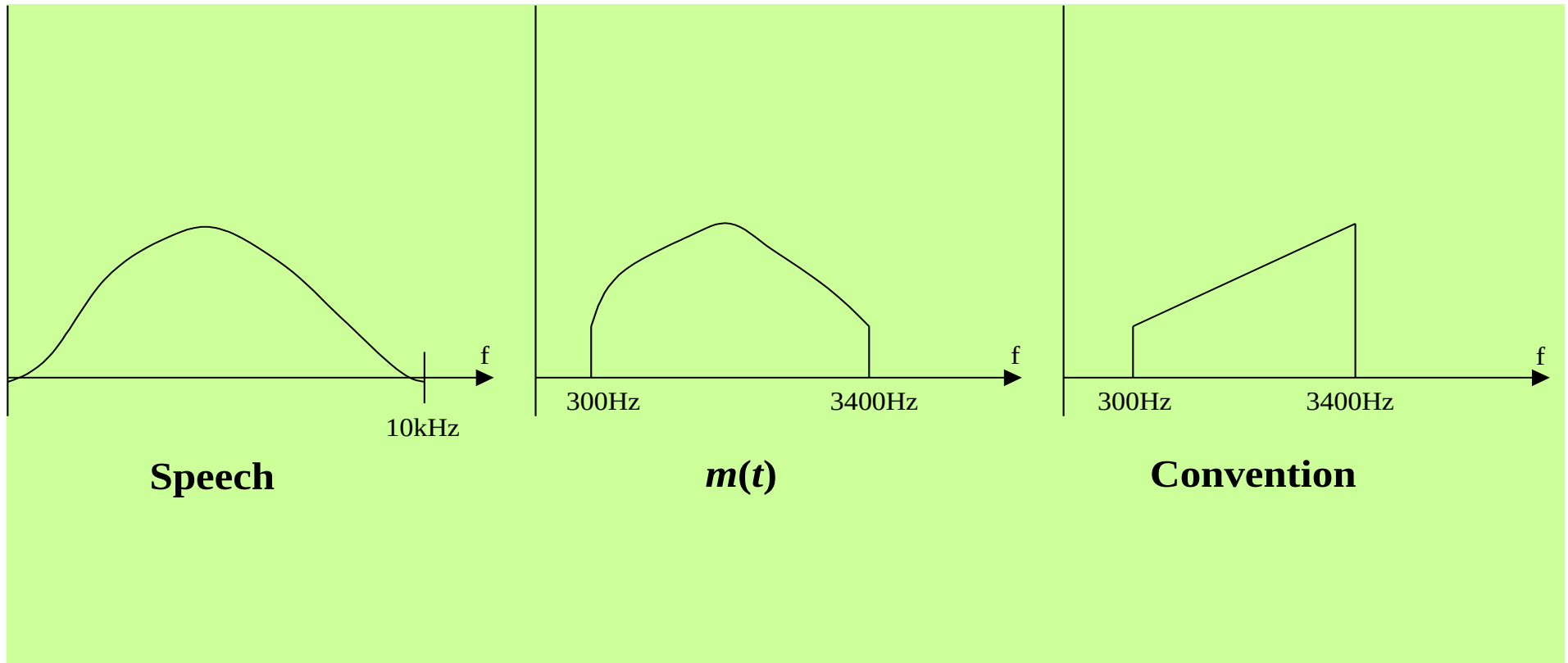
In order to use bandwidth more effectively, SSB is used *i.e.*



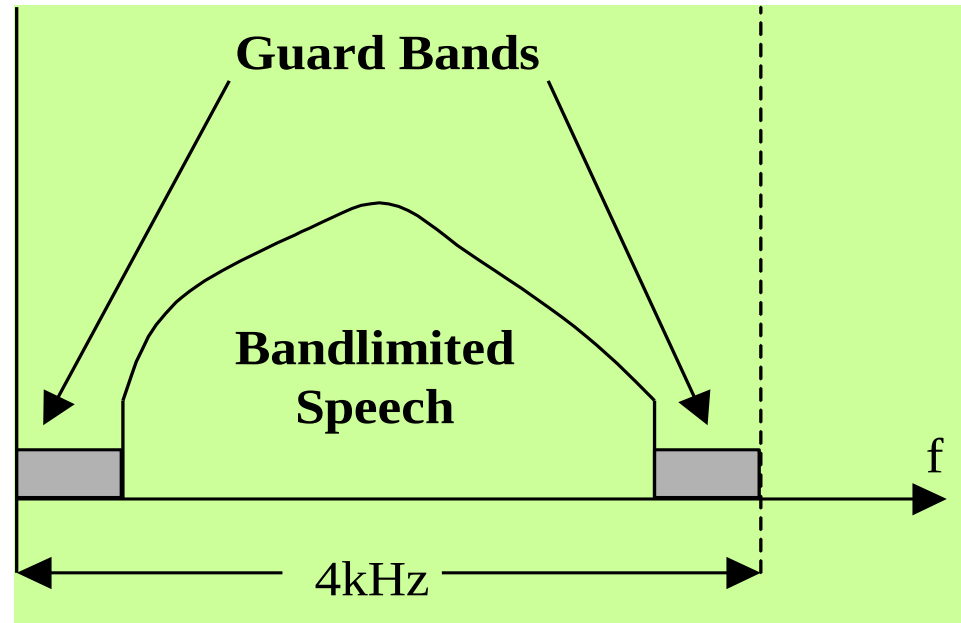
We have also noted that the message signal $m(t)$ is usually band limited, *i.e.*



The Band Limiting Filter (BLF) is usually a band pass filter with a pass band 300Hz to 3400Hz for speech. This is to allow **guard bands** between **adjacent channels**.



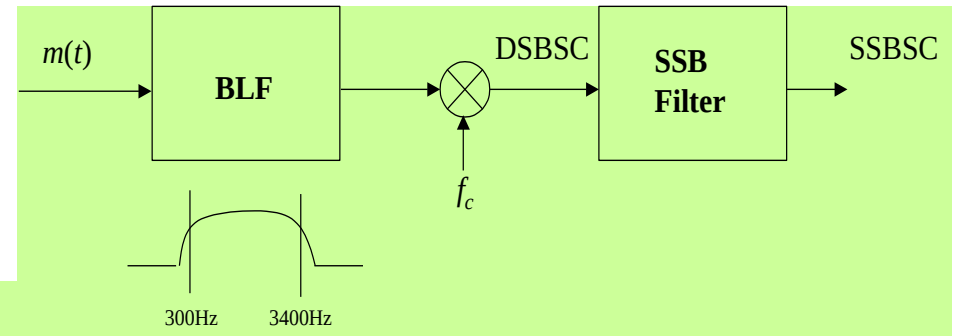
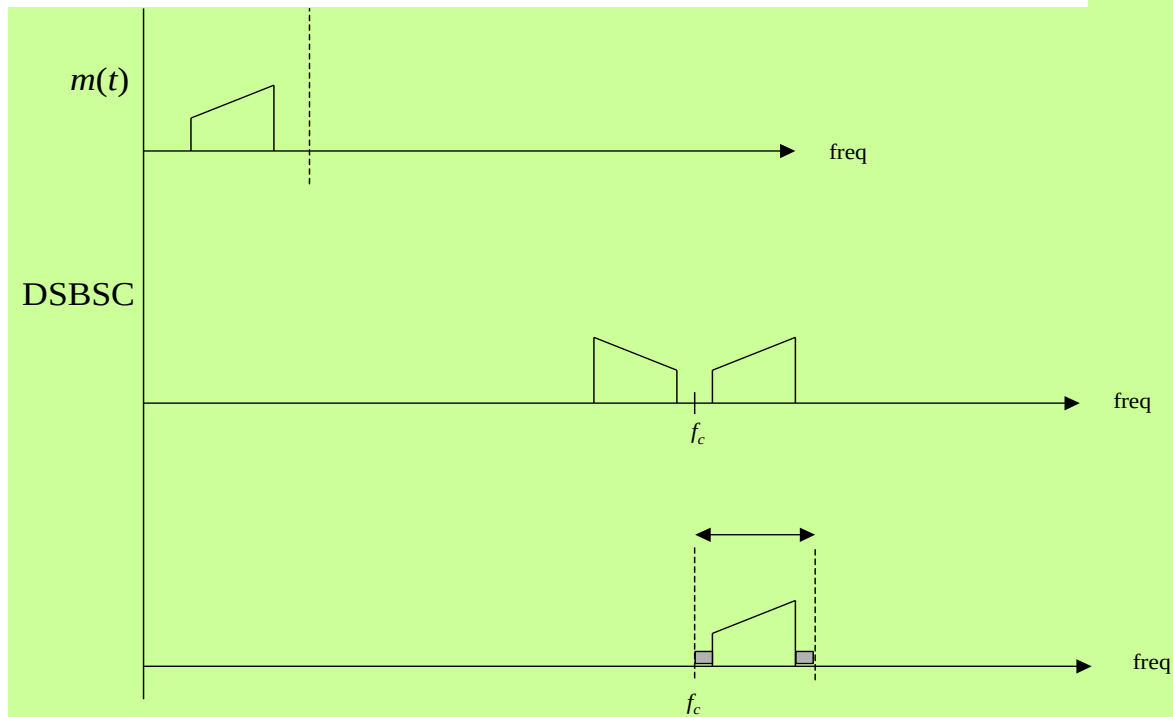
For telephony, the physical line is divided (notionally) into 4kHz bands or channels, *i.e.* the channel spacing is 4kHz. Thus we now have:



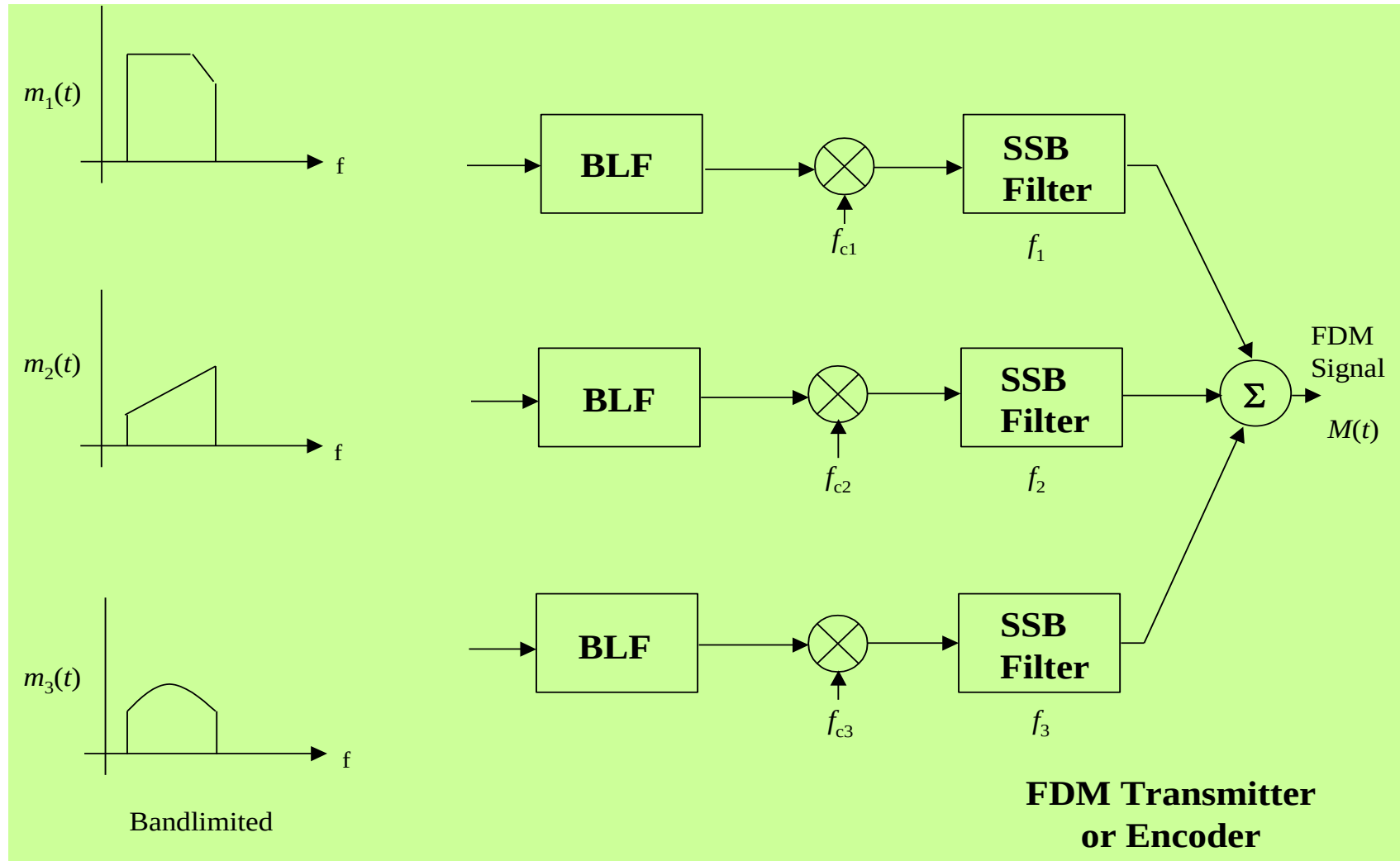
Note, the BLF does not have an ideal cut-off – the guard bands allow for filter ‘roll off’ in order to reduce adjacent channel crosstalk.

Consider now a single channel SSB system.

The spectra will be

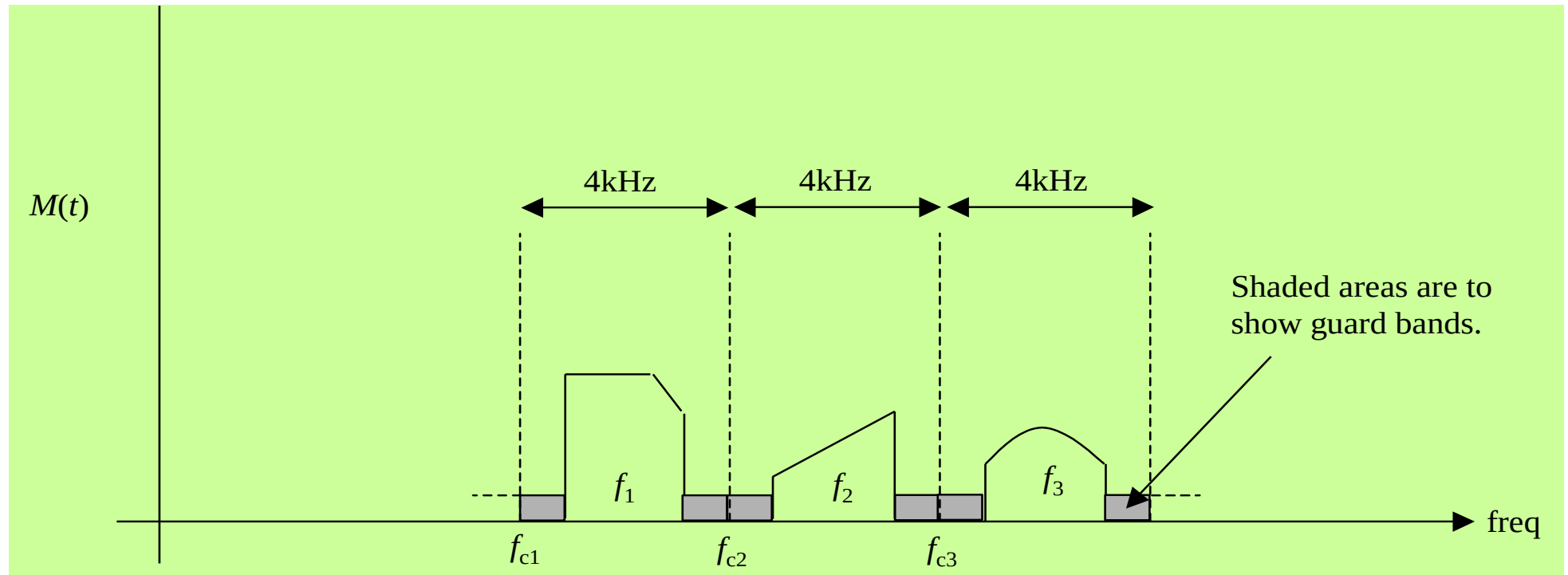


Consider now a system with 3 channels

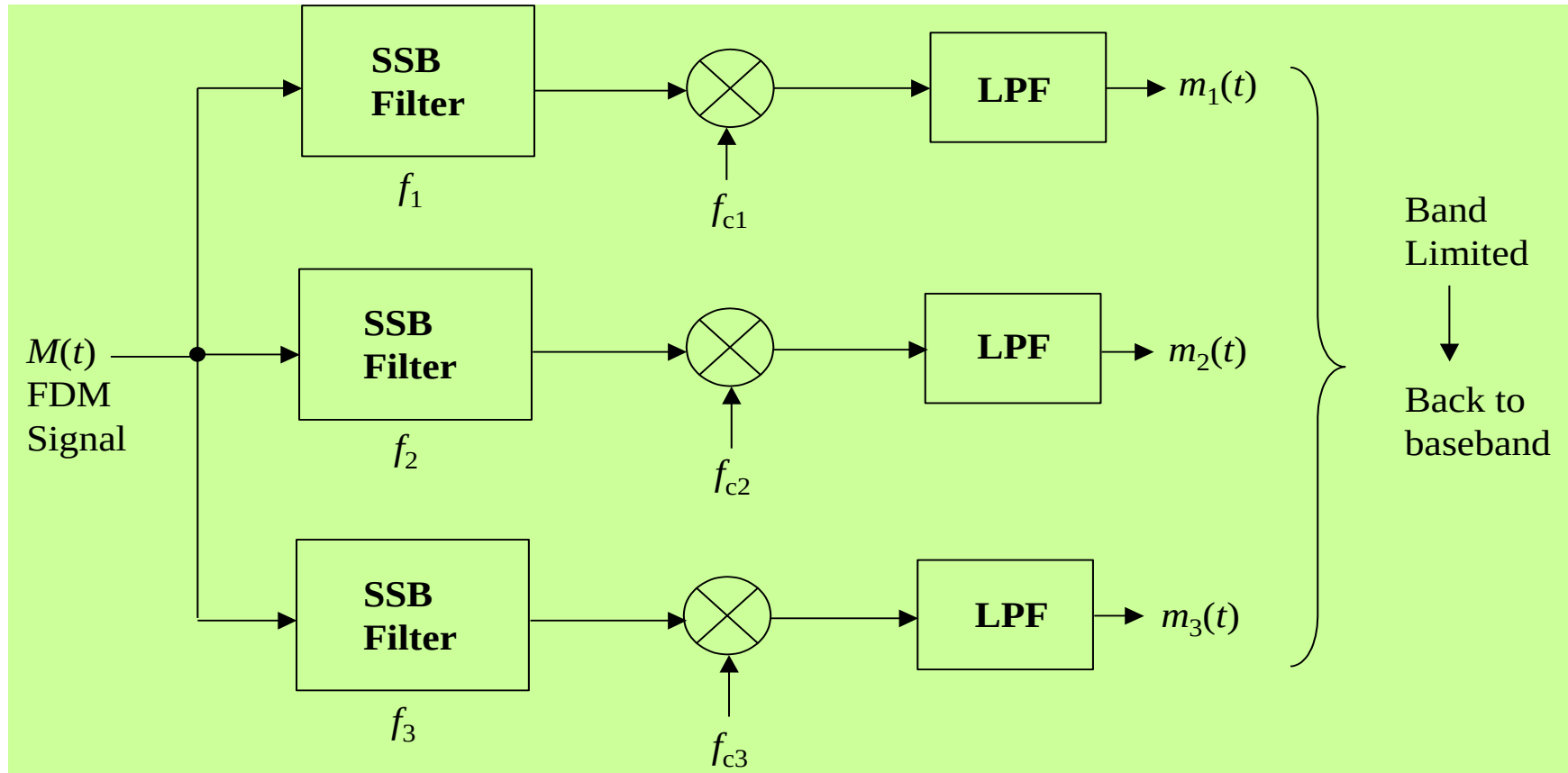


Each carrier frequency, f_{c1} , f_{c2} and f_{c3} are separated by the channel spacing frequency, in this case 4 kHz, *i.e.* $f_{c2} = f_{c1} + 4\text{kHz}$, $f_{c3} = f_{c2} + 4\text{kHz}$.

The spectrum of the FDM signal, $M(t)$ will be:



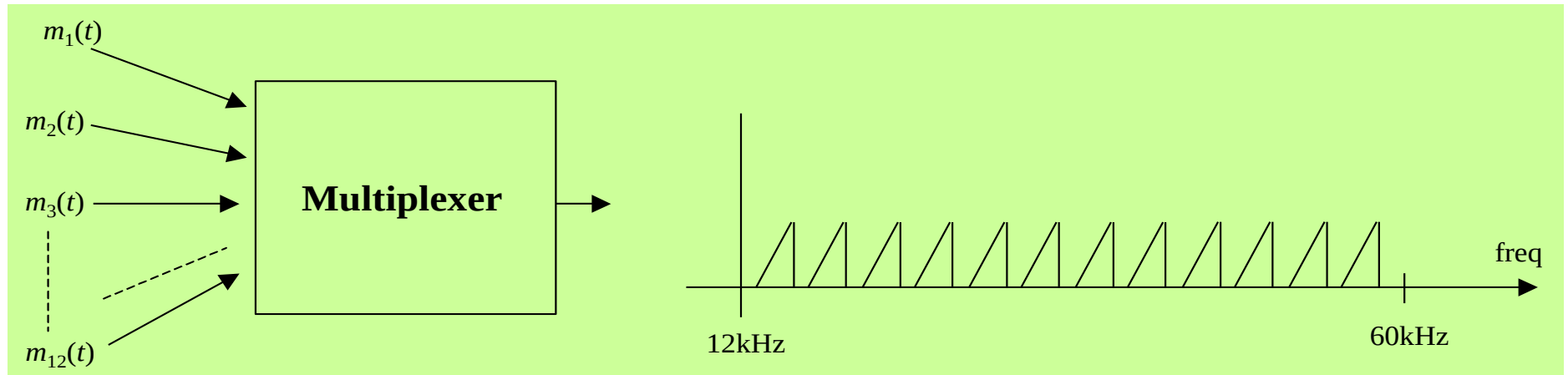
Note that the baseband signals $m_1(t)$, $m_2(t)$, $m_3(t)$ have been multiplexed into adjacent channels, the channel spacing is 4kHz. Note also that the SSB filters are set to select the USB, tuned to f_1 , f_2 and f_3 respectively. A receiver FDM decoder is illustrated below:



- The SSB filters are the same as in the encoder, *i.e.* each one centred on f_1 , f_2 and f_3 to select the appropriate sideband and reject the others. These are then followed by a synchronous demodulator, each fed with a synchronous LO, f_{c1} , f_{c2} and f_{c3} respectively.
- For the 3 channel system shown there is 1 design for the BLF (used 3 times), 3 designs for the SSB filters (each used twice) and 1 design for the LPF (used 3 times).
- A co-axial cable could accommodate several thousand 4 kHz channels, for example 3600 channels is typical. The bandwidth used is thus $3600 \times 4\text{kHz} = 14.4\text{Mhz}$. Potentially therefore there are 3600 different SSB filter designs. Not only this, but the designs must range from kHz to MHz.

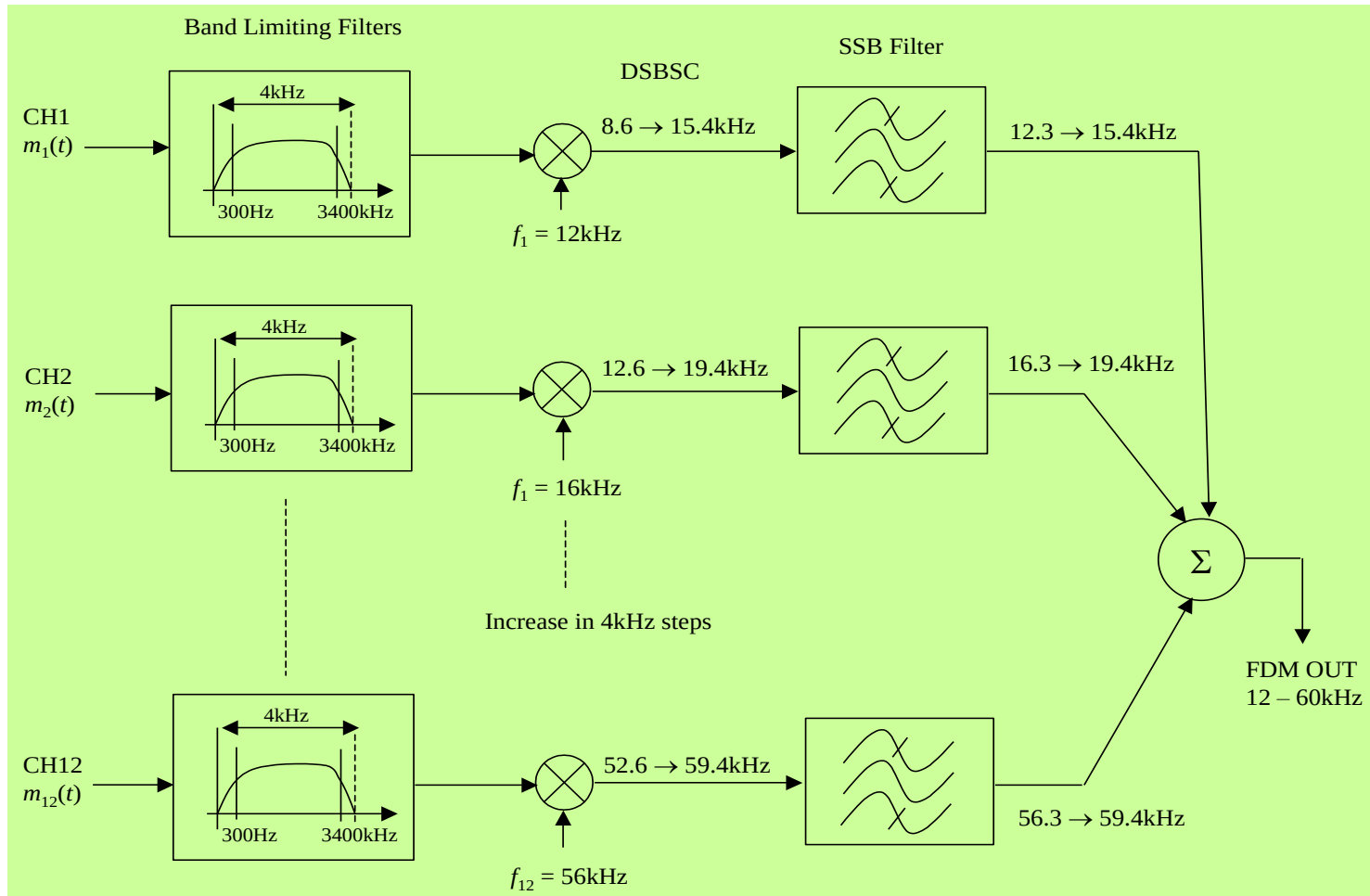
Basic 12 Channel Group

The diagram below illustrates the FDM principle for 12 channels (similar to 3 channels) to form a basic group.



i.e. 12 telephone channels are multiplexed in the frequency band 12kHz $\rightarrow$ 60 kHz in 4kHz channels $\equiv$ **basic group**.

A design for a basic 12 channel group is shown below:



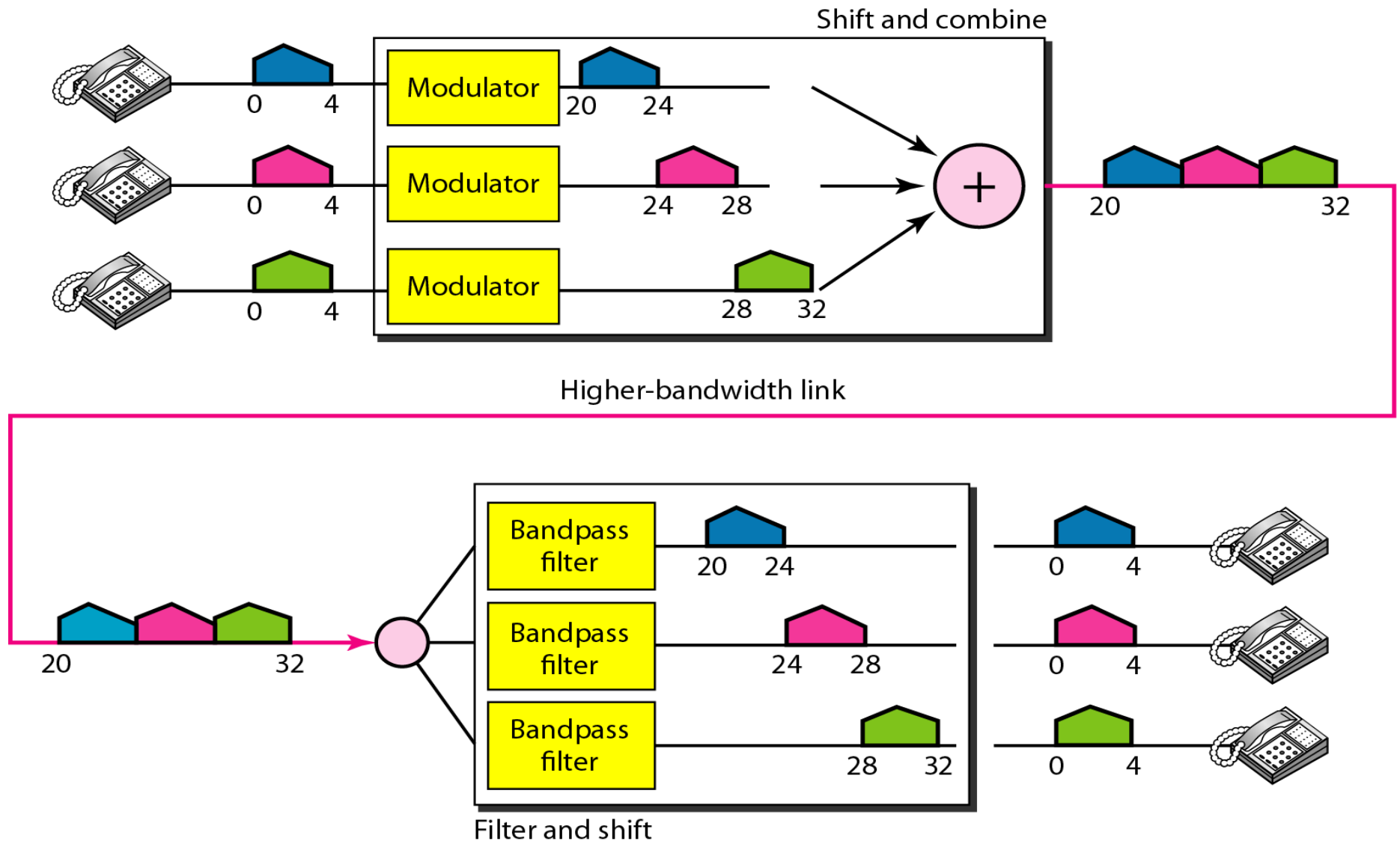


Example:

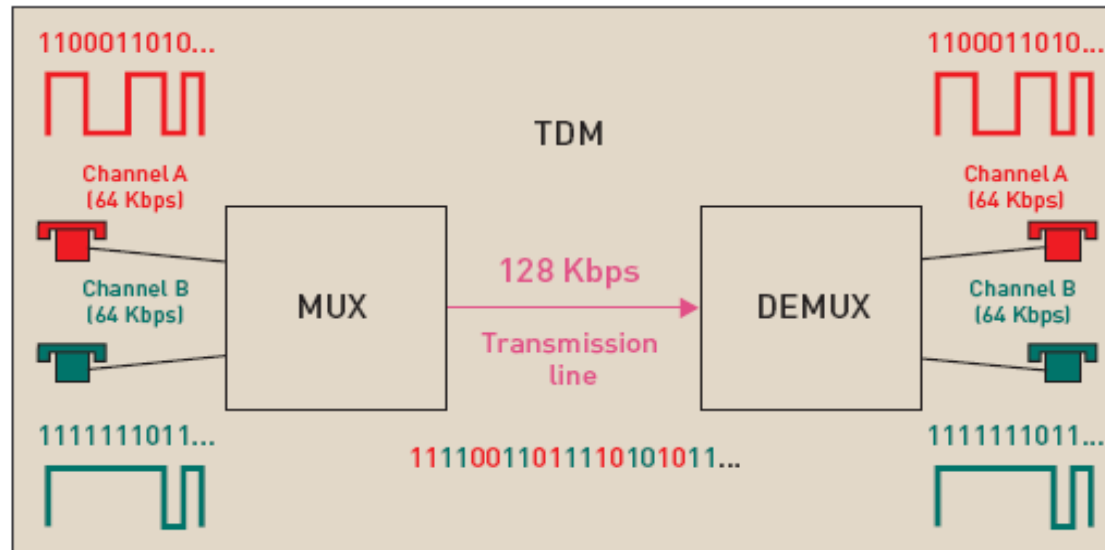
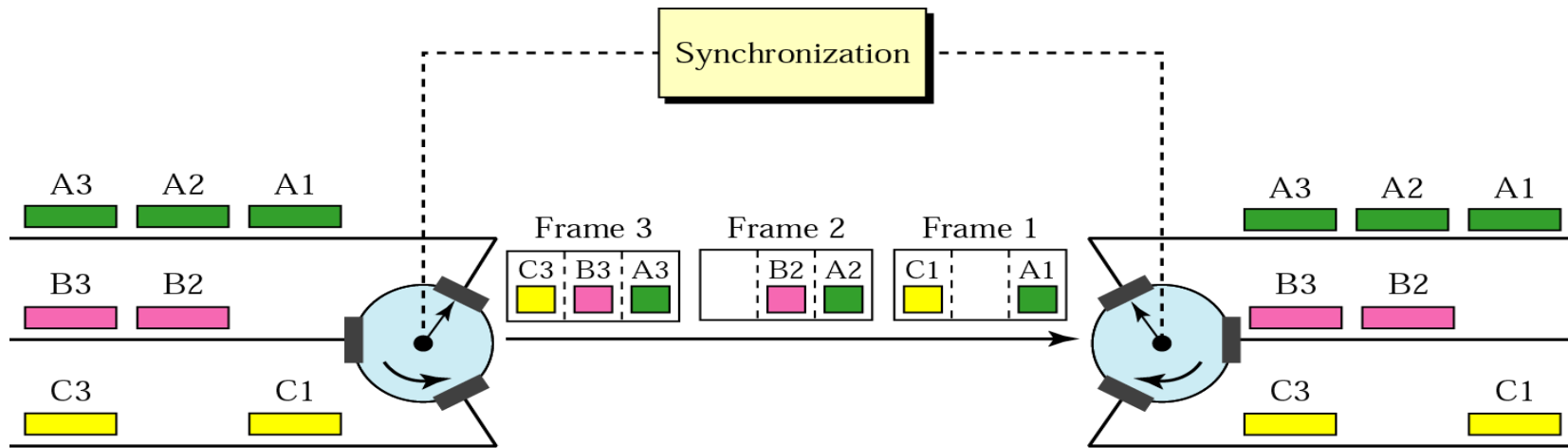
Assume that a voice channel occupies a bandwidth of 4 kHz. We need to combine three voice channels into a link with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain. Assume there are no guard bands.

Solution:

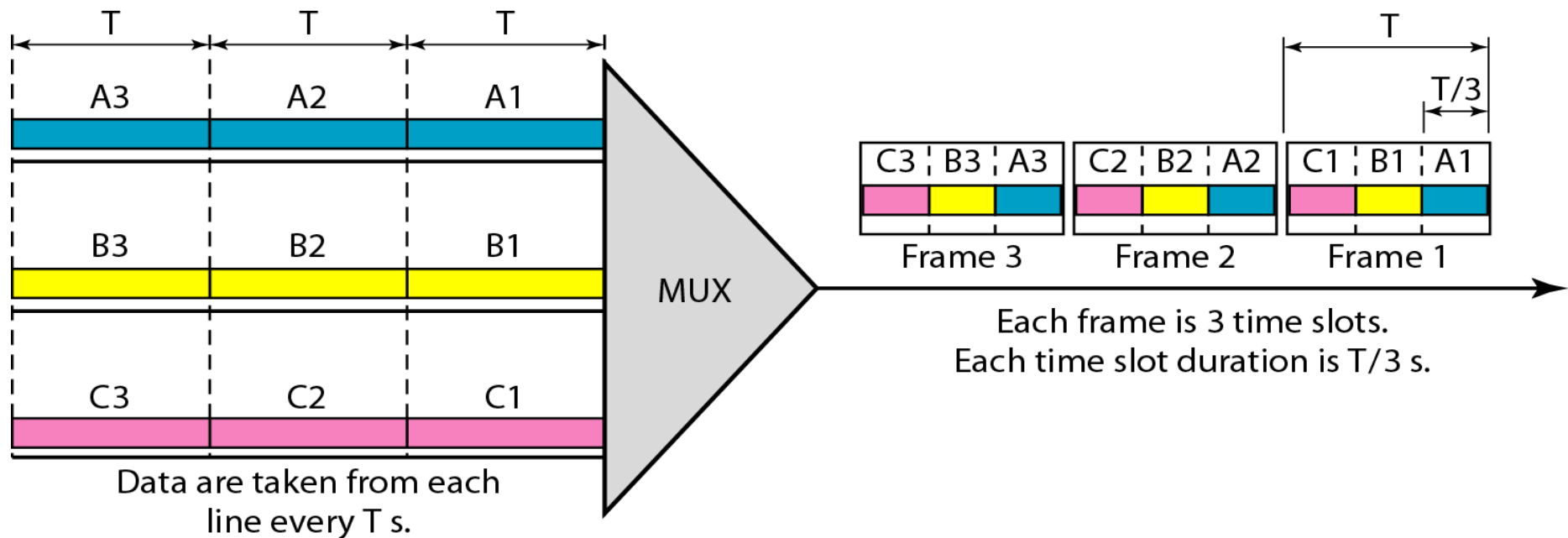
We shift (modulate) each of the three voice channels to a different bandwidth, as shown in Figure 6.6. We use the 20- to 24-kHz bandwidth for the first channel, the 24- to 28-kHz bandwidth for the second channel, and the 28- to 32-kHz bandwidth for the third one.



Time Division Multiplexing



TDM is a digital multiplexing technique for combining several low-rate digital channels into one high-rate one.





Example:

In Figure 6.13, the data rate for each one of the 3 input connection is 1 kbps. If 1 bit at a time is multiplexed (a unit is 1 bit), what is the duration of (a) each input slot, (b) each output slot, and (c) each frame?

Solution:

We can answer the questions as follows:

- a. The data rate of each input connection is 1 kbps. This means that the bit duration is $1/1000$ s or 1 ms. The duration of the input time slot is 1 ms (same as bit duration).*



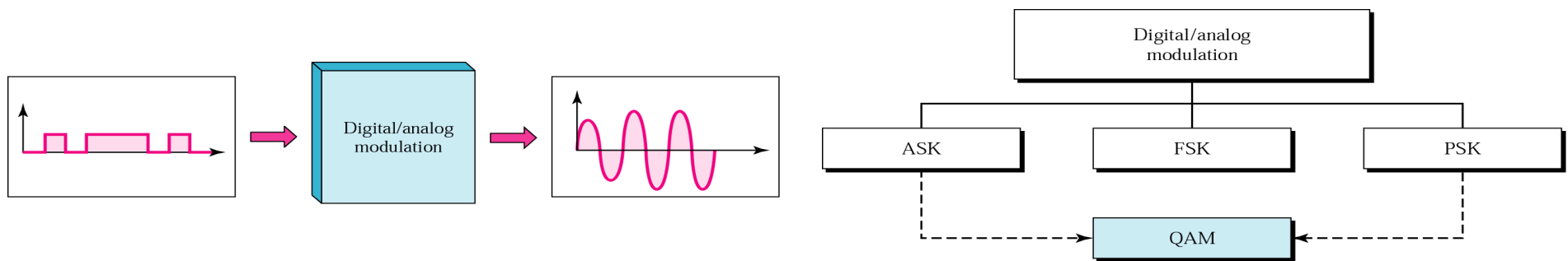
Example: (continued)

- b.*** *The duration of each output time slot is one-third of the input time slot. This means that the duration of the output time slot is $1/3$ ms.*
 - c.*** *Each frame carries three output time slots. So the duration of a frame is $3 \times 1/3$ ms, or 1 ms.*
- Note:** *The duration of a frame is the same as the duration of an input unit.*

Lecture-19-

*Analog Transmission:
ASK, FSK, PSK*

- Modulation of binary data or digital-to-analog modulation is the process of changing one of the characteristics of an analog signal based on the information in a digital signal (0s and 1s).
- Telephone wires carry analog signals.
- When we vary any one of these characteristics [amplitude or frequency or phase], we create a different version of that wave.
- Three mechanisms for modulating digital data into an analog signal: amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK).



Digital-to-analog modulation

Aspects of Digital-to-Analog Conversion

- A signal unit is composed of 1 or more bits.
- Bit Rate and Baud Rate:
 - Bit rate is the number of bits per second.
 - Baud rate is the number of signal units per second.
 - Bit rate equals the baud rate times the number of bits represented by each signal unit.
 - Baud rate equals the bit rate divided by the number of bits represented by each signal unit.
 - Baud rate is less than or equal to the bit rate.
- Baud rate determines the bandwidth required to send the signal.

Example 1

An analog signal carries 4 bits in each signal unit. If 1000 signal units are sent per second, find the baud rate and the bit rate

Solution

Baud rate = 1000 bauds per second (baud/s)

Bit rate = $1000 \times 4 = 4000$ bps

Example 2

The bit rate of a signal is 3000. If each signal unit carries 6 bits, what is the baud rate?

Solution

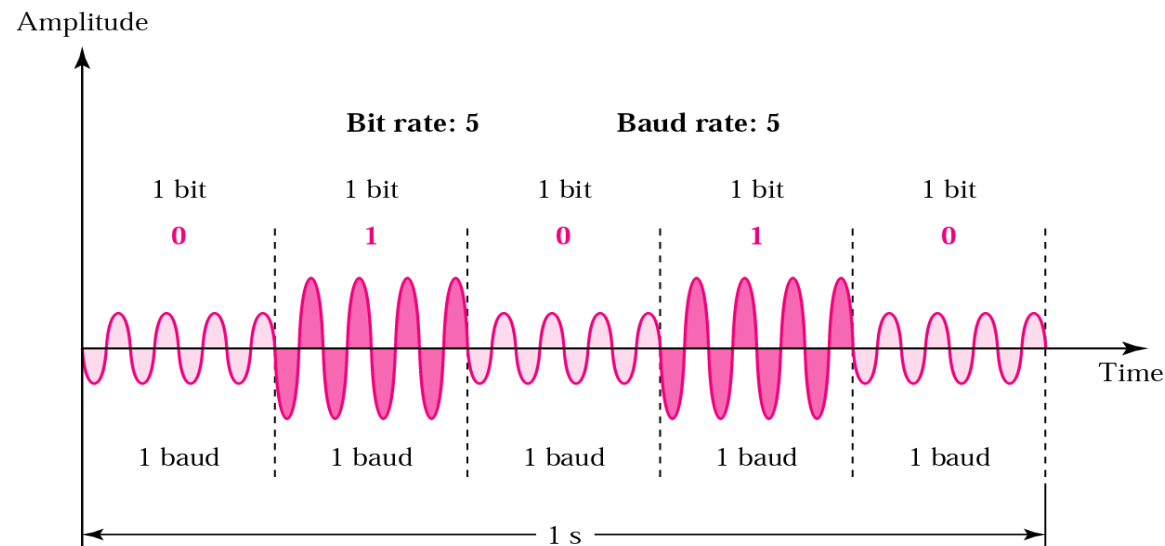
Baud rate = $3000 / 6 = 500$ baud/s

Carrier Signal

- In analog signal, the sending device produces a high-frequency signal that acts as a basis for the information signal. This base signal is called the carrier signal or carrier frequency.
- Receiving device is tuned to the frequency of the carrier signal that it expects from the sender.
- Digital information then modulates the carrier signal by modifying one or more of its characteristics (amplitude, frequency, or phase). This kind of modification is called modulation (or shift keying, and the information signal is called the modulating signal.

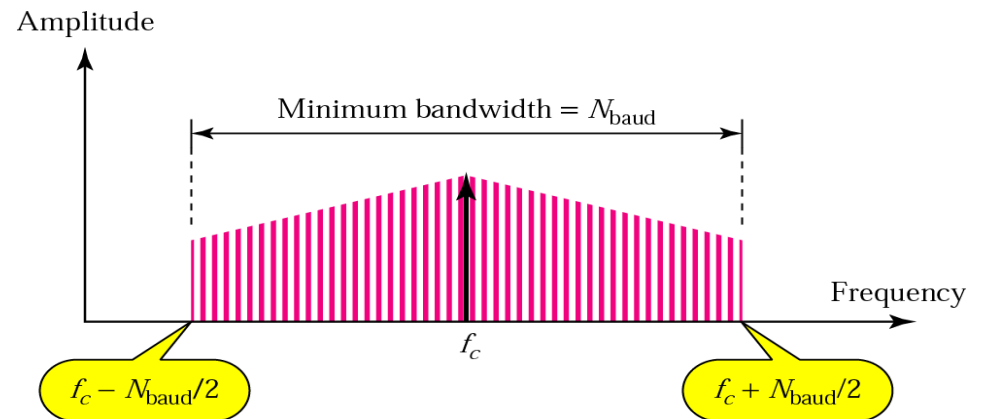
Amplitude Shift Keying (ASK)

- The strength of the carrier signal is varied to represent binary 1 or 0.
- Both frequency and phase remain constant while the amplitude changes.
- A bit duration is the period of time that defines 1 bit.
- Peak amplitude of the signal during each bit duration is constant, and its value depends on the bit (0 or 1).
- ASK is susceptible to noise interference. Noise refers to unintentional voltages introduced onto a line by various phenomena such as heat or electromagnetic induction created by other sources.



Bandwidth of a signal is the total range of frequencies occupied by that signal.

- When we decompose an ASK-modulated signal, we get a spectrum of many simple frequencies.
- Most significant ones are those between $f_c - N_{\text{baud}}/2$ and $f_c + N_{\text{baud}}/2$ with the carrier frequency f_c at the middle.
- Bandwidth $BW = (1 + d) * N_{\text{baud}}$
- BW is bandwidth, (N_{baud}) is baud rate, and (d) is a factor related to the modulation process (with a minimum value of 0).
- Although there is only one carrier frequency, the process of modulation produces a complex signal that is a combination of many simple signals, each with a different frequency.



Relationship between baud rate and bandwidth in ASK

Example 3

Find the minimum bandwidth for an ASK signal transmitting at 2000 bps. The transmission mode is half-duplex.

Solution

In ASK the baud rate and bit rate are the same. The baud rate is therefore 2000. An ASK signal requires a minimum bandwidth equal to its baud rate. Therefore, the minimum bandwidth is 2000 Hz.

Example 4

Given a bandwidth of 5000 Hz for an ASK signal, what are the baud rate and bit rate?

Solution

In ASK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But because the baud rate and the bit rate are also the same for ASK, the bit rate is 5000 bps.

Example 5

Given a bandwidth of 10,000 Hz (1000 to 11,000 Hz), draw the full-duplex ASK diagram of the system. Find the carriers and the bandwidths in each direction. Assume there is no gap between the bands in the two directions.

Solution

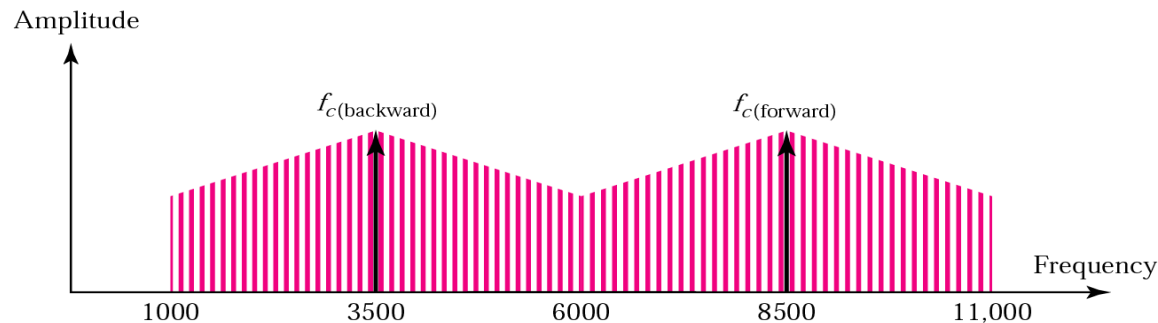
For full-duplex ASK, the bandwidth for each direction is

$$BW = 10000 / 2 = 5000 \text{ Hz}$$

The carrier frequencies can be chosen at the middle of each band.

$$f_c(\text{forward}) = 1000 + 5000/2 = 3500 \text{ Hz}$$

$$f_c(\text{backward}) = 11000 - 5000/2 = 8500 \text{ Hz}$$

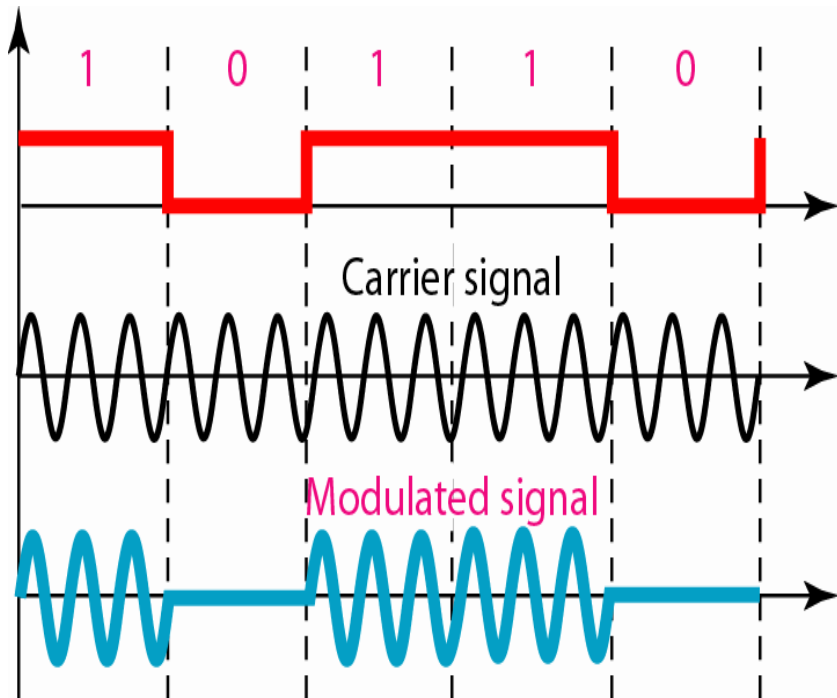
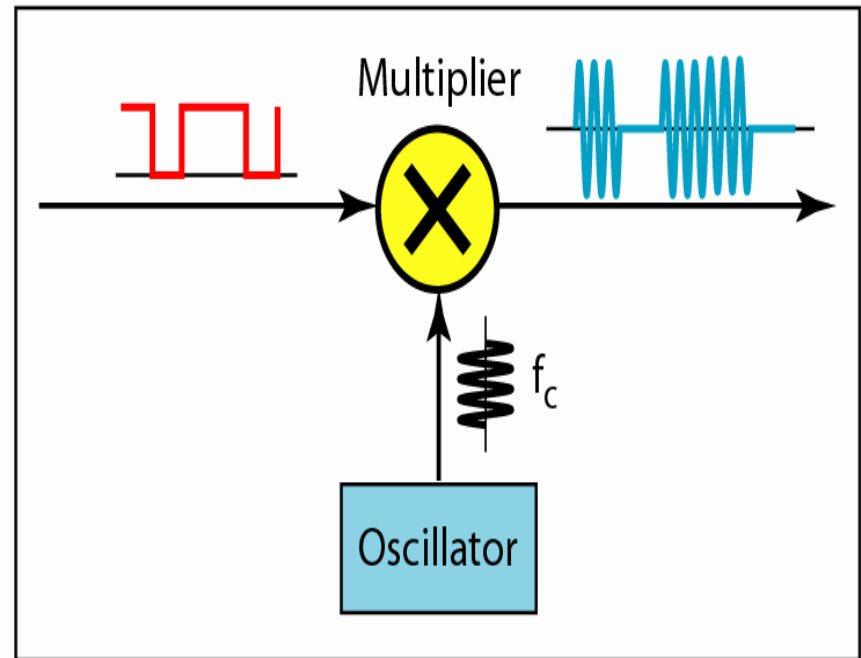


Advantage: simplicity

Disadvantage: ASK is very susceptible to noise interference –noise usually (only) affects the amplitude, therefore ASK is the modulation technique most affected by noise.

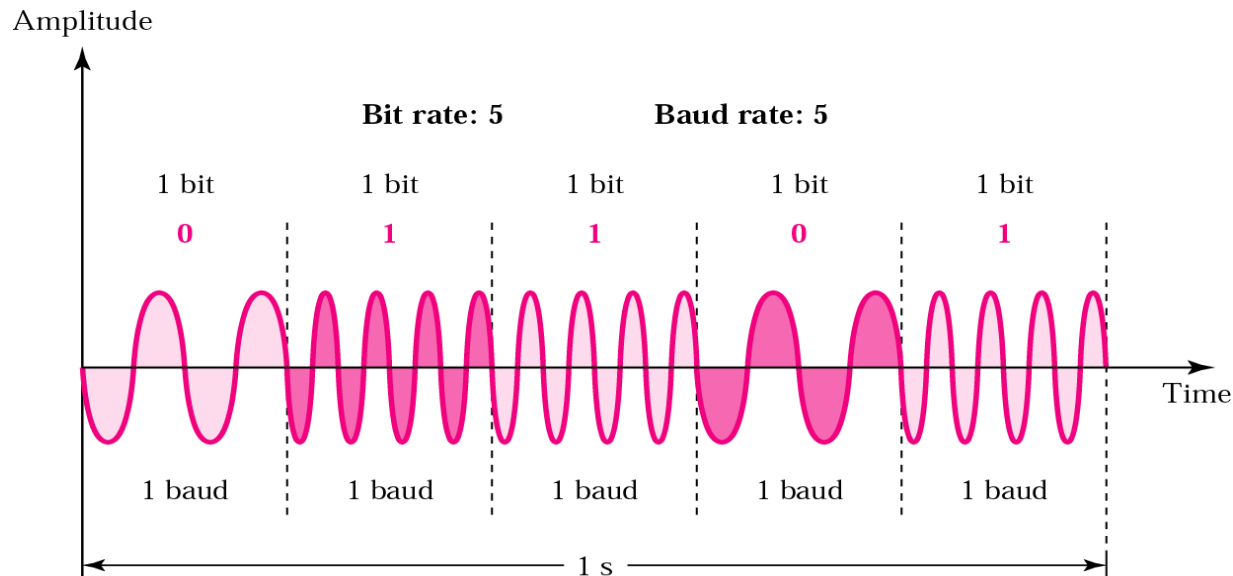
Application: ASK is used to transmit digital data over optical fiber

ASK Example

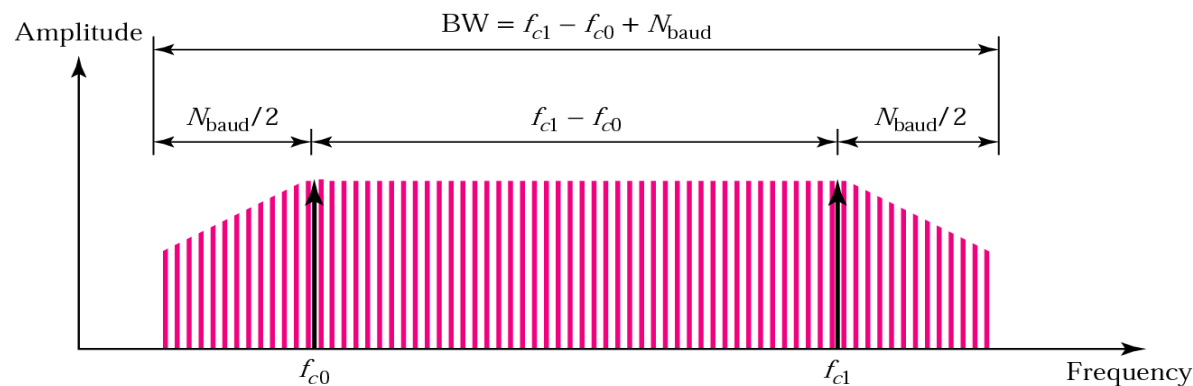


Frequency Shift Keying (FSK)

- Frequency of the carrier signal is varied to represent binary 1 or 0.
- Frequency of the signal during each bit duration is constant, and its value depends on the bit (0 or 1); both peak amplitude and phase remain constant.
- FSK avoids most of the problems from noise.
- Because the receiving device is looking for specific frequency changes over a given number of periods, it can ignore voltage spikes.



- Although FSK shifts between two carrier frequencies, it is easier to analyse as two co-existing frequencies.
- FSK spectrum is a combination of two ASK spectra centered on f_{c0} and f_{c1} . The bandwidth required for FSK transmission is equal to the baud rate of the signal plus the frequency shift (difference between the two carrier frequencies): $BW = f_{c1} - f_{c0} + N_{\text{baud}}$
- Although there are only two carrier frequencies, the process of modulation produces a composite signal that is a combination of many simple signals, each with a different frequency.



Relationship between baud rate and bandwidth in FSK

Example 6

Find the minimum bandwidth for an FSK signal transmitting at 2000 bps. Transmission is in half-duplex mode, and the carriers are separated by 3000 Hz.

Solution

For FSK:

$$BW = \text{baud rate} + f_{c1} - f_{c0}$$

$$BW = \text{bit rate} + f_{c1} - f_{c0} = 2000 + 3000 = 5000 \text{ Hz}$$

Example 7

Find the maximum bit rates for an FSK signal if the bandwidth of the medium is 12,000 Hz and the difference between the two carriers is 2000 Hz. Transmission is in full-duplex mode.

Solution

Because the transmission is full duplex, only 6000 Hz is allocated for each direction.

$$BW = \text{baud rate} + f_{c1} - f_{c0}$$

$$\text{Baud rate} = BW - (f_{c1} - f_{c0}) = 6000 - 2000 = 4000$$

But because the baud rate is the same as the bit rate, the bit rate is 4000 bps.

Demodulation: demodulator must be able to determine which of two possible frequencies is present at a given time.

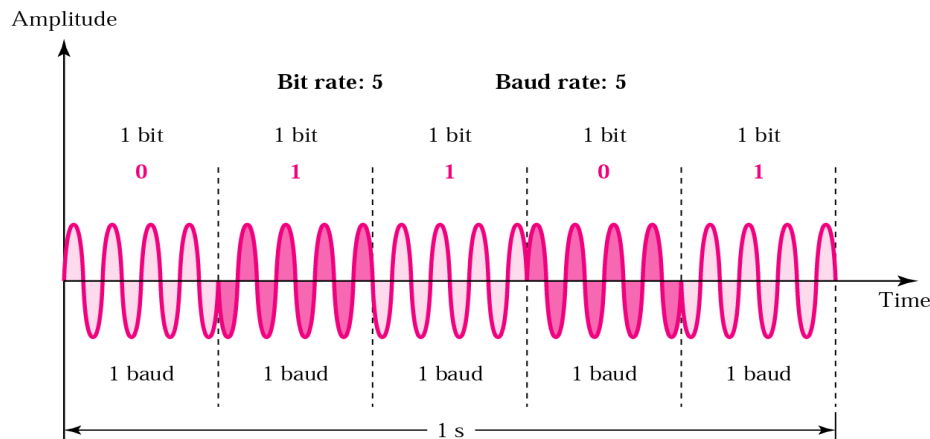
Advantage: FSK is less susceptible to errors than ASK – receiver looks for specific frequency changes over a number of intervals, so voltage (noise) spikes can be ignored.

Disadvantage: FSK spectrum is 2 x ASK spectrum.

Application: over voice lines, in high-freq. radio transmission, etc.

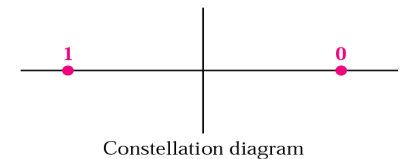
Phase Shift Keying (PSK)

- The phase of the carrier is varied to represent binary 1 or 0.
- Both peak amplitude and frequency remain constant as the phase changes.
- If we start with a phase of 0° to represent binary 0, then we can change the phase to 180° to send binary 1.
- The phase of the signal during each bit duration is constant, and its value depends on the bit (0 or 1).
- 2-PSK or binary PSK: Two different phases (0° and 180°) are used. Constellation or phase-state diagram shows the relationship by illustrating only the phases.



Bit	Phase
0	0
1	180

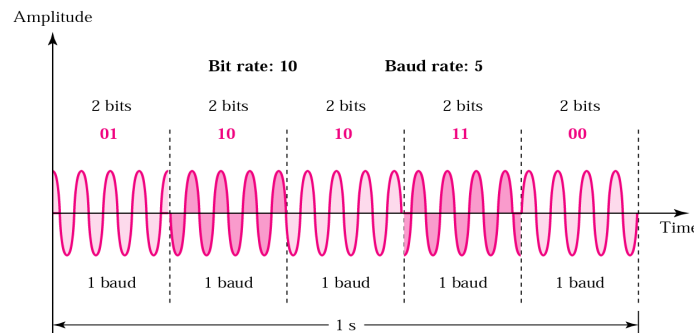
Bits



The 4-PSK method

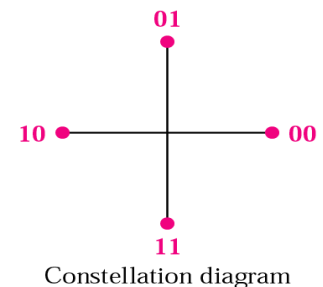
PSK is not susceptible to the noise degradation that affects ASK or to the bandwidth limitations of FSK.

- Even smaller variations in the signal can be detected reliably by the receiver.
- Instead of utilizing only two variations of a signal, each representing 1 bit, we can use four variations and let each phase shift represent 2 bits.
- A phase of 0° now represents 00; 90° represents 01; 180° represents 10; and 270° represents 11. This technique is called 4-PSK or Q-PSK. The pair of bits represented by each phase is called a **dibit**. We can transmit data twice as efficiently using 4-PSK as we can using 2-PSK.



Dibit	Phase
00	0
01	90
10	180
11	270

Dibit
(2 bits)

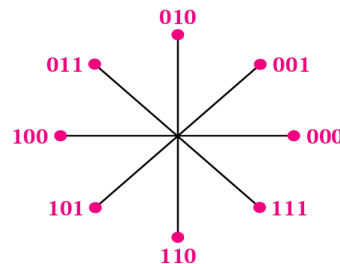
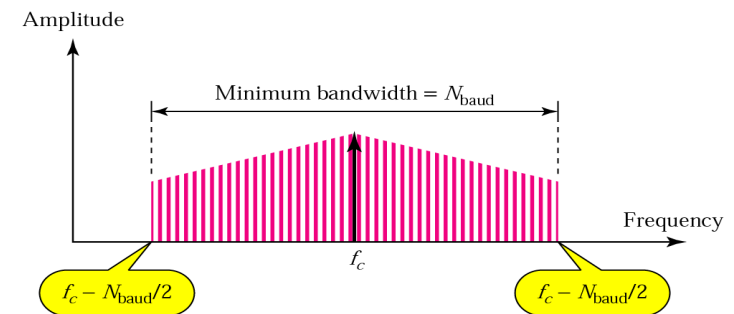


The 8-PSK characteristics

- 8-PSK: Instead of 90, we now vary the signal by shifts of 45.
- With eight different phases, each shift can represent 3 bits (1 tribit) at a time.
- 8-PSK is 3 times as efficient as 2-PSK.
- Minimum bandwidth required for PSK transmission is the same as that required for ASK transmission.
- Maximum bit rate in PSK transmission is much greater than that of ASK.
- While the maximum baud rates of ASK and PSK are the same for a given bandwidth, PSK bit rates using the bandwidth can be 2 or more times greater.

Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Tribits
(3 bits)



Example 8

Find the bandwidth for a 4-PSK signal transmitting at 5000 bps. Transmission is in half-duplex mode.

Solution

For PSK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But in 8-PSK the bit rate is 3 times the baud rate, so the bit rate is 15,000 bps.

Example 9

Given a bandwidth of 5000 Hz for an 8-PSK signal, what are the baud rate and bit rate?

Solution

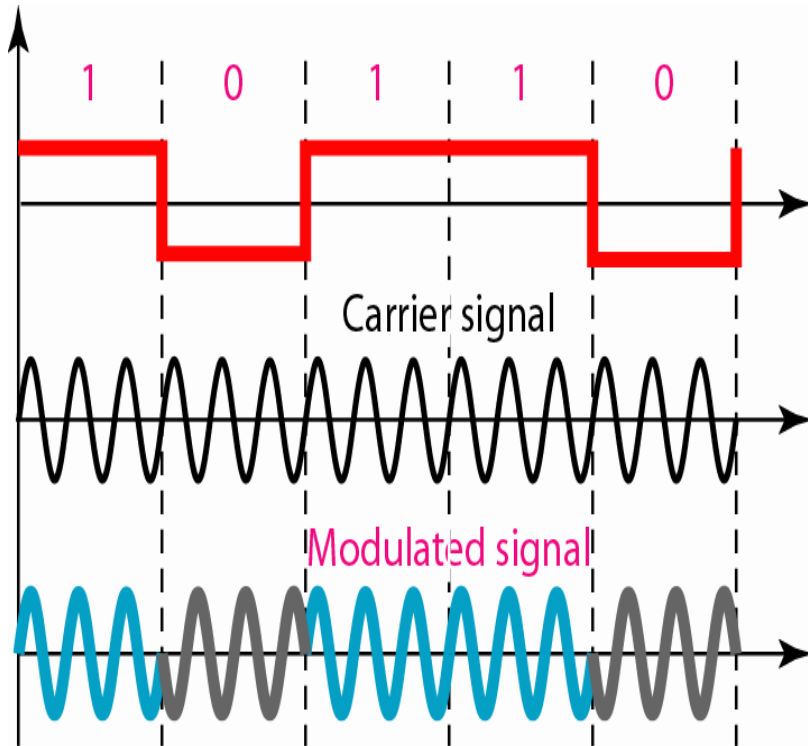
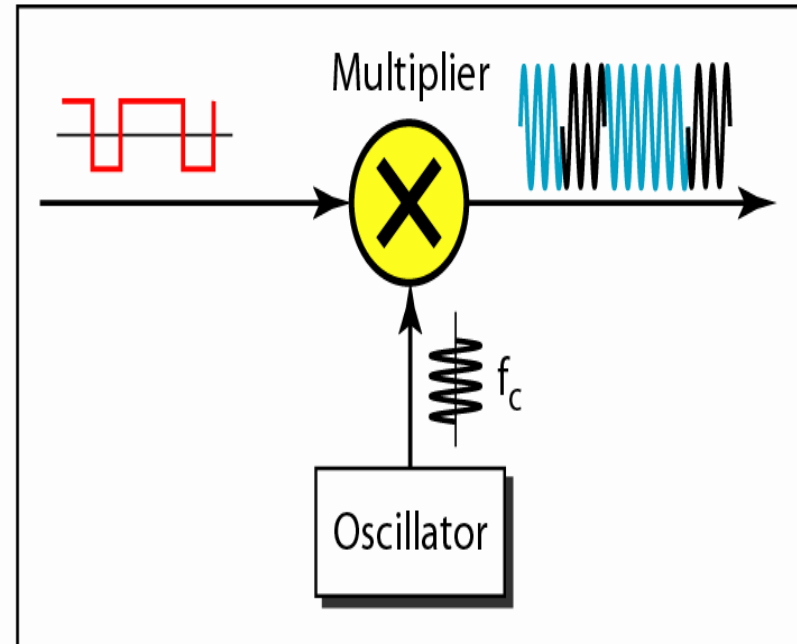
For PSK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But in 8-PSK the bit rate is 3 times the baud rate, so the bit rate is 15,000 bps.

Demodulation: demodulator must determine the phase of received sinusoid with respect to some reference phase.

Advantage: PSK is less susceptible to errors than ASK, while it requires/occupies the same bandwidth as ASK. More efficient use of bandwidth (higher data-rate) are possible, compared to FSK !!!

Disadvantage: more complex signal detection / recovery process, than in ASK and FSK.

PSK Example



PSK is equivalent to multiplying carrier signal by +1 when the information is 1, and by -1 when the information is 0.

Lecture-20-

*Multiple Division Techniques:
FDMA, TDMA, CDMA*

Multiple Access Techniques

- The transmission from the BS in the downlink can be heard by each and every mobile user in the cell, and is referred as *broadcasting*. Transmission from the mobile users in the uplink to the BS is many-to-one, and is referred to as multiple access.
- Multiple access schemes to allow many users to share simultaneously a finite amount of radio spectrum resources.
 - Should not result in severe degradation in the performance of the system as compared to a single user scenario.
 - Approaches can be broadly grouped into two categories: narrowband and wideband.

Multiple Access Techniques

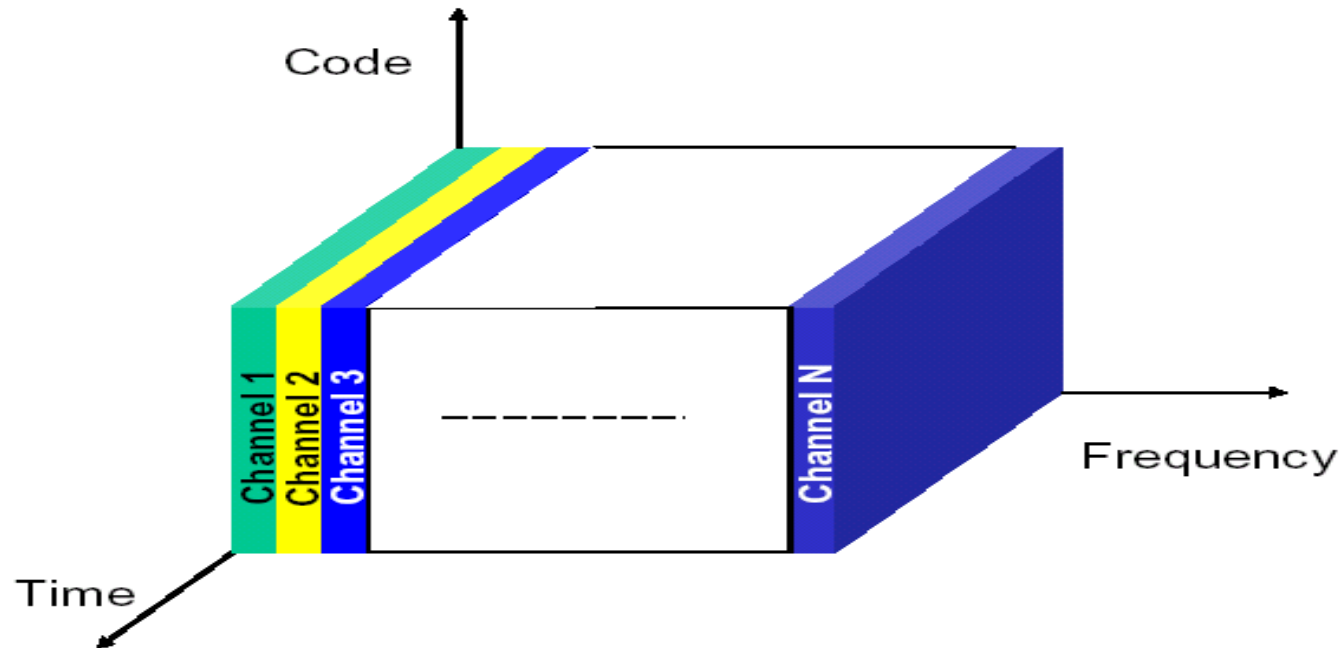
- Multiple Accessing Techniques :
 - Frequency division multiple access (FDMA)
 - Time division multiple access (TDMA)
 - Code division multiple access (CDMA)
 - Space division multiple access (SDMA)
- To provide simultaneous two-way communication (duplex communication) :
 - Frequency division duplexing (FDD)
 - Time Division Duplexing (TDD)
- FDMA uses FDD, TDMA & CDMA uses TDD @FDD

Concepts and Models of FDMA, TDMA and CDMA

- In one BS radio service range, may be many MSs are located.
- MS must distinguish which signal meant for itself among many signals being transmitted by other users.
- BS should be able to recognize the signal sent by a particular user.
- In cellular system, MS not only can distinguish a signal from a serving BS but also can discriminate the signal from adjacent BS. – Multiple access techniques important in mobile cellular system.

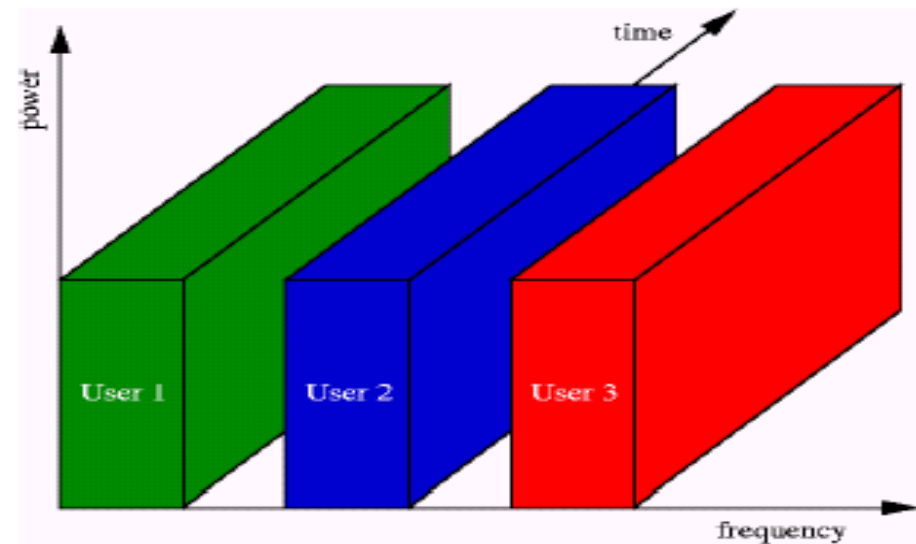
FDMA

Basic principles - FDMA



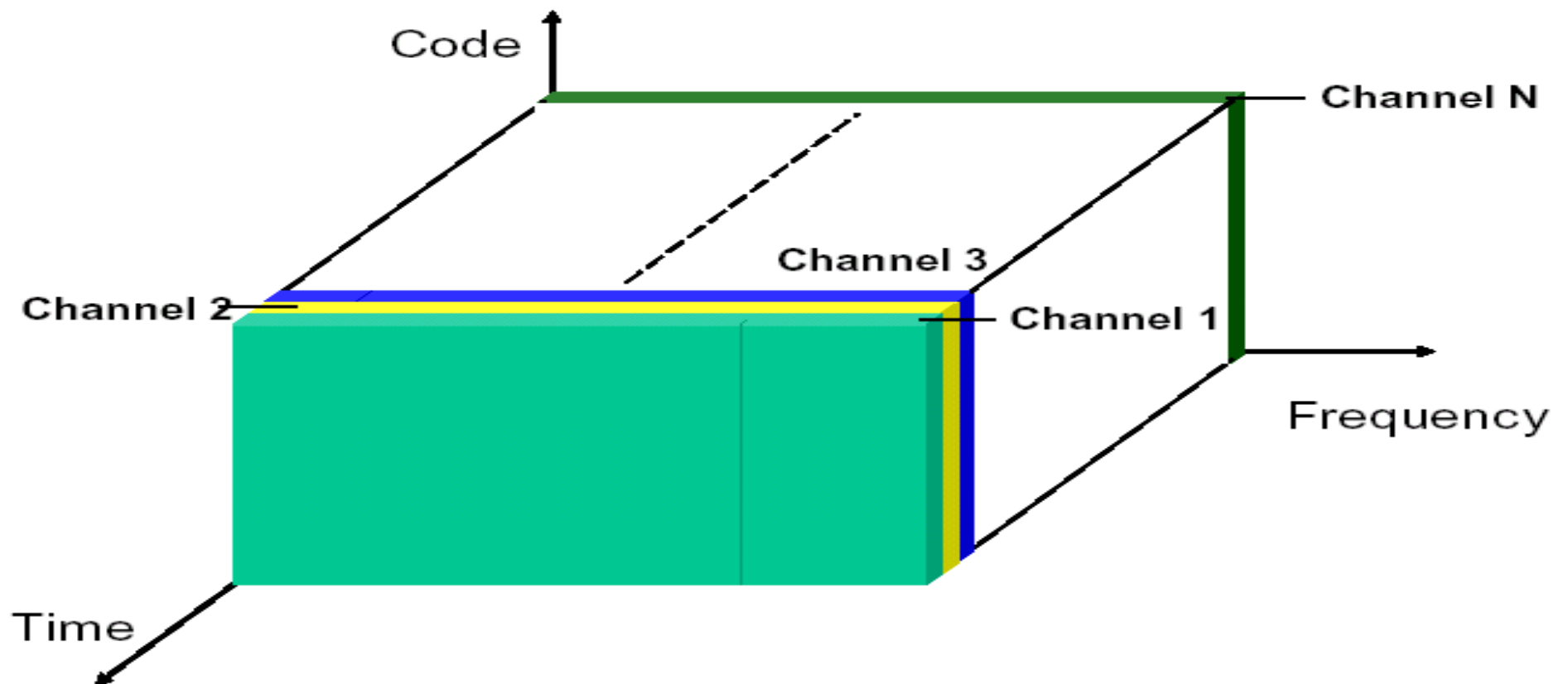
FDMA

- ❑ Individual channels are assigned to individual users for the time of an ongoing communication
- ❑ Inefficient if customer does not use the channel (voice call)
- ❑ In case of FDD a pair of frequencies is formed to a channel
- ❑ No equalization needed (symbol time $>$ delay spread)
- ❑ No synchronization and framing bits are needed as in TDMA systems
- ❑ Continuous transmission
- ❑ AMPS first analog cellular system in the US uses FDMA/FDD



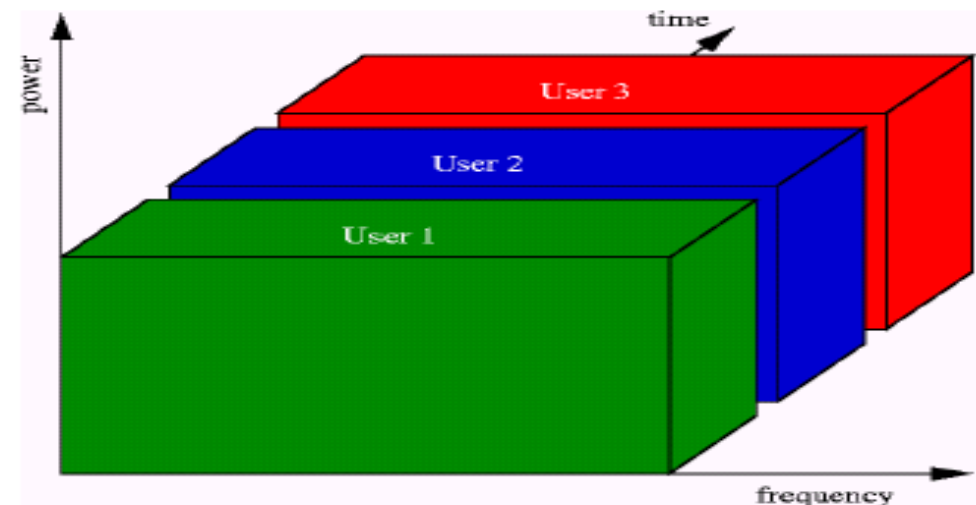
TDMA

Basic principles - TDMA

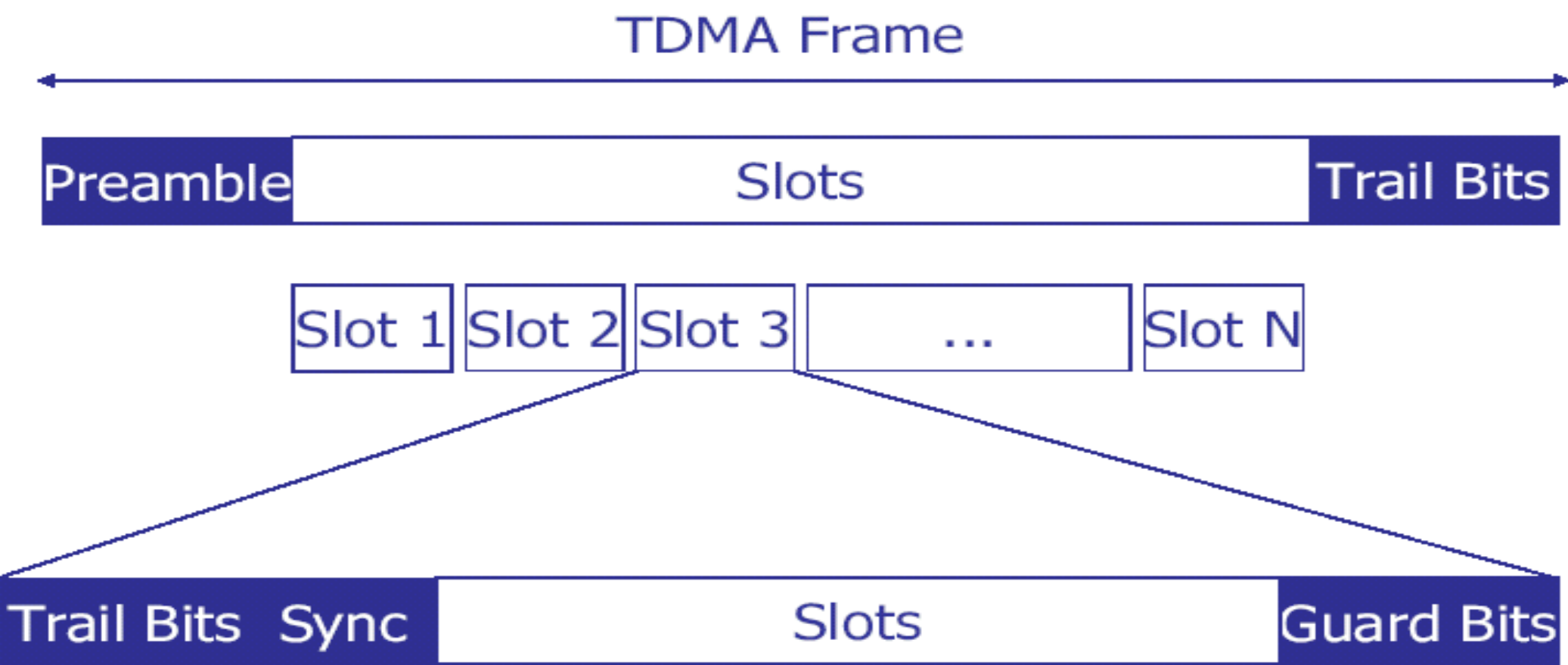


TDMA

- ❑ Spectrum is divided into time slots, where only one user is allowed to send per slot
- ❑ Cyclic usage of the slots (1, N+1, N+2, etc), N slots per frame
- ❑ Each frame and slot starts with preamble containing synchronization information
- ❑ Non-continuous transmission
- ❑ Guard times needed
- ❑ Data transmission in bursts result in low battery consumption
- ❑ Multiple slots per user possible
- ❑ Easy handoff because of idle times

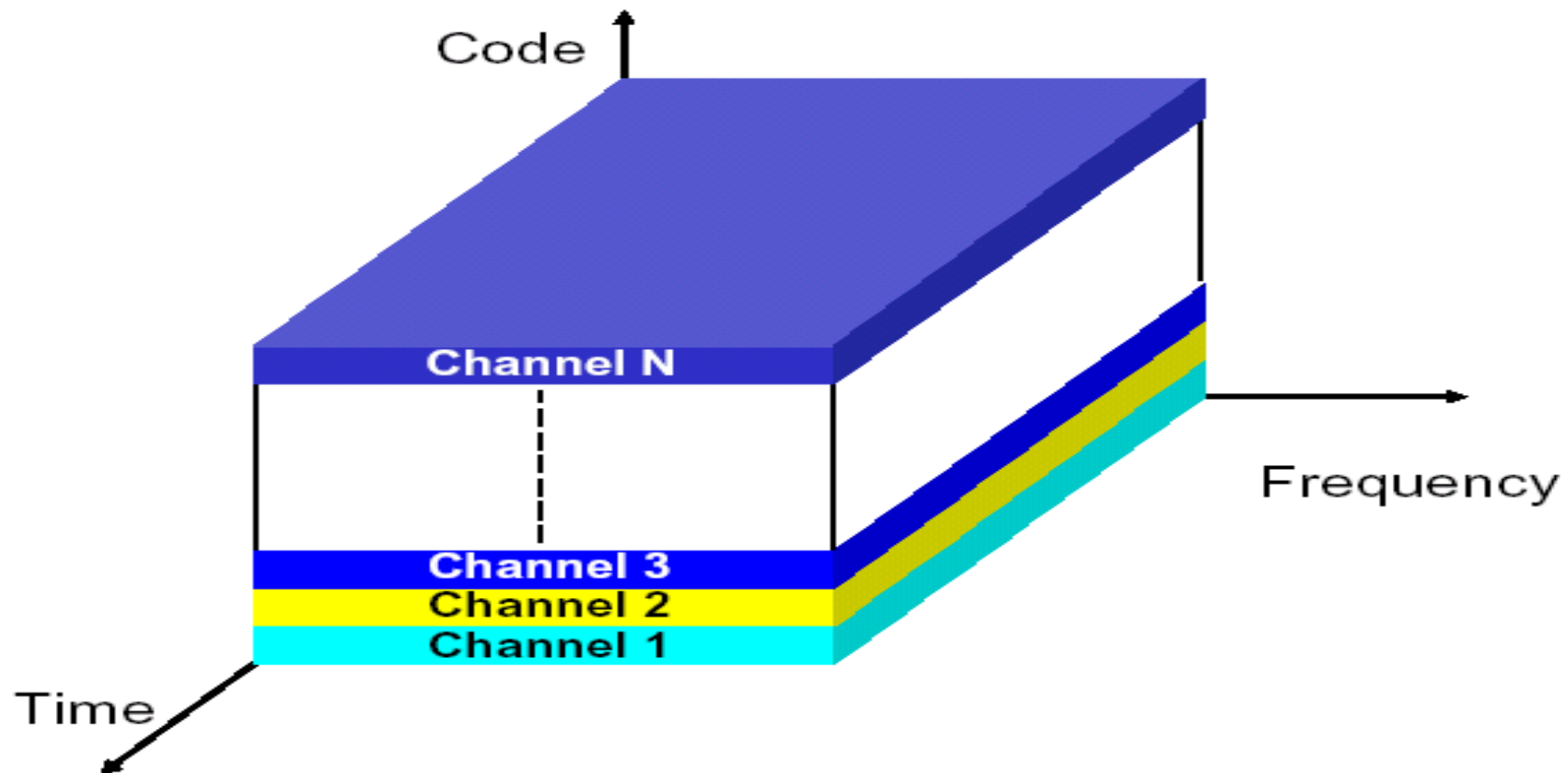


TDMA



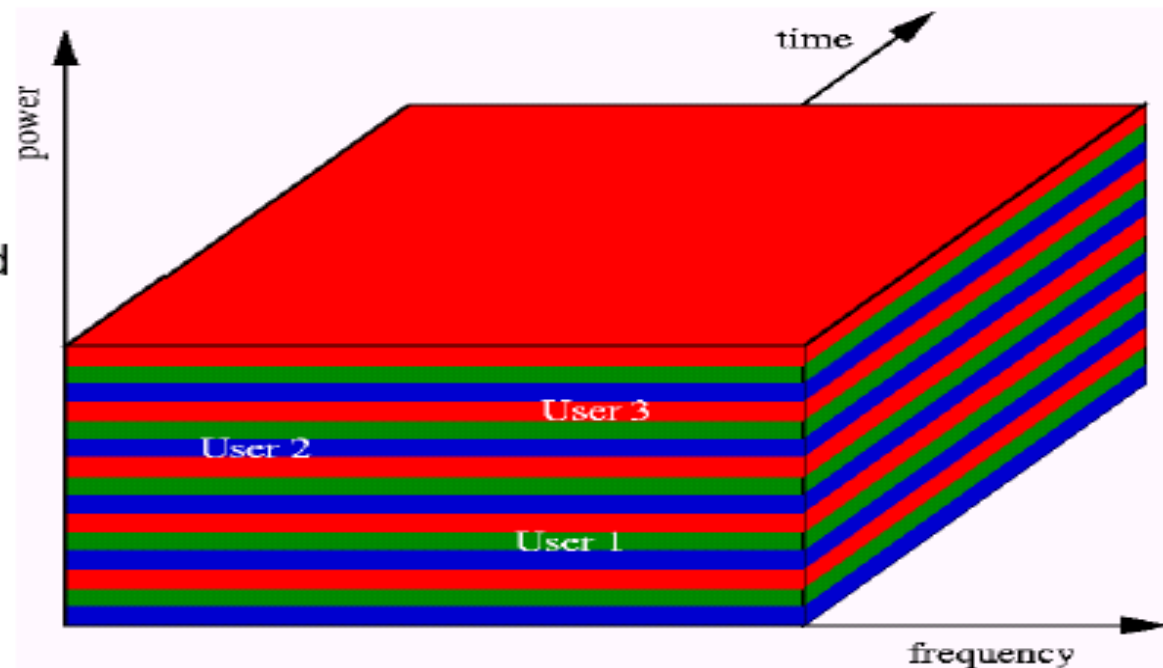
CDMA

Basic principles - CDMA



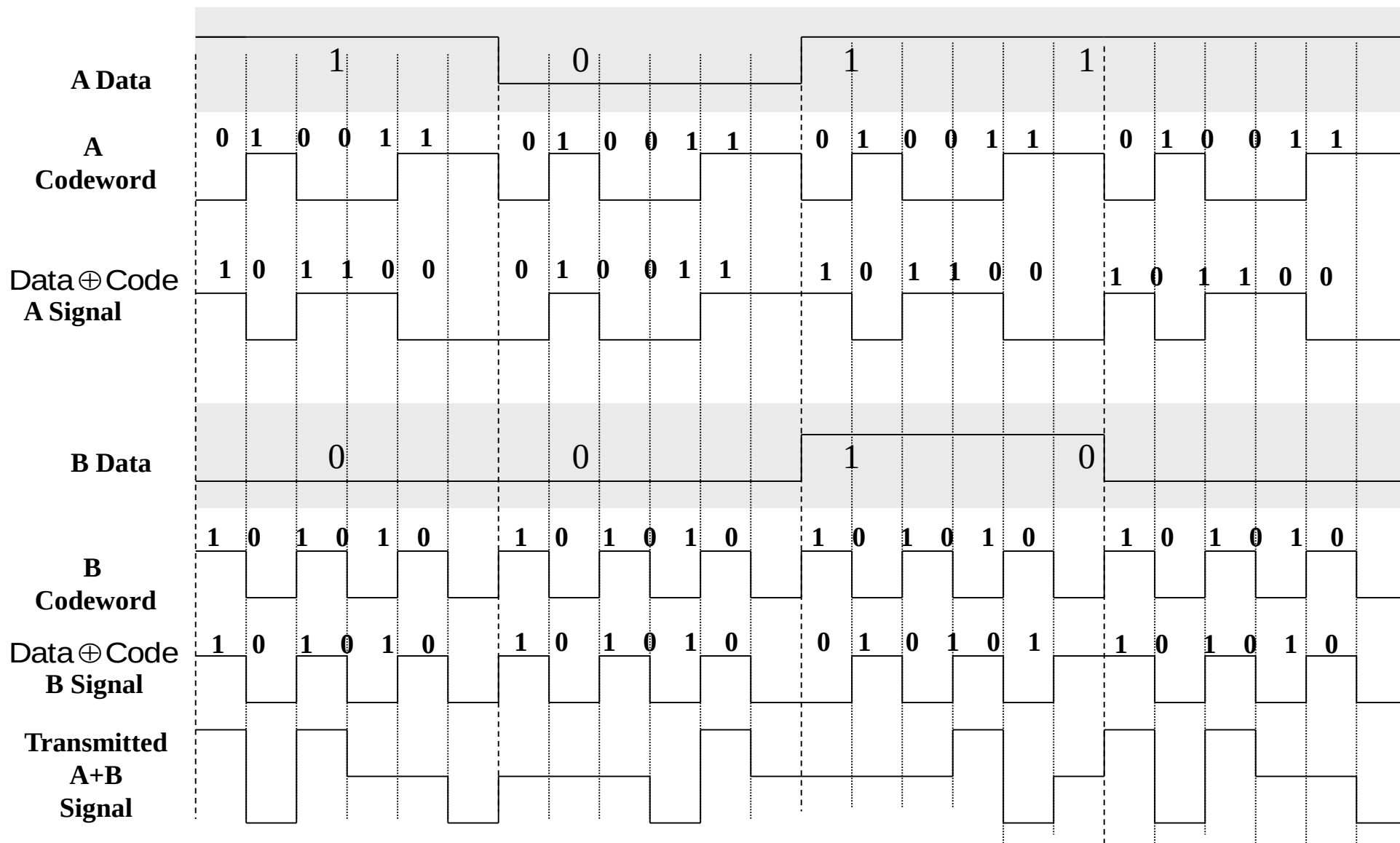
CDMA

- ❑ The user's signal is spread by an unique sequence
- ❑ All user share the same bandwidth with different sequences
- ❑ A communication is identify by the sequence
- ❑ Sender and receiver know the sequence in advance
- ❑ Other ongoing communication appears to be noise
- ❑ Power control needed to avoid near far effect
- ❑ Soft capacity limit
- ❑ Multi-path is reduced due to spreading sequence

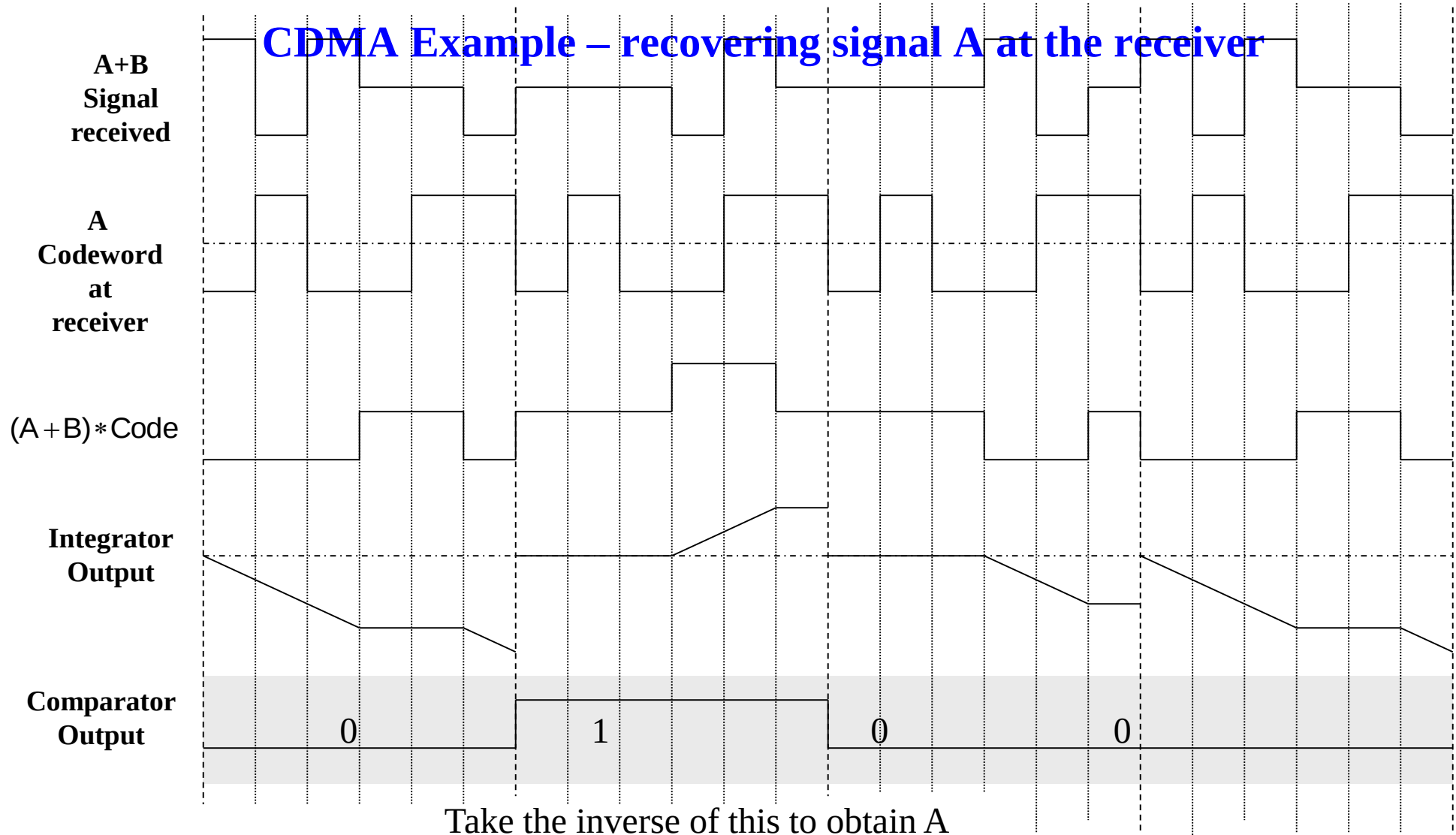


CDMA

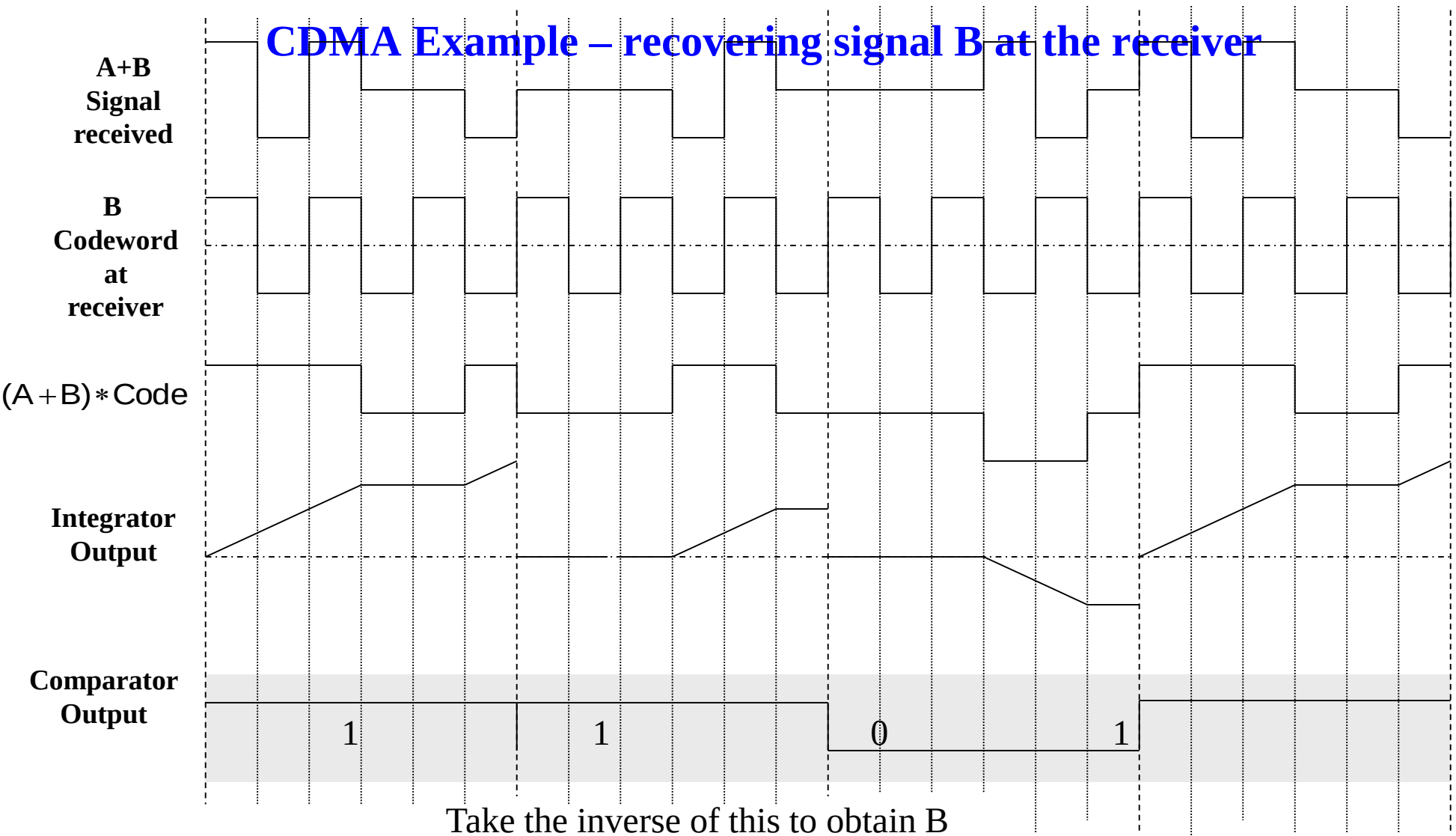
- CDMA is a system based on spread-spectrum technology.
- Spread-spectrum – transmission technique wherein data occupy a larger bandwidth than necessary.
- There are two basic types of implementation methodologies:
 - Direct Sequence (DS).
 - Frequency Hopping (FH).



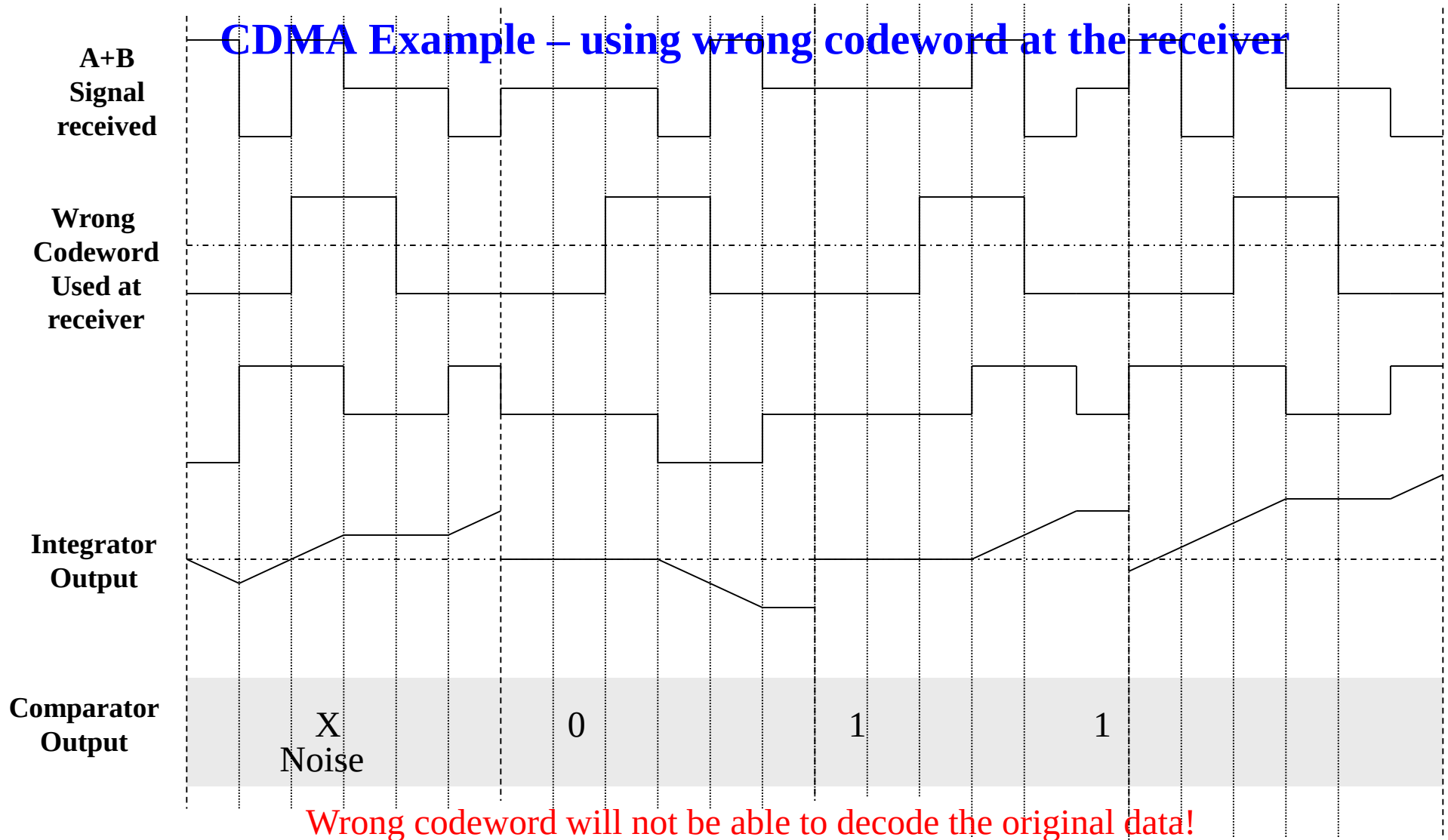
CDMA Example – recovering signal A at the receiver



CDMA Example – recovering signal B at the receiver



CDMA Example – using wrong codeword at the receiver



Lecture-21-

Bluetooth

What is Bluetooth?

- Bluetooth is a new standard developed by a group of electronics manufacturers that will allow any sort of electronic equipment -- from computers and cell phones to keyboards and headphones -- *to make its own connections, without wires, cables or any direct action from a user.*
- A key difference with other existing wireless technologies is that bluetooth enables *combined usability models based on functions provided by different devices.*
- The name is attributed to Harald Bluetooth was king of Denmark around the turn of the last millennium.

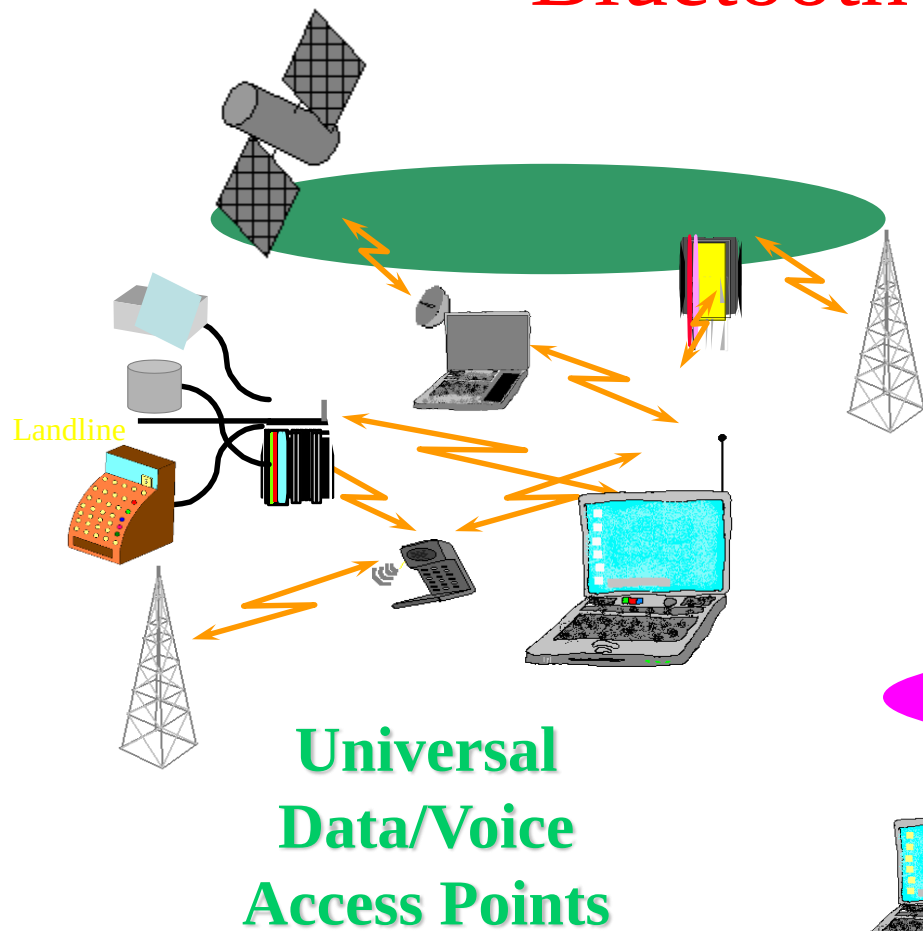
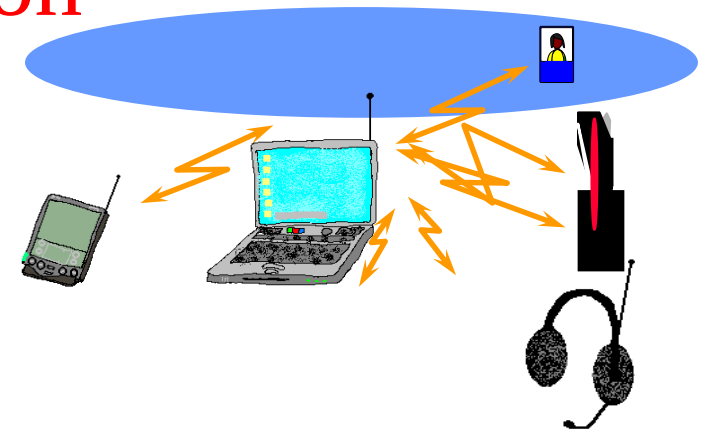
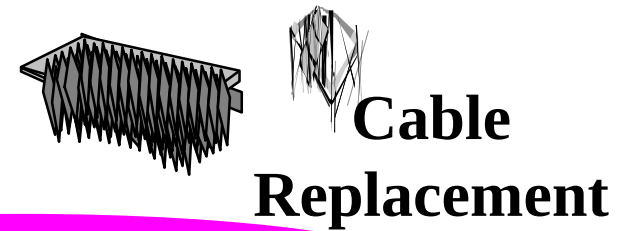
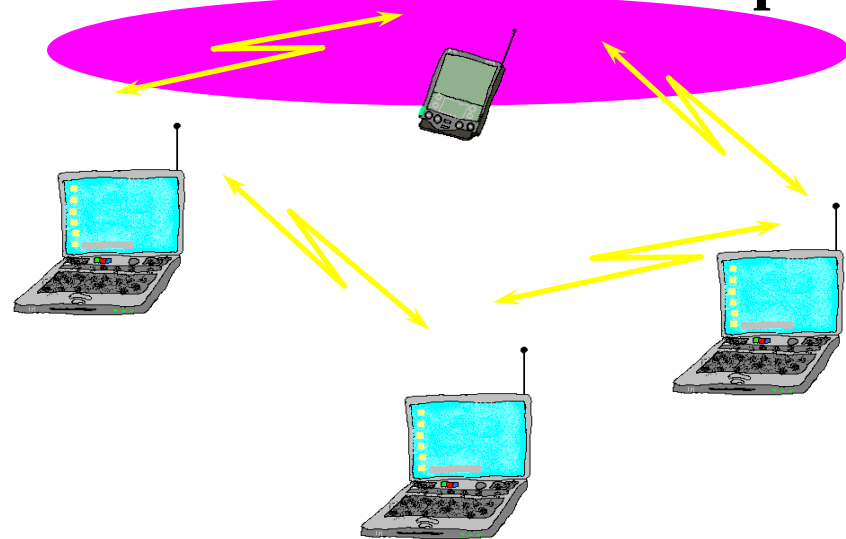
Why Bluetooth?

- Present wireless technology like *infra red* data communication has two problems –1)*Line of Sight* 2) *One to One*.
- Using *data synchronizing*– e.g. hot syn on a PDA --- problem of using the right cradle and cable.
- **BLUETOOTH OVERCOMES THESE PROBLEMS.**

Bluetooth Overview

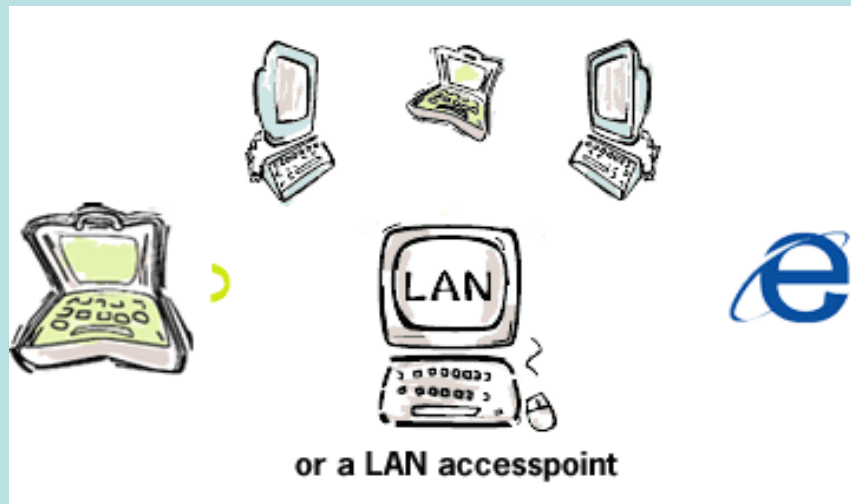
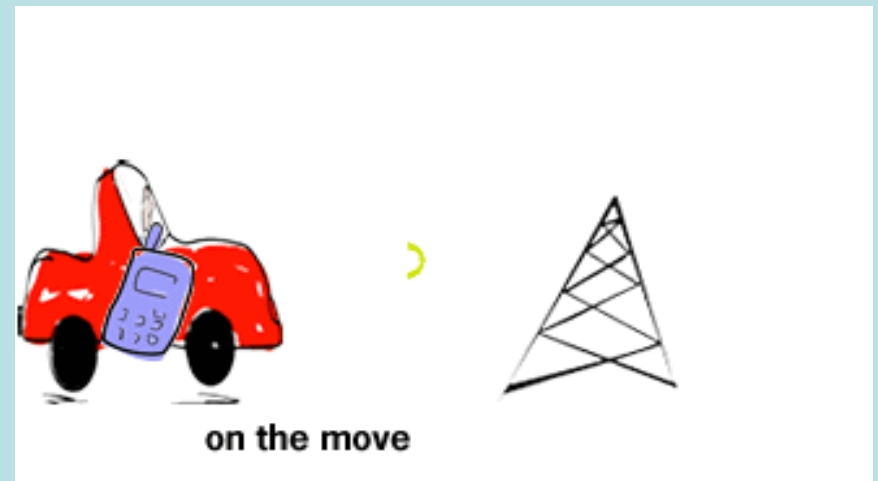
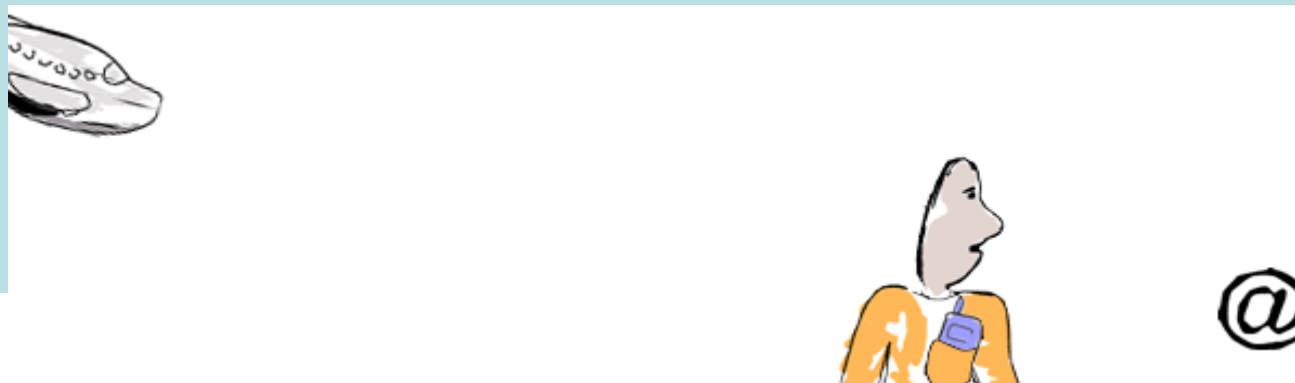
- Wireless technology for short-range voice and data communication.
- Low-cost and low-power.
- Provides a communication platform between a wide range of “smart” devices.
- Not limited to “line of sight” communication.

Bluetooth Vision



Personal Ad-hoc Networks

Data Access Points



Cable Replacement



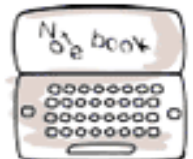
wirelessly connected



to your mobile phone



or to a PSTN adapter



Bluetooth Applications

- Automatic synchronization between mobile and stationary devices.
- Connecting mobile users to the internet using bluetooth-enabled wire-bound connection ports.
- Dynamic creation of private networks.

Connecting to Internet

- Being able to gain access to the Internet by using “Bluetooth access points”:
 - Access point is used as a gateway to the internet.
 - Both the access point and the device are Bluetooth-enabled.
 - An example of Service Discovery Protocol
 - Access point provides a service to the device.

Ad Hoc Networks

- Up to 8 devices can be actively connected in master/slave configuration.
- Piconets can be combined to form scatter nets providing unlimited device connectivity.
- A **piconet** is an ad-hoc computer network linking a wireless user group of devices using Bluetooth technology protocols.

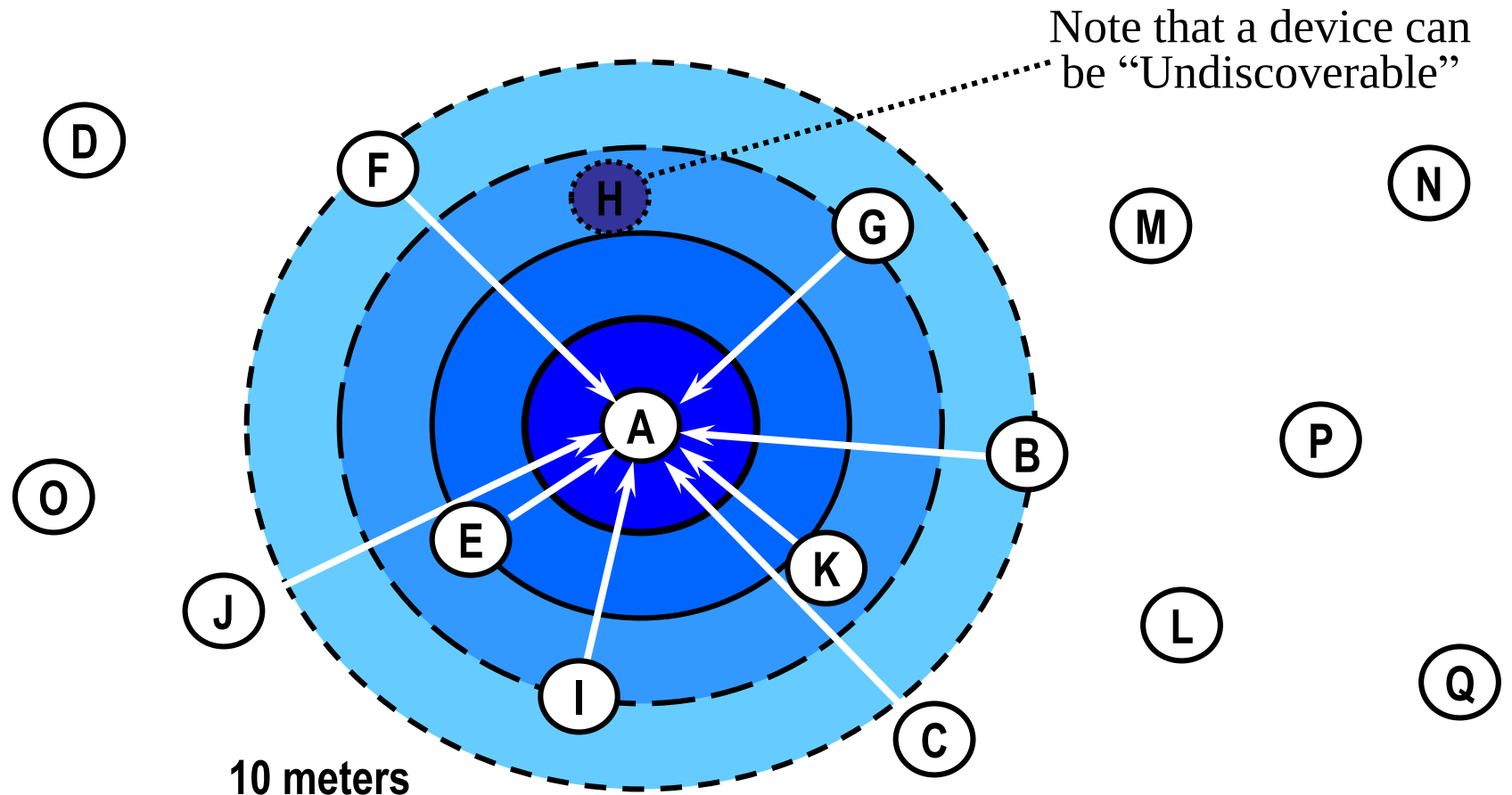
Bluetooth Radio

- Uses 2.4 GHz ISM band spread spectrum radio (2400 – 2483.5 MHz). 79 hop frequencies: $f = 2402 + k$ MHz, $k = 0, \dots, 78$.
- Nominal output power = 0 dBm (1 mW).
- GFSK modulation.
- Advantages:
 - Free.
 - Open to everyone worldwide.
- Disadvantages:
 - Can be noisy (microwaves, cordless phones, garage door openers).
- In order to mitigate interference, Bluetooth implements frequency hopping.
- 1600 hops per second through 79 1MHz channels.
- Spreads Bluetooth traffic over the entire ISM band.

Inquiry Procedure

1. Sends out an inquire, which is a request for nearby devices (within 10 meters).
2. Devices that allow themselves to be discoverable issue an inquiry response.
3. Can take up to 10.24 seconds, after which the inquiring device should know everyone within 10 meters of itself.

Device Discovery Illustrated



After inquiry procedure, A knows about others within range

What Does Bluetooth Do?

Topology	Supports up to 7 simultaneous links	Each link requires another cable
Flexibility	Goes through walls, bodies, cloths...	Line of sight or modified environment
Data rate	1 MSPS, 720 Kbps	Varies with use and cost
Power	0.1 watts active power	0.05 watts active power or higher
Size/Weight	25 mm x 13 mm x 2 mm, several grams	Size is equal to range. Typically 1-2 meters. Weight varies with length (ounces to pounds)
Cost	Long-term \$5 per endpoint	~ \$3-\$100/meter (end user cost)
Range	10 meters or less Up to 100 meters with PA	Range equal to size. Typically 1-2 meters
Universal	Intended to work anywhere in the world	Cables vary with local customs
Security	Very, link layer security, SS radio	Secure (its a cable)

Lecture-22-

Biological Effects of Radio Waves

Radiation

- Radiation is divided into two categories:
- Ionizing radiation
 - Alpha particles, Beta particles,
 - X rays, cosmic rays
- Non-ionizing radiation
 - Light, including visible, Infra red and Ultra violet
 - Radio waves from ULF to millimeter waves
- Also of interest:
- 60 Hz fields from power lines and other sources

Safety Standards

- International standards set by World Health Organization (WHO)
- National Standards set by government departments or agencies and national (independent) bodies
- CDRH in US
- National Radiological Protection Board in UK
- Department of Post and Telecommunications in Japan

International Exposure Levels

- Maximum permitted exposure
- UK 1.0 - 10 mW/cm²
- US, Canada, Japan, Germany 0.2 – 1.0 mW/cm²
- Australia 0.2 mW/cm²
- Italy 0.05 mW/cm²
- Russia, Switzerland 0.002 – 0.01 mW/cm²
- Higher exposure may be permitted for short period of time

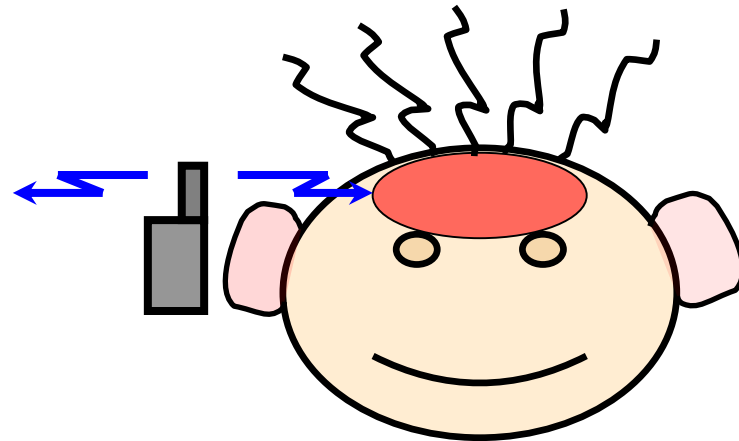
FCC Rules for Cell Phones

- Particular concern because half energy from antenna is absorbed in head
- 900 MHz (AMPS) cell phones
- Tx power limit is around 0.5 watts
- 1.8 – 2.0 GHz (PCS) cell phones
- Limit is 0.3 W

Cell Phones and Cancer

- Recent World Health Organization report called cell phones a possible factor in cancer, along with coffee, car exhaust ...
- FCC statement:
- *There is no scientific evidence to date that proves that wireless phone usage can lead to cancer or a variety of other health effects, including headaches, dizziness or memory loss.*

About 48% of power from cell phone transmitter is absorbed by user's head



Children and Cell Phones

Microwave radiation penetrates a child's head
much further than an adult's

