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Principles of Communication System

Chapter 3 (Part 1): Angle Modulation

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Learning outcomes

By the end of this topic, you should be able to:

- Explain the basic concept of angle modulation and how it differs from amplitude modulation
- Solve problems involving frequency-modulated signals

Analog Modulation

Amplitude modulation (AM)

- AM is the process of varying the instantaneous amplitude of Carrier signal accordingly with instantaneous amplitude of information signal.

Angle Modulation

Frequency modulation (FM)

- FM is the process of varying the in instantaneous frequency of Carrier signal accordingly with instantaneous amplitude of information signal.

Phase modulation (PM)

- PM is the process of varying the instantaneous phase of Carrier signal accordingly with instantaneous amplitude of information signal.

Angle Modulation

- Frequency Modulation(FM) & Phase Modulation (PM) are two types of angle modulation.
- FM is most commonly used analog modulation technique
- PM is rarely used in analog systems but its' variation is used often in digital communication.

Frequency Modulation

The frequency of the carrier wave is changed according to the information signal.

Waveforms that are more spaced apart represent the valleys of the sine wave

Waveforms that are closed together represent the peaks of the sine wave.

Frequency Modulation

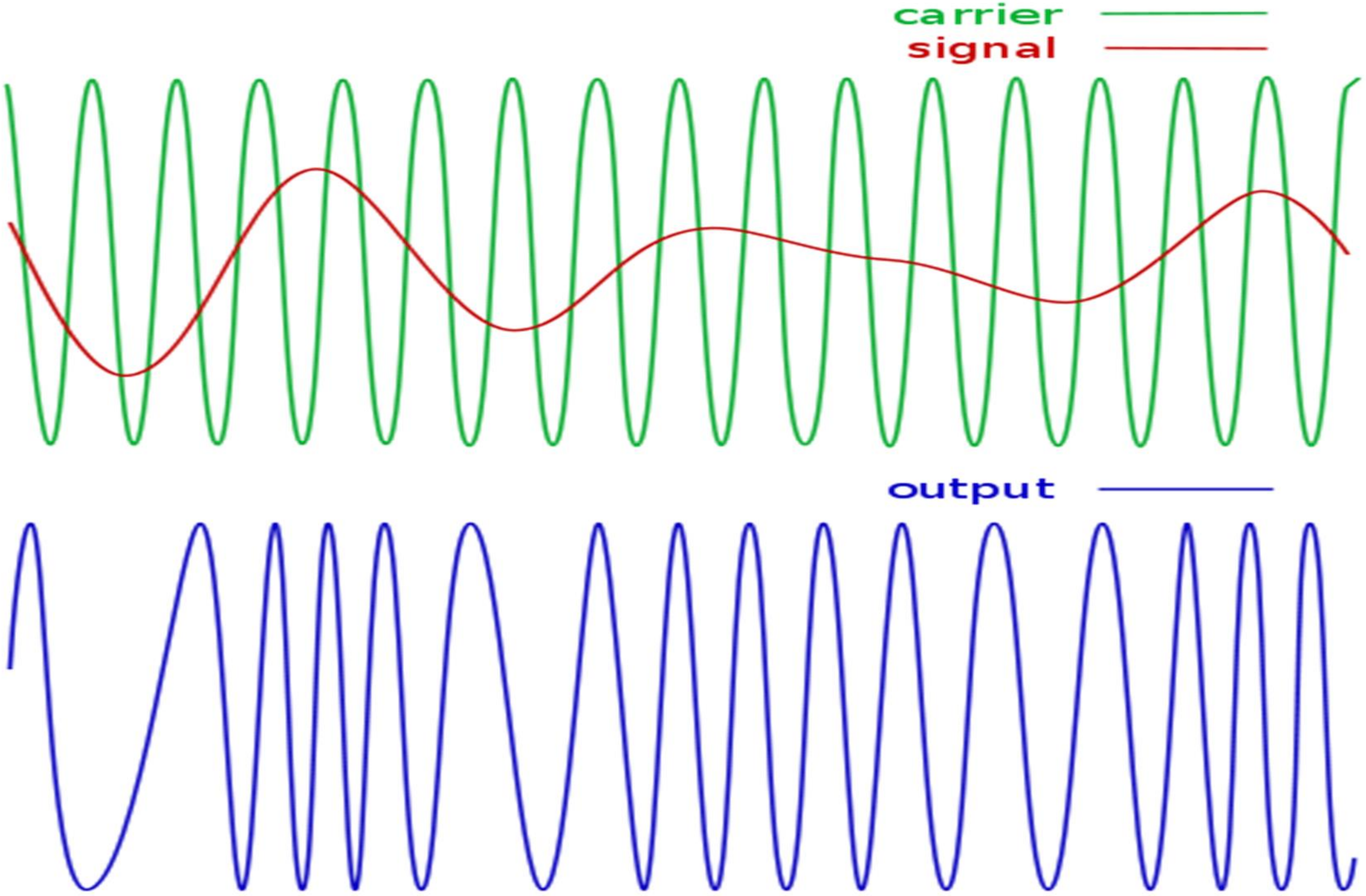


Image source: https://commons.wikimedia.org/wiki/File:Frequency_Modulation.svg

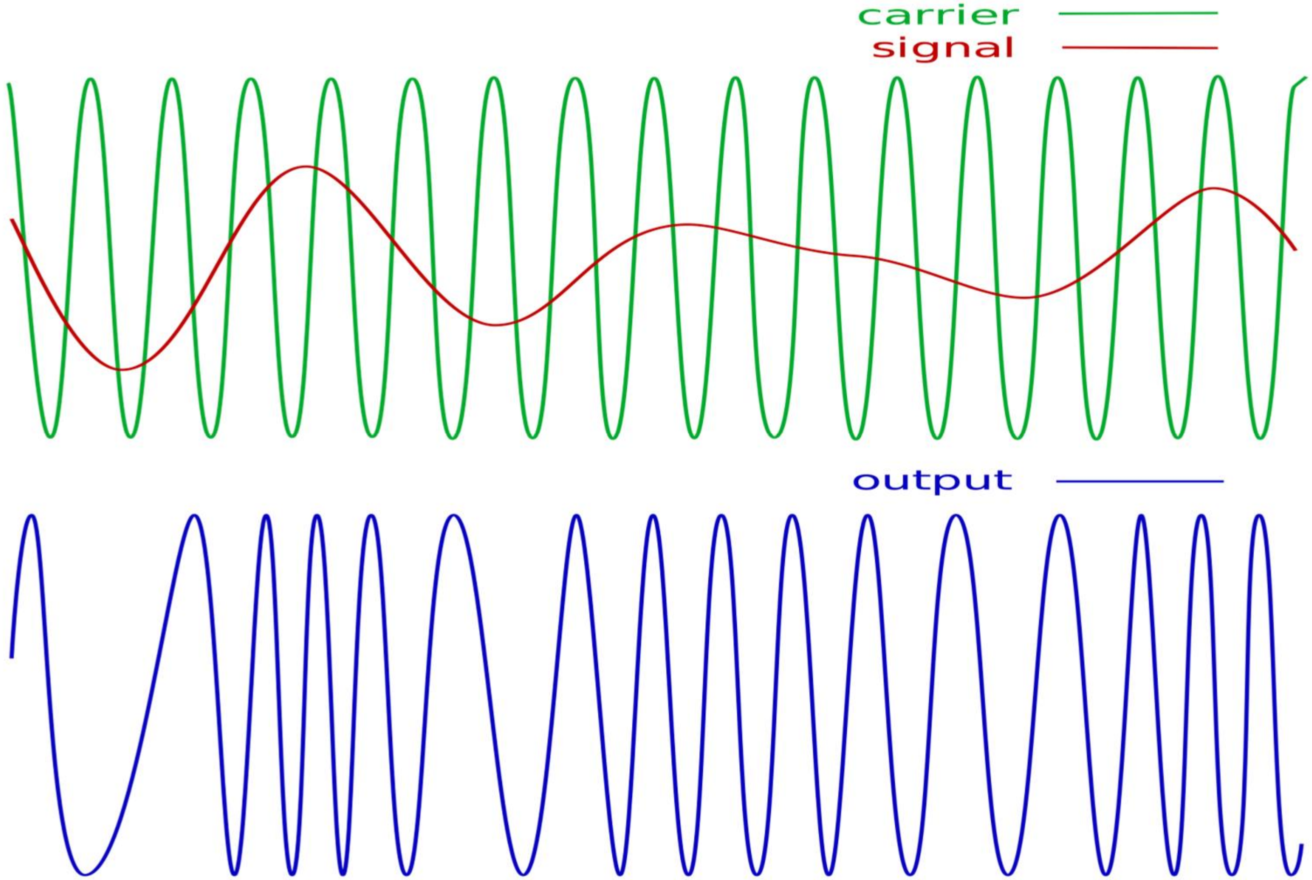
Phase Modulation

Here, the phase of the carrier wave is altered according to the information signal.

Waveforms that are closed together represent the sine wave transition from –ve to +tve.

Waveforms that are more spaced apart represent the sine wave transition from +ve to -ve.

Phase Modulation



Angle Modulation

The angle modulation can be expressed mathematically as:

$$v(t) = E_c \cos[2\pi f_c t + \theta(t)]$$

FM: change of FREQUECY/PHASE

$v(t)$ = angle modulated wave
E_c = peak carrier amplitude (Volt)
f_c = carrier frequency (hertz)
$\theta(t)$ = instantaneous phase deviation (radians)

$\theta(t)$ is a function of the modulating signal: $\theta(t) = F[v_m(t)]$

Where $v_m(t) = E_m \sin 2\pi f_m t$ is the modulating signal

FM Or PM ?

FM	PM
Instantaneous frequency of the carrier is varied from its reference value by an amount proportional to the modulating signal amplitude Freq. carrier - - - > directly varied Phase carrier - - -> indirectly varied	Phase angle of the carrier is varied from its reference value by an amount proportional to the modulating signal amplitude Phase carrier - - - > directly varied Freq. carrier - - -> indirectly varied

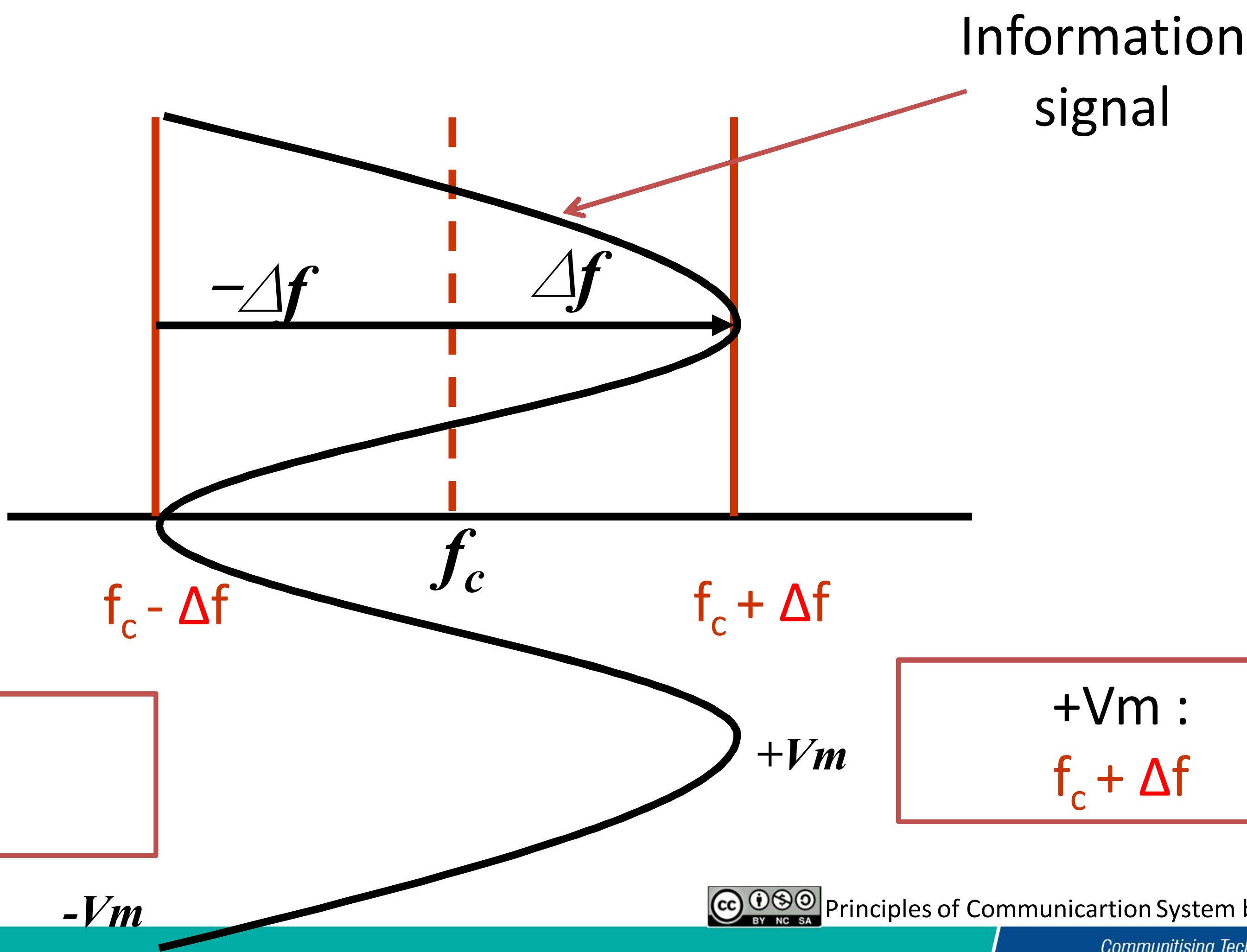
Å Both must occur whenever either form of angle modulation is performed.

Basic Principles of FM

- Frequency Deviation
- Modulation Index
- Bessel Function
- Power Analysis

Frequency deviation (Δf)

Relative displacement of the carrier frequency compared to the original carrier frequency (unit: Hertz).



-Vm:
$f_c - \Delta f$

+Vm :
$f_c + \Delta f$

Frequency Deviation ∆f

- In FM, , the carrier frequency change in proportion with modulating signal amplitude.

- The amount of change in carrier frequency is called peak Frequency Deviation (Δf).
  - Sometimes it is expressed as maximum carrier swing which is equal to 2Δf
  - The deviation is proportional to the amplitude of the modulating signal.

Frequency Deviation Δf

- Peak frequency deviation can be calculated as:

$$\Delta f = K_f V_m \quad Hz$$

- Where
  - K_f is deviation sensitivity
  - V_m is peak modulating signal voltage

- So we can see that Δf directly proportional to modulating signal's amplitude

Deviation Sensitivity, K

Å Deviation sensitivity is a constant that shows the sensitivity of frequency modulator

Å Represent the input-output transfers of the modulator: relationship between input voltage (V_m) and the resulting frequency shift (Δω)

$$K_f = \frac{\Delta\omega}{\Delta V_m} \left(\frac{\text{rad/s}}{\text{V}}\right)$$ or in Herz/V: $$K_f = \frac{\Delta f}{\Delta V_m} \left(\frac{\text{Hz}}{\text{V}}\right)$$

Å in short, it shows how 'well' the modulator works

Frequency modulation index (m)

Modulation index (*m*) in FM is the ratio of the frequency deviation (Δf) to the modulating frequency f_m:

$$m = \frac{K_f(\frac{rad}{volt})V_m}{\omega_m} \text{(unitless)}$$

Or K_f can also be expressed in hertz. So, m is:

$$m = \frac{K_f(\frac{hertz}{volt})V_m}{f_m} \text{(unitless)}$$

since: $$\Delta f = K_f V_m \quad Hz$$

Thus: $$m = \frac{\Delta f\,(Hz)}{f_m(Hz)}$$

Modulation Index (m)

$$m = \frac{\Delta f\,(Hz)}{f_m(Hz)}$$

Percent Modulation

$$\%\ \text{modulation} = \frac{\Delta f_{(actual)}}{\Delta f_{(\max)}} \times 100$$

Å Usually both the frequency deviation and the modulating frequency has maximum limits

$$f_c \pm f_m,\ f_c \pm 2f_m,\ f_c \pm nf_m$$

Example 1

Determine the modulation index for FM signal for the following system:

(a) modulating frequency is 5KHz deviated by ±10kHz.

- ✓Answer : (10KHz/5KHz) = 2 .0 (unitless)

(b) modulating frequency is 5KHz deviated by ±15kHz.

- ✓Answer : (15KHz/5KHz) = 3 .0 (unitless)

FM Sidebands

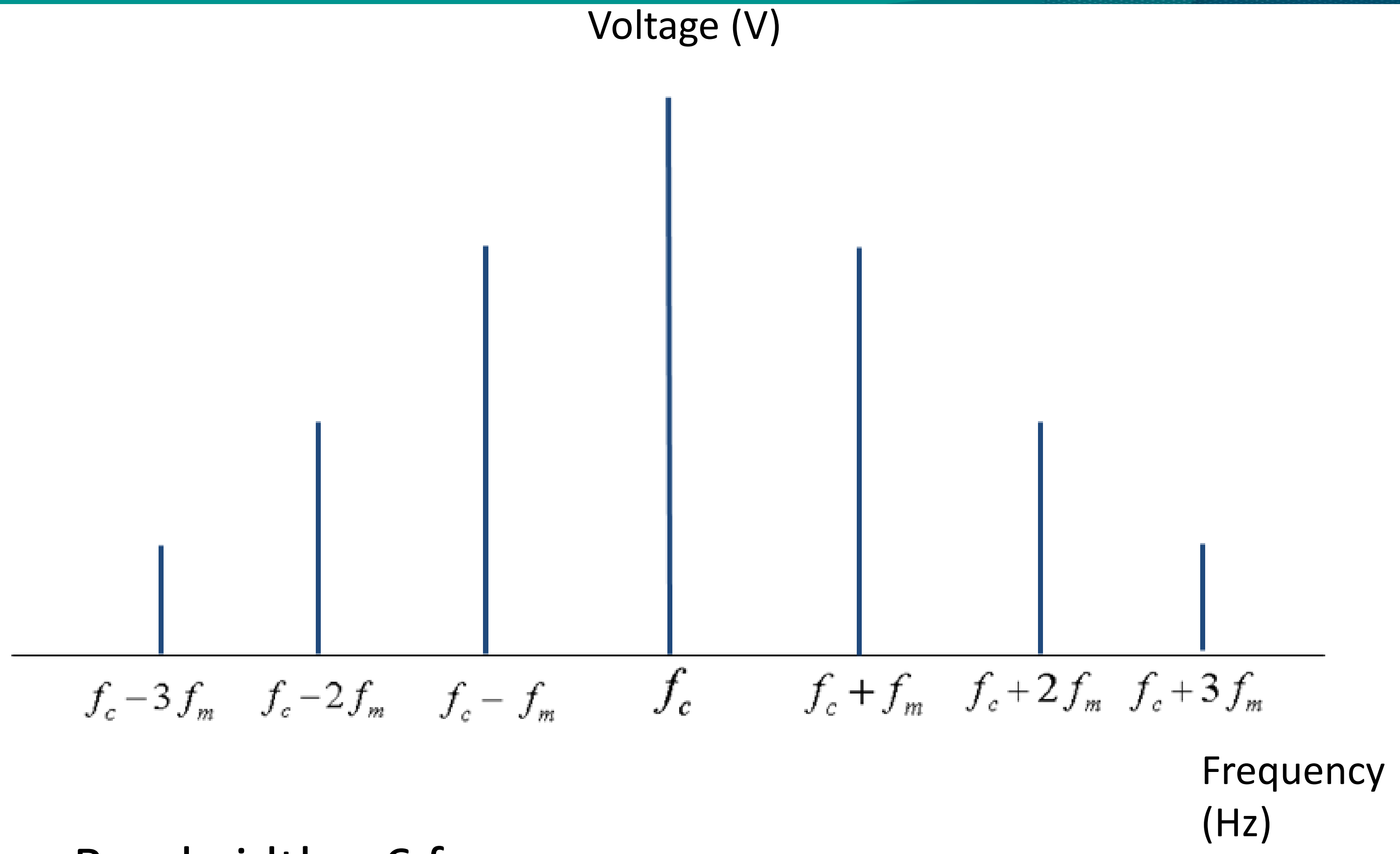
FM & PM both produce infinite number of pairs of upper and lower sidebands

Although this means that the bandwidth is bigger, more sidebands results in more immunity to noise

FM produces pairs of sidebands spaced from the carrier in multiples of the modulating frequency.

The number of significant pairs of sidebands determines by modulation index (m).

FM Sidebands



Bandwidth = 6 f_m

FM equation

When a modulating signal is a single sine wave, the FM equation is:

$$\therefore V_{fm}(t) = V_c \cos[\omega_c t + m \sin(\omega_m t)]$$

Or : $V_{fm}(t) = V_c \sin[\omega_c t + m \sin(\omega_m t)]$

Å To expand the equation into complete FM equation, including its sidebands is difficult.

Å Thus Bessel function is used to solve the equation

Bessel Function for FM

FM equation is given by: $v_{FM}(t) = V_c \cos[\omega_c t + m \sin \omega_m t]$

Use Trigonometric identities:

$$\cos(A+B) = \cos(A)\cos(B) - \sin(A)\sin(B)$$

The equation now becomes:

$$v_{FM}(t) = V_c \cos(\omega_c t)\cos[m \sin(\omega_m t)] - V_c \sin(\omega_c t)\ \sin[m \sin(\omega_m t)] \quad \text{...(1)}$$

Where ***cos[m sin(ω_mt)]*** and ***sin[m sin(ω_mt)]*** is a trigonometric series called as ***Bessel Function***.

Bessel Function for FM

Equation 1 is expanded using Fourier series, thus it becomes:

$$\cos[m\sin(\omega_m t)] = J_0(m) + \sum_{n=even}^{\infty} 2J_n(m)\cos(n\omega_m t) \quad \textbf{\textit{n} = even}$$

$$\sin[m\sin(\omega_m t)] = \sum_{n=odd}^{\infty} 2J_n(m)\sin(n\omega_m t) \quad \textbf{\textit{n} = odd}$$

Substitute in v_{FM}

$$v_{FM}(t) = E_c\cos(\omega_c t)[J_0(m) + \sum_{n=even}^{\infty} 2J_n(m)\cos(n\omega_m t)]$$

$$-E_c\sin(\omega_c t)\sum_{n=odd}^{\infty} 2J_n(m)\sin(n\omega_m t)$$

$$= E_c J_0(m)\cos(\omega_c t) + 2E_c\sum_{n=even}^{\infty} J_n(m)\cos(\omega_c t)\cos(n\omega_m t)$$

$$-2E_c\sum_{n=odd}^{\infty} J_n(m)\sin(\omega_c t)\sin(n\omega_m t)$$

$$= E_c J_0(m)\cos(\omega_c t) + E_c\sum_{n=odd}^{\infty} J_n(m)[\cos(\omega_c + n\omega_m)t - \cos(\omega_c - n\omega_m)t]$$

$$+E_c\sum_{n=even}^{\infty} J_n(m)[\cos(\omega_c + n\omega_m)t + \cos(\omega_c - n\omega_m)t]$$

- **Using Bessel identities :** $J_{-n}(m) = (-1)^n J_n(m)$

$$J_n(m) = \begin{cases} J_{-n}(m) & n\ \ even \\ -J_{-n}(m) & n\ \ odd \end{cases}$$

Bessel Function for FM

$$v_{FM}(t) = E_c \sum_{-\infty}^{\infty} J_n(m)\cos[(\omega_c + n\omega_m)t]$$

Expand the equation yields :

$$\begin{aligned}
v_{FM}(t) = {} & E_c J_0(m)\cos(\omega_c t) \\
& - E_c J_1(m)\{\cos[(\omega_c + \omega_m)t] - \cos[(\omega_c - \omega_m)t]\} \\
& + E_c J_2(m)\{\cos[(\omega_c + 2\omega_m)t] + \cos[(\omega_c - 2\omega_m)t]\} \\
& - E_c J_3(m)\{\cos[(\omega_c + 3\omega_m)t] - \cos[(\omega_c - 3\omega_m)t]\} \\
& + E_c J_4(m)\{\cos[(\omega_c + 4\omega_m)t] + \cos[(\omega_c - 4\omega_m)t]\} \\
& - \ldots + E_c J_n(m)\{\cos[(\omega_c + n\omega_m)t] + \cos[(\omega_c - n\omega_m)t]\}
\end{aligned}$$

Carrier band

Sideband 1

Sideband 2

Sideband 3

Sideband 4

Sideband n

Bessel Function for FM

Where

m = modulation index

Vc = peak amplitude of the unmodulated carrier

$J_0(m)$= carrier component

$J_1(m)$=first set of side frequencies displaced from the carrier by ω_m

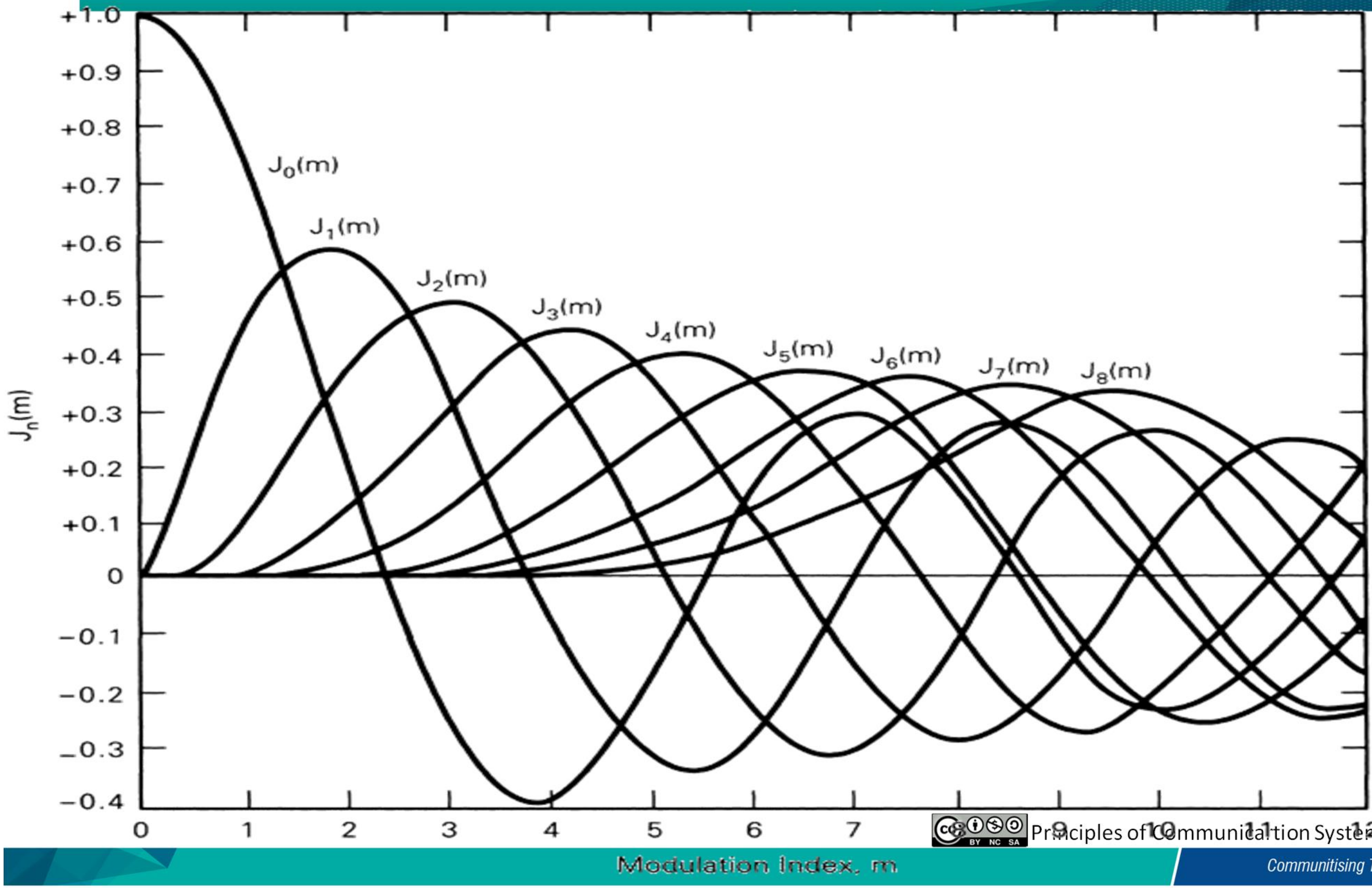
$J_2(m)$=second set of side frequencies displaced from the carrier by $2\omega_m$

$J_n(m)$=nth set of side frequencies displaced from the carrier by $n\omega_m$

Bessel Table

Modulation Index	Carrier	Sidebands (Pairs)															
		1st	2d	3d	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th
0.00	1.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.25	0.98	0.12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.5	0.94	0.24	0.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1.0	0.77	0.44	0.11	0.02	—	—	—	—	—	—	—	—	—	—	—	—	—
1.5	0.51	0.56	0.23	0.06	0.01	—	—	—	—	—	—	—	—	—	—	—	—
2.0	0.22	0.58	0.35	0.13	0.03	—	—	—	—	—	—	—	—	—	—	—	—
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	—	—	—	—	—	—	—	—	—	—	—
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01	—	—	—	—	—	—	—	—	—	—
4.0	−0.40	−0.07	0.36	0.43	0.28	0.13	0.05	0.02	—	—	—	—	—	—	—	—	—
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02	—	—	—	—	—	—	—	—
6.0	0.15	−0.28	−0.24	0.11	0.36	0.36	0.25	0.13	0.06	0.02	—	—	—	—	—	—	—
7.0	0.30	0.00	−0.30	−0.17	0.16	0.35	0.34	0.23	0.13	0.06	0.02	—	—	—	—	—	—
8.0	0.17	0.23	−0.11	−0.29	−0.10	0.19	0.34	0.32	0.22	0.13	0.06	0.03	—	—	—	—	—
9.0	−0.09	0.24	0.14	−0.18	−0.27	−0.06	0.20	0.33	0.30	0.21	0.12	0.06	0.03	0.01	—	—	—
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.31	0.29	0.20	0.12	0.06	0.03	0.01	—	—
12.0	−0.05	−0.22	−0.08	0.20	0.18	−0.07	−0.24	−0.17	0.05	0.23	0.30	0.27	0.20	0.12	0.07	0.03	0.01
15.0	−0.01	0.21	0.04	0.19	−0.12	0.13	0.21	0.03	−0.17	−0.22	−0.09	0.10	0.24	0.28	0.25	0.18	0.12

Bessel function of the first kind



Bessel function of the first kind

$$J_0^2 + 2J_1^2 + 2J_2^2 + 2J_3^2 + \ldots + 2J_n^2 = J_0^2 + 2\sum_{n=1}^{\infty} J_n^2 = 1$$

Modulation Index	Carrier	Sidebands (Pairs) 1st	2d	3d	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th
0.00	1.00	—	—	—	—	—	—	—	—	—							
0.25	0.98	0.12	—	—	—	—	—	—	—	—							
0.5	0.94	0.24	0.03	—	—	—	—	—	—	—							
1.0	0.77	0.44	0.11	0.02	—	—	—	—	—	—							
1.5	0.51	0.56	0.23	0.06	0.01	—	—	—	—	—	—	—	—	—	—	—	—
2.0	0.22	0.58	0.35	0.13	0.03	—	—	—	—	—	—	—	—	—	—	—	—
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	—	—	—	—	—	—	—	—	—	—	—
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01	—	—	—	—	—	—	—	—	—	—
4.0	−0.40	−0.07	0.36	0.43	0.28	0.13	0.05	0.02	—	—	—	—	—	—	—	—	—
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02	—	—	—	—	—	—	—	—
6.0	0.15	−0.28	−0.24	0.11	0.36	0.36	0.25	0.13	0.06	0.02	—	—	—	—	—	—	—
7.0	0.30	0.00	−0.30	−0.17	0.16	0.35	0.34	0.23	0.13	0.06	0.02	—	—	—	—	—	—
8.0	0.17	0.23	−0.11	−0.29	−0.10	0.19	0.34	0.32	0.22	0.13	0.06	0.03	—	—	—	—	—
9.0	−0.09	0.24	0.14	−0.18	−0.27	−0.06	0.20	0.33	0.30	0.21	0.12	0.06	0.03	0.01	—	—	—
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.31	0.29	0.20	0.12	0.06	0.03	0.01	—	—
12.0	−0.05	−0.22	−0.08	0.20	0.18	−0.07	−0.24	−0.17	0.05	0.23	0.30	0.27	0.20	0.12	0.07	0.03	0.01
15.0	−0.01	0.21	0.04	0.19	−0.12	0.13	0.21	0.03	−0.17	−0.22	−0.09	0.10	0.24	0.28	0.25	0.18	0.12

*Significant sidebands are those that have **amplitude > 1% (0.01)** in the Bessel table.

an

Example: **m = 1.0** → 3 significant sidebands

Modulation Index	Carrier	Sidebands (Pairs) 1st	2d	3d	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th
0.00	1.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.25	0.98	0.12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.5	0.94	0.24	0.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1.0	0.77	0.44	0.11	0.02	—	—	—	—	—	—	—	—	—	—	—	—	—
1.5	0.51	0.56	0.23	0.06	0.01	—	—	—	—	—	—	—	—	—	—	—	—
2.0	0.22	0.58	0.35	0.13	0.03	—	—	—	—	—	—	—	—	—	—	—	—
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	—	—	—	—	—	—	—	—	—	—	—
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01	—	—	—	—	—	—	—	—	—	—
4.0	−0.40	−0.07	0.36	0.43	0.28	0.13	0.05	0.02	—	—	—	—	—	—	—	—	—
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02	—	—	—	—	—	—	—	—
6.0	0.15	−0.28	−0.24	0.11	0.36	0.36	0.25	0.13	0.06	0.02	—	—	—	—	—	—	—
7.0	0.30	0.00	−0.30	−0.17	0.16	0.35	0.34	0.23	0.13	0.06	0.02	—	—	—	—	—	—
8.0	0.17	0.23	−0.11	−0.29	−0.10	0.19	0.34	0.32	0.22	0.13	0.06	0.03	—	—	—	—	—
9.0	−0.09	0.24	0.14	−0.18	−0.27	−0.06	0.20	0.33	0.30	0.21	0.12	0.06	0.03	0.01	—	—	—
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.31	0.29	0.20	0.12	0.06	0.03	0.01	—	—
12.0	−0.05	−0.22	−0.08	0.20	0.18	−0.07	−0.24	−0.17	0.05	0.23	0.30	0.27	0.20	0.12	0.07	0.03	0.01
15.0	−0.01	0.21	0.04	0.19	−0.12	0.13	0.21	0.03	−0.17	−0.22	−0.09	0.10	0.24	0.28	0.25	0.18	0.12

Amplitude distribution from Bessel table:

m	carrier	1st	2nd	3rd
1.0	0.77	0.44	0.11	0.02

E_c = amplitude of carrier signal

f_c = frequency of carrier signal

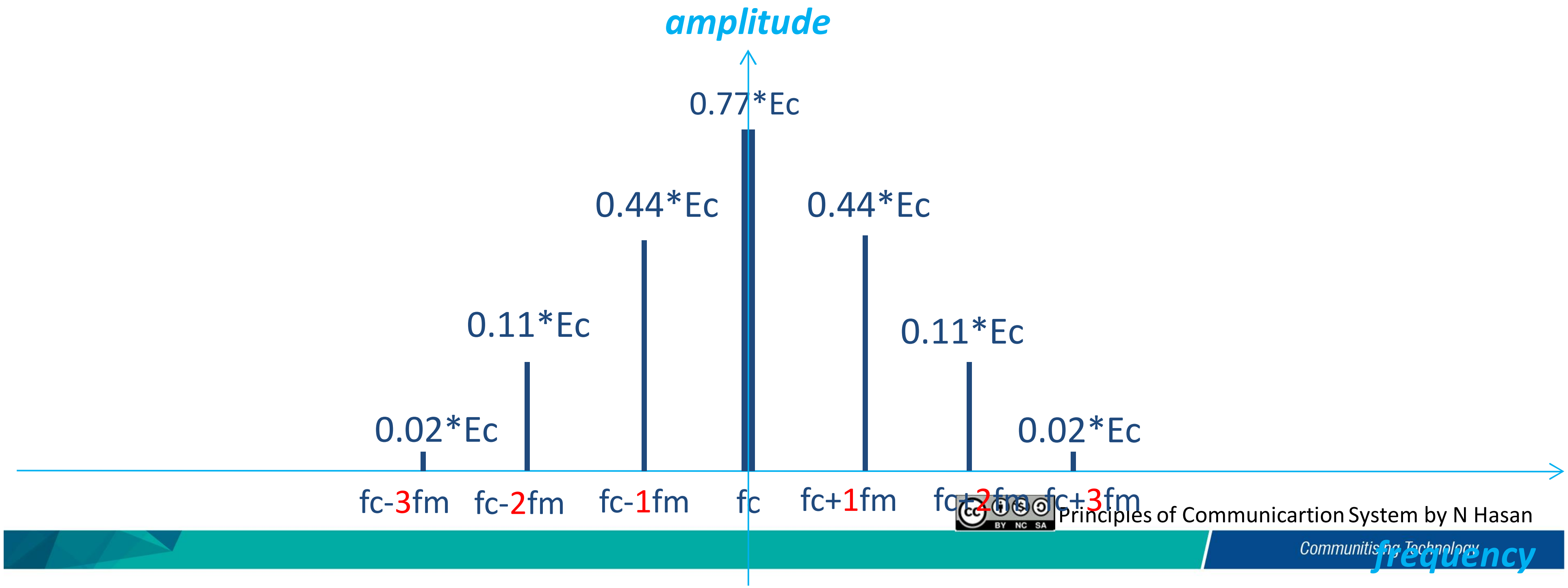
fm = frequency of modulating signal

$$E_c\,J_0 = \text{amplitude at fc}$$

$$E_c\,J_1 = \text{amplitude at 1st sidebands}$$

$$E_c\,J_2 = \text{amplitude at 2nd sidebands}$$

$$E_c\,J_3 = \text{amplitude at 3rd sidebands}$$



Example 2: **m = 2.0** → 4 significant sidebands

Modulation Index	Carrier	Sidebands (Pairs) 1st	2d	3d	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th
0.00	1.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.25	0.98	0.12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.5	0.94	0.24	0.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1.0	0.77	0.44	0.11	0.02	—	—	—	—	—	—	—	—	—	—	—	—	—
1.5	0.51	0.56	0.23	0.06	0.01	—	—	—	—	—	—	—	—	—	—	—	—
2.0	0.22	0.58	0.35	0.13	0.03	—	—	—	—	—	—	—	—	—	—	—	—
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	—	—	—	—	—	—	—	—	—	—	—
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01	—	—	—	—	—	—	—	—	—	—
4.0	−0.40	−0.07	0.36	0.43	0.28	0.13	0.05	0.02	—	—	—	—	—	—	—	—	—
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02	—	—	—	—	—	—	—	—
6.0	0.15	−0.28	−0.24	0.11	0.36	0.36	0.25	0.13	0.06	0.02	—	—	—	—	—	—	—
7.0	0.30	0.00	−0.30	−0.17	0.16	0.35	0.34	0.23	0.13	0.06	0.02	—	—	—	—	—	—
8.0	0.17	0.23	−0.11	−0.29	−0.10	0.19	0.34	0.32	0.22	0.13	0.06	0.03	—	—	—	—	—
9.0	−0.09	0.24	0.14	−0.18	−0.27	−0.06	0.20	0.33	0.30	0.21	0.12	0.06	0.03	0.01	—	—	—
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.31	0.29	0.20	0.12	0.06	0.03	0.01	—	—
12.0	−0.05	−0.22	−0.08	0.20	0.18	−0.07	−0.24	−0.17	0.05	0.23	0.30	0.27	0.20	0.12	0.07	0.03	0.01
15.0	−0.01	0.21	0.04	0.19	−0.12	0.13	0.21	0.03	−0.17	−0.22	−0.09	0.10	0.24	0.28	0.25	0.18	0.12

Amplitude distribution from Bessel table:

m	carrier	1st	2nd	3rd	4th
2.0	0.22	0.58	0.35	0.13	0.03

E_c = amplitude of carrier signal

f_c = frequency of carrier signal

f_m = frequency of modulating signal

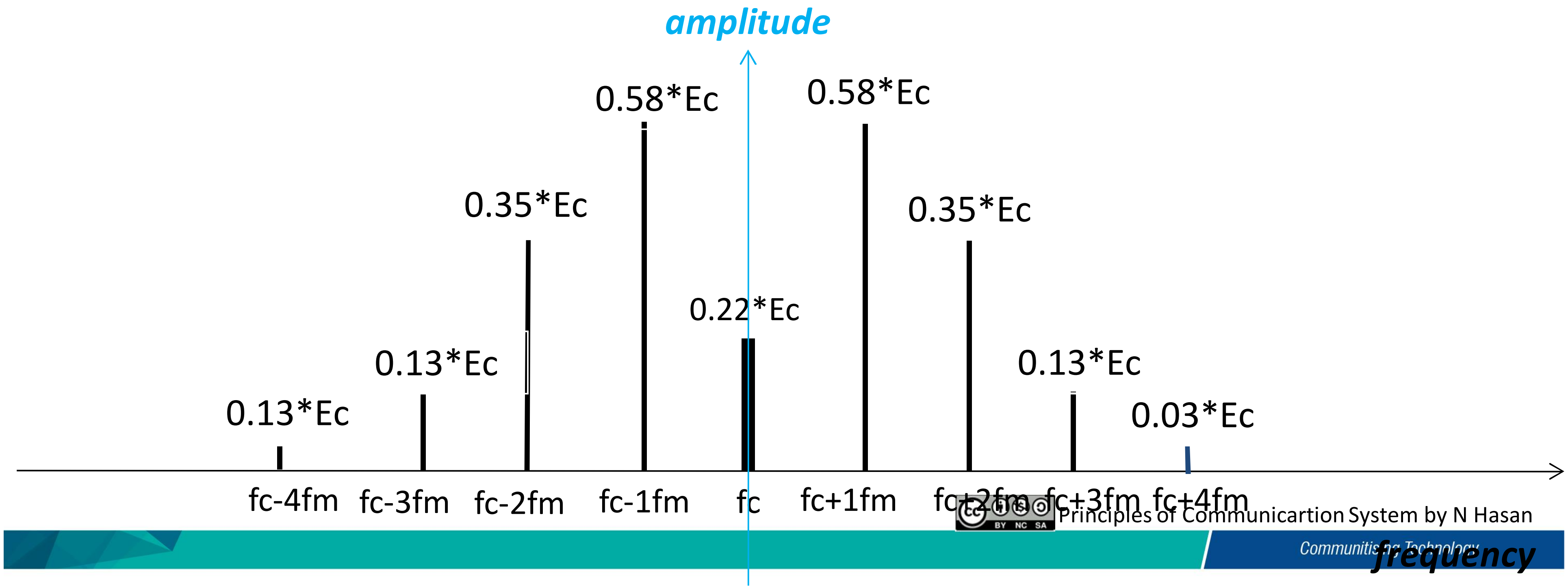
$E_c\,J_0 = a\text{mplitude at fc}$

$E_c\,J_1 = a\text{mplitude at 1st sidebands}$

$E_c\,J_2 = a\text{mplitude at 2nd sidebands}$

$E_c\,J_3 = a\text{mplitude at 3rd sidebands}$

$E_c\,J_4 = a\text{mplitude at 4th sidebands}$



If E_c = 50 V,

m	J_0	J_1	J_2	J_3
1.0	0.77	0.44	0.11	0.02

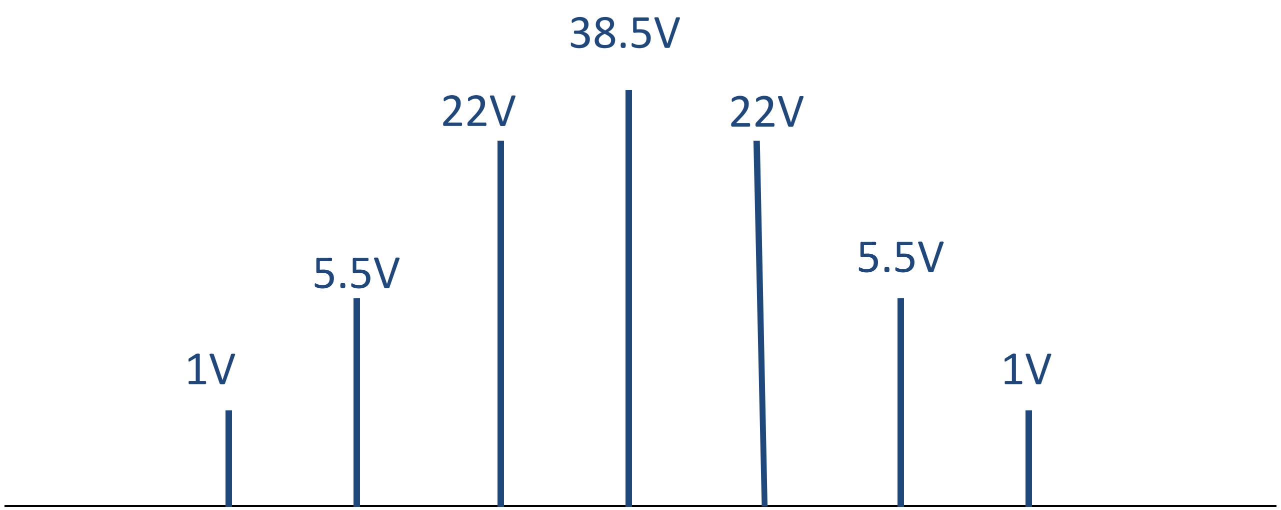
Thus the amplitudes are:

$$E_c\,J_0 = 50 * 0.77 = 38.5\,V$$

$$E_c\,J_1 = 50 * 0.44 = 22\,V$$

$$E_c\,J_2 = 50 * 0.11 = 5.5\,V$$

$$E_c\,J_3 = 50 * 0.02 = 1\,V$$



Power in FM signal

Å Unlike AM the carrier power in FM is re-distributed among the carrier and sidebands, thus the total power is:

$$P_{t(FM)} = P_C$$

$$P_t = P_0 + P_1 + P_2 + \ldots + P_n$$

- P_0= modulated carrier power
- P_1= power in the first set of sidebands
- P_2= power in the second set of sidebands
- P_n= power in the *n*th set of sidebands

NOTE!

$$P_c = \frac{V_c^{\,2}}{2R}$$

And $P_C \neq P_0$

- P_C: unmodulated carrier power
- P_0: modulated carrier power
- R: load resistance

Power in FM signal

Å Total power in FM wave is:

$$P_t = P_0 + P_1 + P_2 + \ldots + P_n$$

Å Or we can also write it as:

$$P_t = \frac{V_0^{\ 2}}{2R} + \frac{2(V_1)^2}{2R} + \frac{2(V_2)^2}{2R} + \ldots + \frac{2(V_n)^2}{2R}$$

Å Where V_0, V_1,…V_n are FM modulated carrier amplitudes and sidebands amplitudes respectively.

Power in FM signal

- R is load resistance
- Thus, we can use Bessel table and further improve the equation to:

$$P_t = \frac{E_c^2 J_0^2}{2R} + 2\left(\frac{E_c^2 J_1^2}{2R} + \frac{E_c^2 J_2^2}{2R} + \frac{E_c^2 J_3^2}{2R} + \ldots + \frac{E_c^2 J_n^2}{2R} \right)$$

$$= \frac{E_c^2}{2R}\left(J_0^2 + 2\sum_{n=1}^{\infty} J_n^2 \right)$$

Bandwidth

The number of significant sidebands depends on modulation index.

Higher modulation index numbers will results in more significant sidebands and the wider the bandwidth of the signal.

When spectrum conservation is necessary, the bandwidth of an FM signal can be restricted by putting an upper limit on the modulation index.

FM bandwidth calculation methods:

FM bandwidth:

- **Approximation: Carson's Rule**

  $$BW = 2(\Delta f + f_m)$$

- **Actual bandwidth: Bessel Table**

  $$BW = 2(n \times f_m)$$

1. Finding bandwidth using Carsonô s Rule

Å Approximates the bandwidth necessary to transmit an angle-modulated systems is twice the sum of peak frequency deviation and the highest modulating signal's frequency:

$$BW = 2(\Delta f + f_m)$$

Å Where *Δf* is maximum frequency deviation

f_m is maximum modulating signal frequency

2. Finding bandwidth using Bessel's table

- The number of significant sidebands, *n* depends on the value of modulation index, *m*.
- Minimum bandwidth is determine mathematically as:

$$BW = 2\left(n \times f_m\right)$$

- Where *n* is the number of significant sidebands
  f_m is maximum modulating signal frequency

Advantages of FM over AM

FM has better immunity to noise compared to AM, because FM system has clipper limiter circuits in the receiver.

FM has **capture effect**, where interfering signals on the same frequency are rejected.

FM signals have a constant amplitude thus eliminating the need to use linear amplifiers to increase power levels.

Disadvantages of FM

FM uses considerably more frequency spectrum space compared to AM.

FM modulator and demodulator has more complex circuit.