Communication systems

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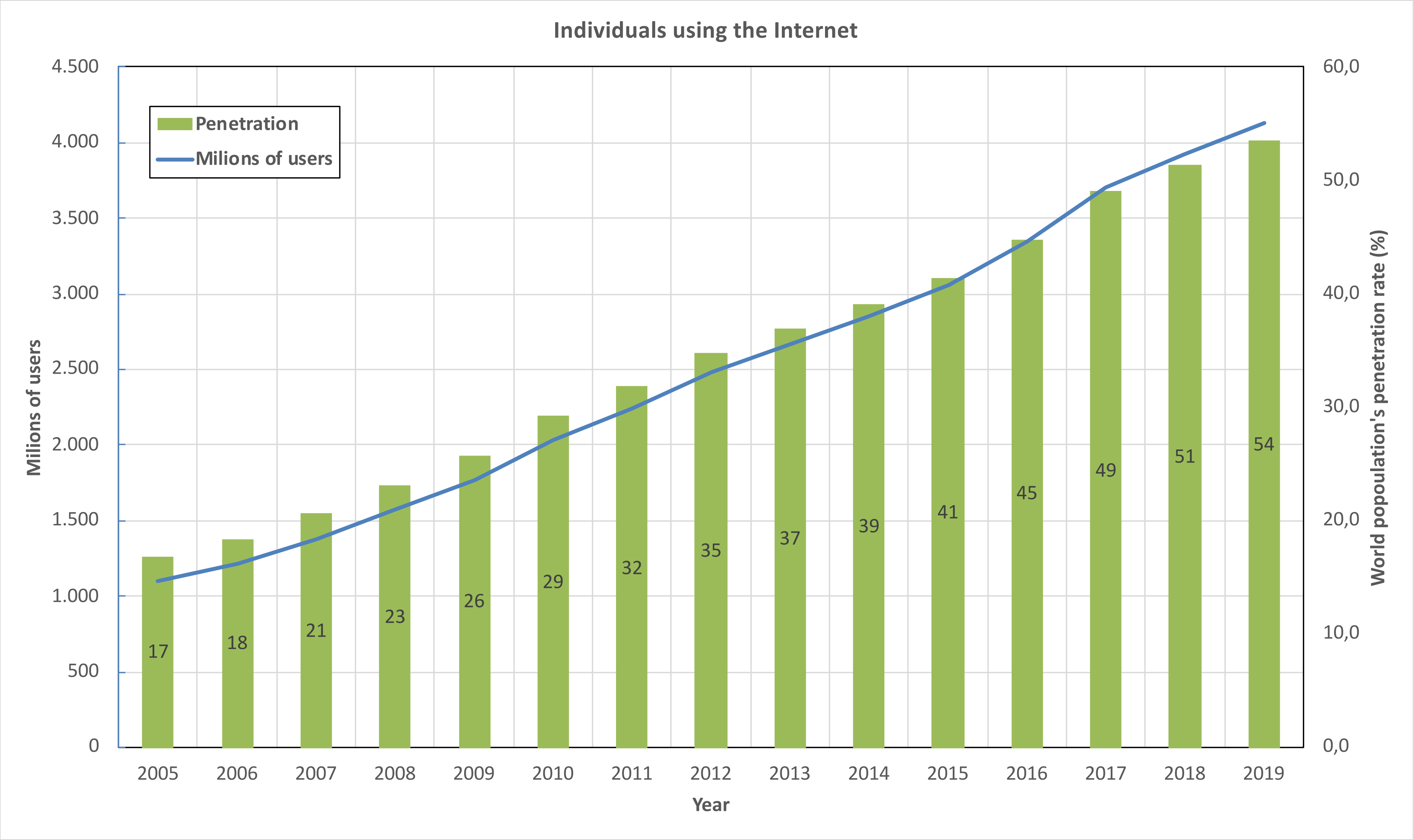
ELECTRONICS AND COMMUNICATIONS SYSTEMS

COMPUTER ENGINEERING

- Some data from the International Telecommunication Union (ITU)…..
- The number of people with access to mobile communications is higher than those with access to working toilets (around 4.5 billions).
- The number of people that owns a mobile phone is larger than the number of people that owns/uses a toothbrush (around 4 billion).



Individuals using the Internet
Penetration
Milions of users
Milions of users
World popoulation's penetration rate (%)
Year
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
500
0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
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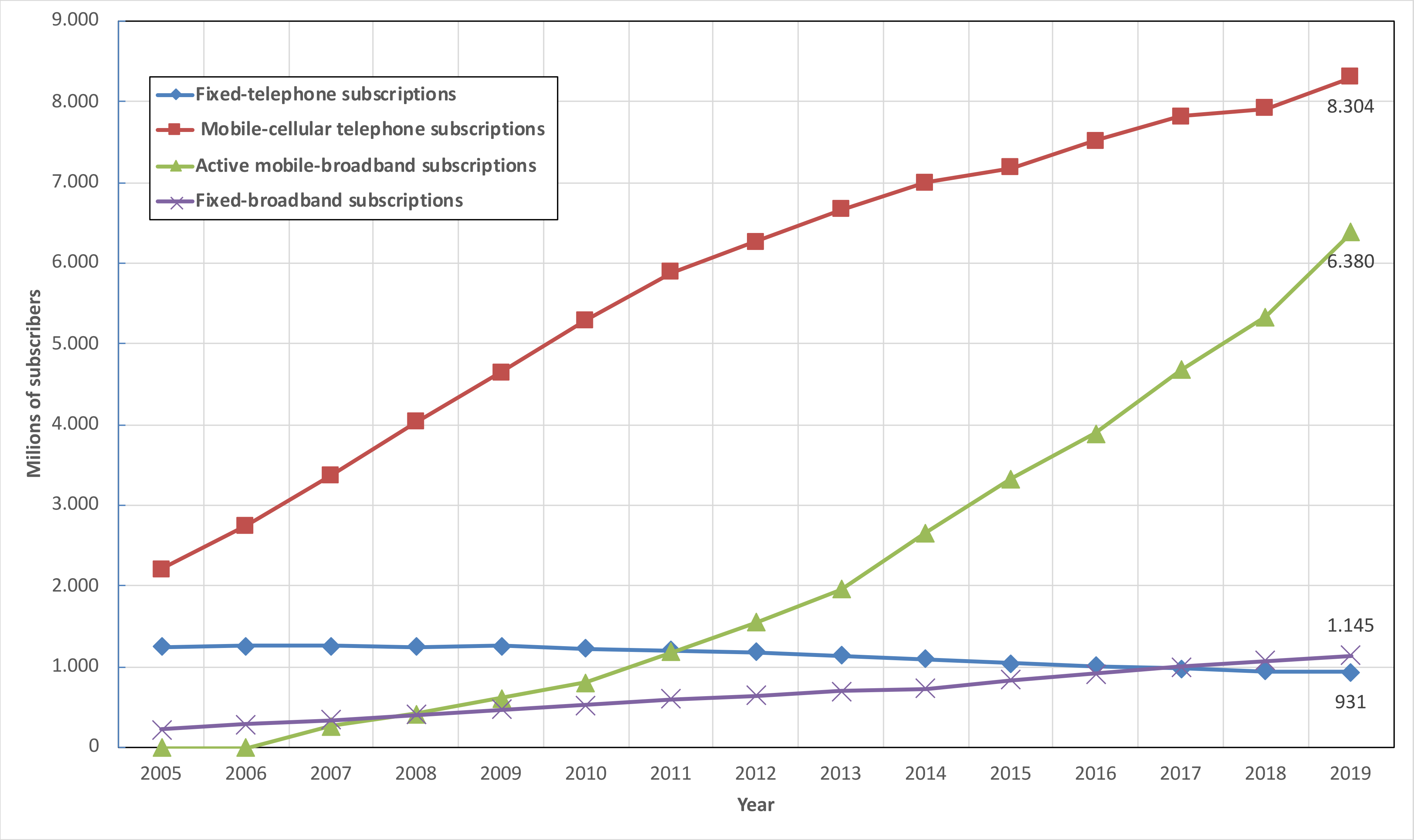
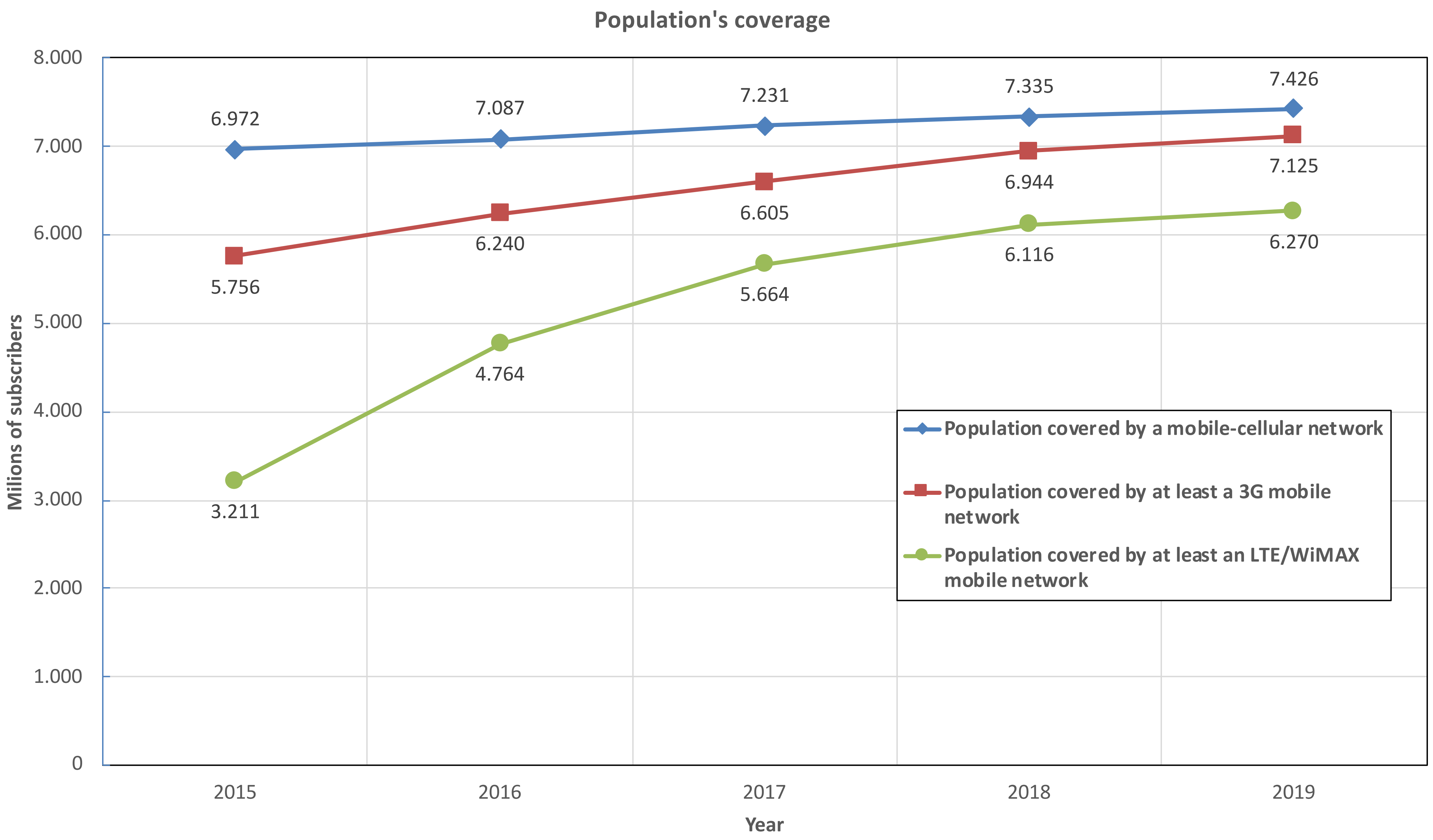
51
54



9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0
Milions of subscribers
Fixed-telephone subscriptions
Mobile-cellular telephone subscriptions
Active mobile-broadband subscriptions
Fixed-broadband subscriptions
8.304
6.380
1.145
931
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year

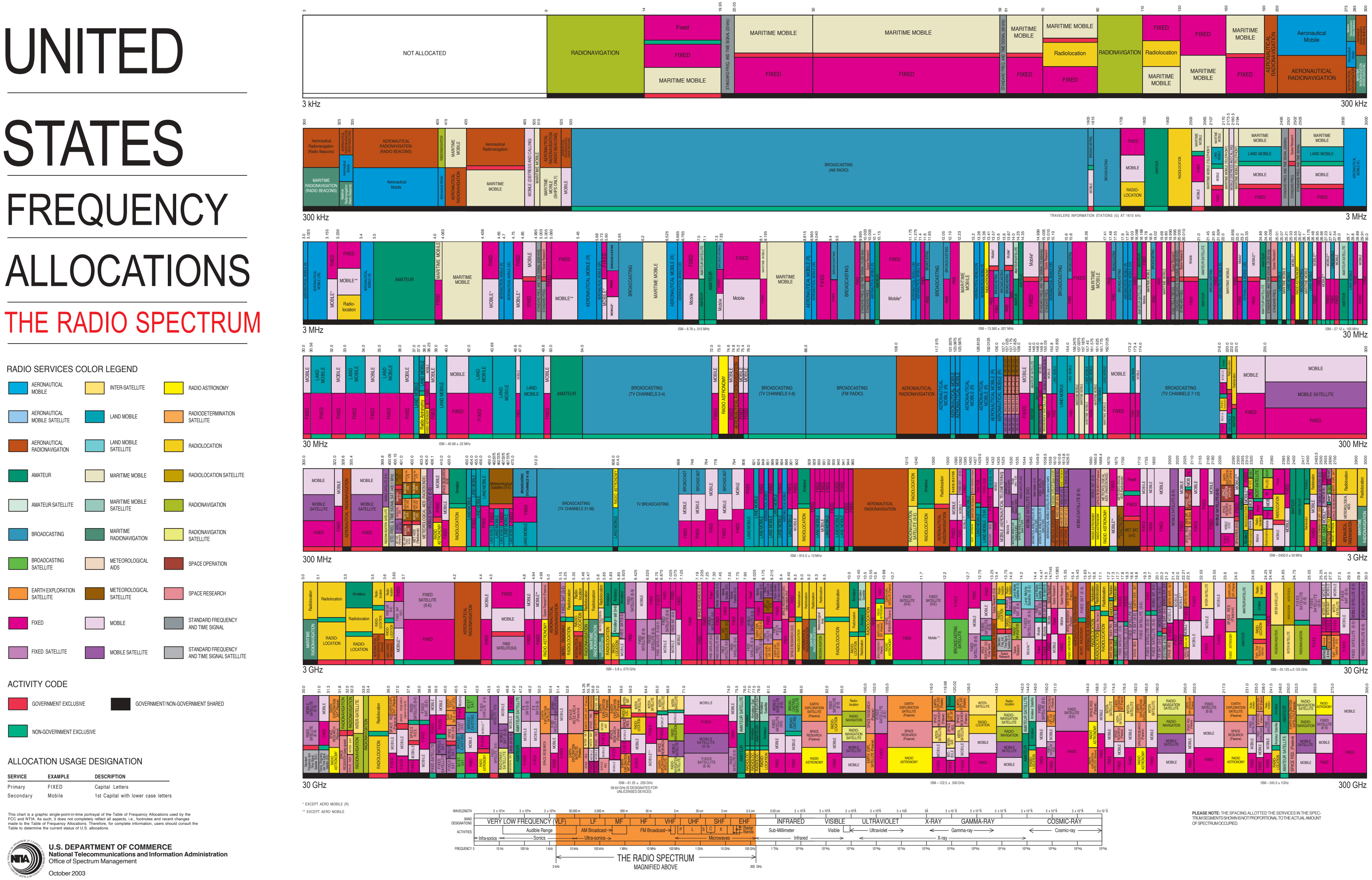

Population's coverage
Milions of subscribers
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0
2015
2016
2017
2018
2019
Year
6.972
7.087
7.231
7.335
7.426
5.756
6.240
6.605
6.944
7.125
3.211
4.764
5.664
6.116
6.270
Population covered by a mobile-cellular network
Population covered by at least a 3G mobile network
Population covered by at least an LTE/WiMAX mobile network

Summary of the topics covered in this course

- Intro
- Analog Communications
- Digital Communications
- Wireless propagation channel
- Multi-carrier modulations
- Diversity techniques, LTE and 5G

Introduction

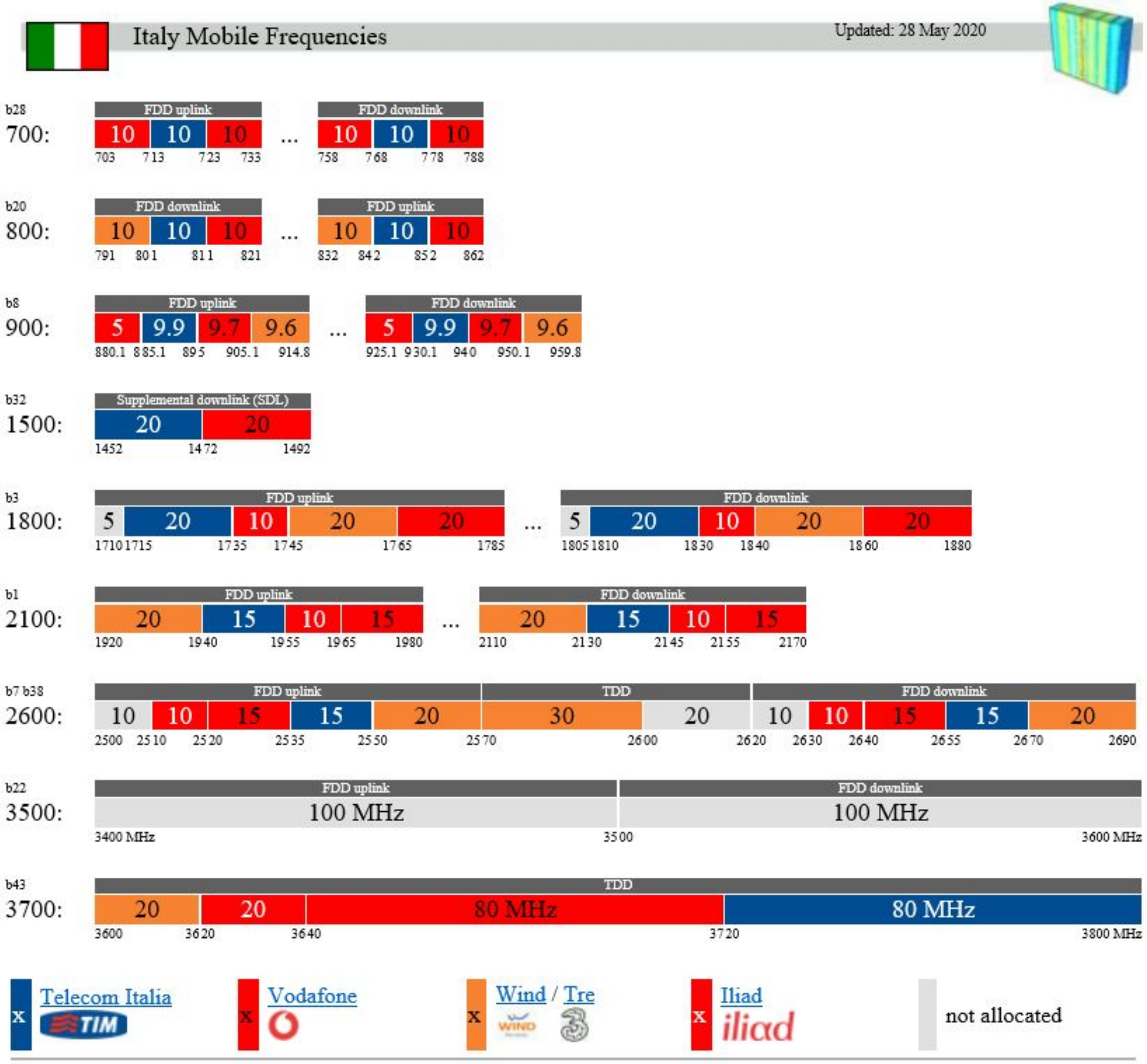
The radio spectrum



Wave propagation

Frequency band	Frequency range	Wave length	Services	Propagation
LF	$30 - 300$ kHz	$10^4 - 10^3$ m	Radio clock, navigation (LORAN), military (navy)	Ground wave
MF	$0.3 - 3$ MHz	$10^3 - 10^2$ m	AM radio (52—1600 kHz), radio beacons	Ground wave, sky wave
HF	$3 - 30$ MHz	$10^2 - 10$ m	Aviation communications, over-the-horizon radar, amateur radio	Sky wave
VHF	$30 - 300$ MHz	$10 - 1$ m	Avionic communications, FM radio ($88 - 108$ MHz), DVB-T (RAI@ 177.5 MHz)	Space wave (line-of-sight)
UHF	$0.3 - 3$ GHz	$1 - 10^{-1}$ m	DVB-T (470-860 MHz), Cellular (900,1800,220 MHz), Wi-Fi, GPS.	
SHF	$3 - 30$ GHz	$10^{-1} - 10^{-2}$ m	Wi-Fi, 5G	
EHF	$30 - 300$ GHz	$10^{-2} - 10^{-3}$ m	Wi-Fi, 5G, DVB-S, Radar, SatCom	

Radio frequency allocation LTE (and 5G) Italy



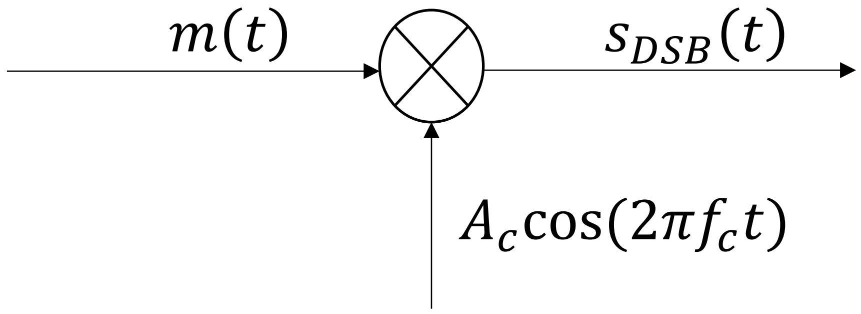
FREQUENZA	PARTECIPANTE	IMPORTO	STATO
700 MHz blocco riservato	ILIAD ITALIA S.P.A.	€ 676.472.792,00	AGGIUDICATO
700 MHz blocco generico	VODAFONE ITALIA S.P.A.	€ 345.000.000,00	AGGIUDICATO
700 MHz blocco generico	TELECOM ITALIA S.P.A.	€ 340.100.000,00	AGGIUDICATO
700 MHz blocco generico	TELECOM ITALIA S.P.A.	€ 340.100.000,00	AGGIUDICATO
700 MHz blocco generico	VODAFONE ITALIA S.P.A.	€ 338.236.396,00	AGGIUDICATO
3700 MHz blocco specifico (80 MHz)	TELECOM ITALIA S.P.A.	€ 1.694.000.000,00	AGGIUDICATO
3700 MHz blocco generico (80 MHz)	VODAFONE ITALIA S.P.A.	€ 1.685.000.000,00	AGGIUDICATO
3700 MHz blocco generico (20 MHz)	WIND TRE S.P.A.	€ 483.920.000,00	AGGIUDICATO
3700 MHz blocco generico (20 MHz)	ILIAD ITALIA S.P.A.	€ 483.900.000,00	AGGIUDICATO
26 GHz blocco generico	TELECOM ITALIA S.P.A.	€ 33.020.000,00	AGGIUDICATO
26 GHz blocco generico	ILIAD ITALIA S.P.A.	€ 32.900.000,00	AGGIUDICATO
26 GHz blocco generico	FASTWEB S.P.A.	€ 32.600.000,00	AGGIUDICATO
26 GHz blocco generico	WIND TRE S.P.A.	€ 32.586.535,00	AGGIUDICATO
26 GHz blocco generico	VODAFONE ITALIA S.P.A.	€ 32.586.535,00	AGGIUDICATO
	TOTALE GENERALE	€ 6.550.422.258,00	

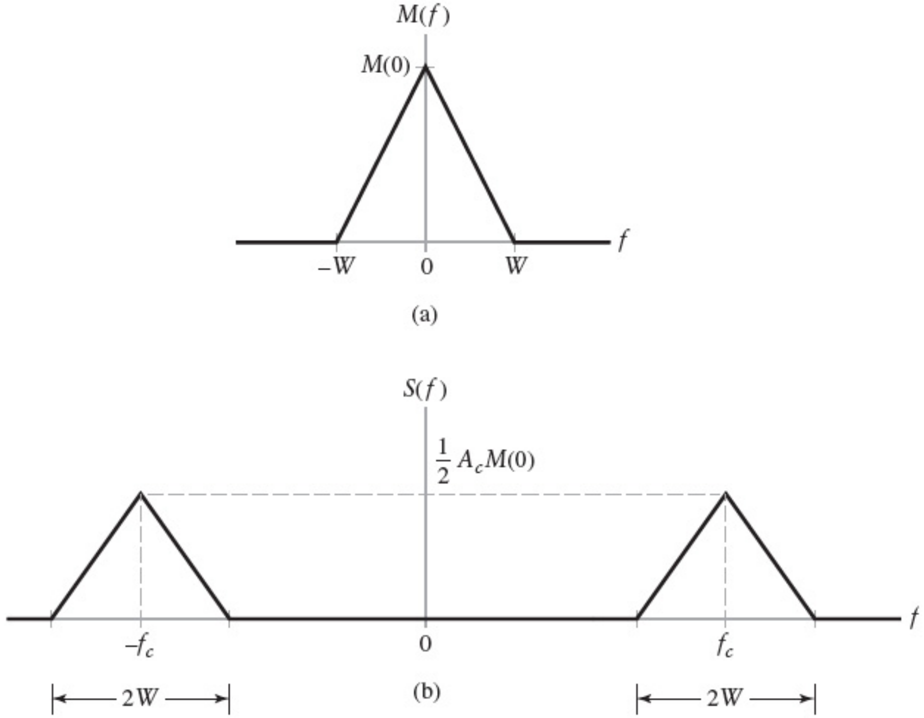
Analog Communications

Amplitude modulation dual side band (AM-DSB)

- The AM-DSB modulation is probably the simplest modulation possible

$$s_{DSB}(t) = \mathrm{A_c} m(t) \cos(2\pi f_c t)$$

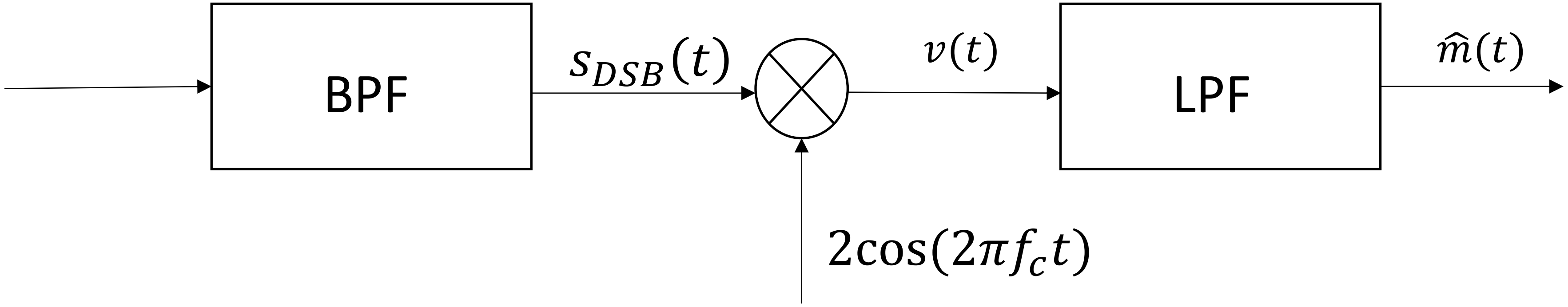




(a)
(b)

DSB coherent detection

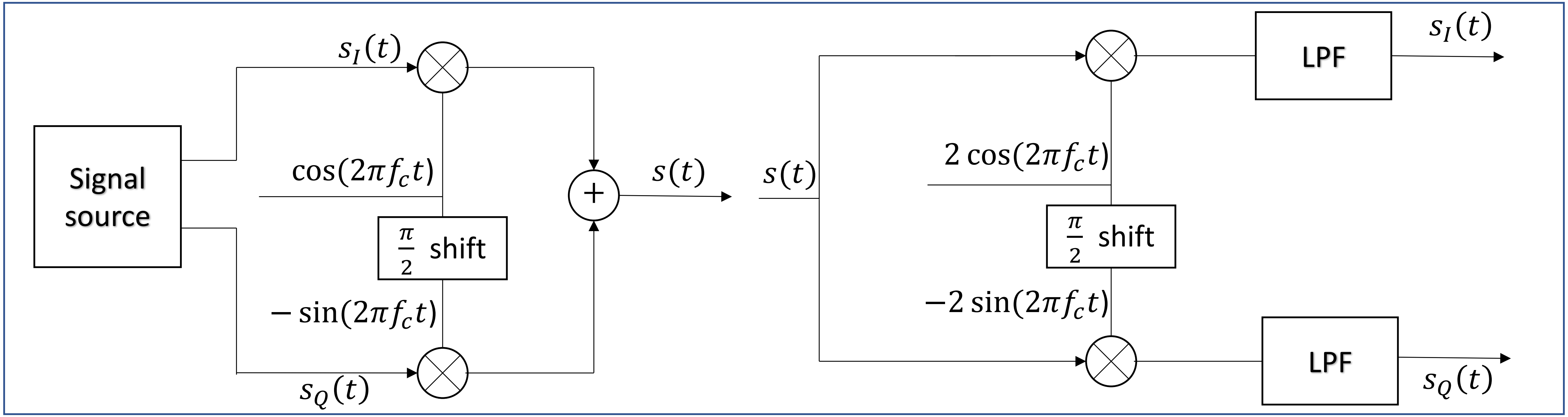
- Neglecting for the moment the effect of the noise and of the propagation channel, recovery of $m(t)$ from $s_{DSB}(t)$ is possible with coherent detection.



Analog Quadrature Amplitude Modulation

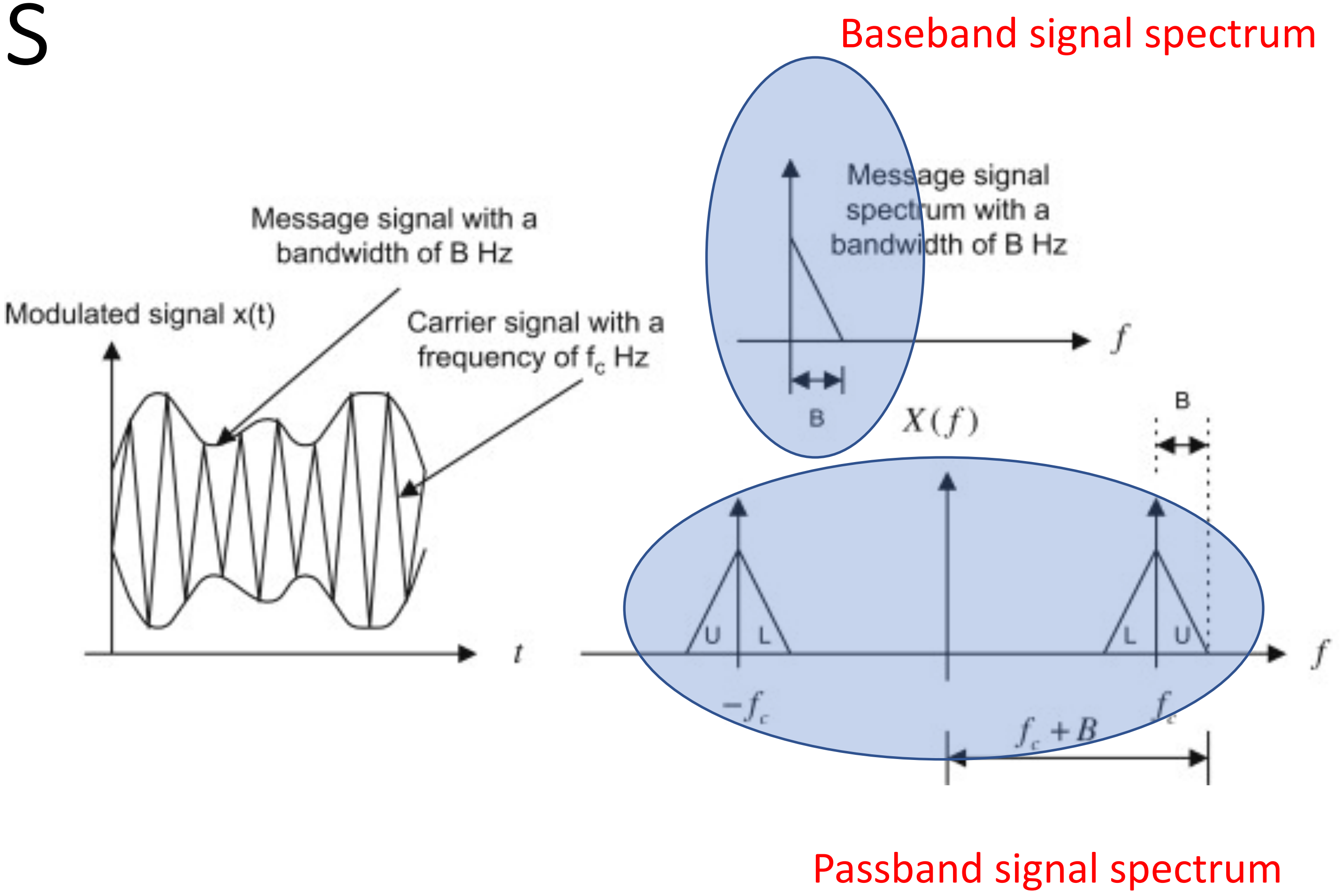
- To double the amount of information transmitted on a given bandwidth, it is possible to multiplex two DSB signal on the same channel exploiting the orthogonality of $\sin(2\pi f_c t)$ and $\cos(2\pi f_c t)$

$$s(t) = A_c m_1(t)\cos(2\pi f_c t) - A_c m_2(t)\sin(2\pi f_c t)$$



Passband signals

- The vast majority of communication systems are passband systems.
- The transmitted signal $s(t)$ has its energy concentrated in a bandwidth $2B$ centered around some nominal carrier frequency f_c and above and relatively far away from dc.
- For a *passband* signal it is
$$f_c \gg 2B$$



Complex envelope of a passband signal

- Any passband signal $s(t)$ can be represented as

$$s(t) = \mathrm{Re}\left\{\tilde{s}(t)e^{j2\pi f_c t}\right\} = s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)$$

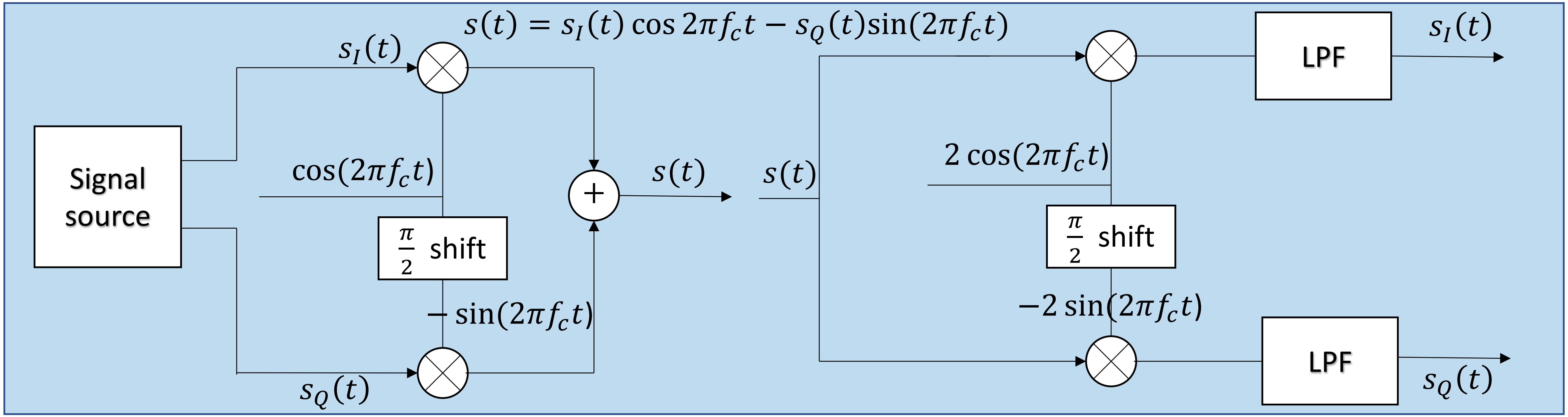
  where $\tilde{s}(t) = s_I(t) + js_Q(t)$ is the *complex envelope* of the signal with $s_I(t)$ and $s_Q(t)$ the in-phase and quadrature components.

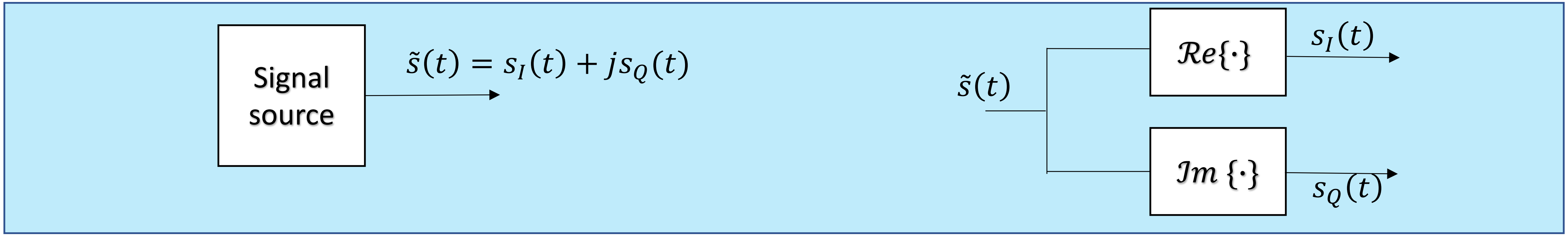
- Complex envelope for known modulated signals
  - $\tilde{s}_{DSB}(t) = A_c m(t)$; $s_I(t) = A_c m(t), s_Q(t) = 0.$
  - $\tilde{s}_{QAM}(t) = A_c m_1(t) + jA_c m_2(t)$; $s_I(t) = A_c m_1(t),\ s_Q(t) = A_c m_2(t).$

Complex envelope of a passband signal

- The complex envelope is an equivalent baseband representation of a passband signal.
- Employing the baseband equivalent has several benefits:
  - A baseband model is simpler to study, since it removes the effects of the carrier frequency from the signal model.
  - A baseband model can be numerically simulated with much lower computation than a passband model because the bandwidth and, as a consequence, the sampling rate is much lower.
  - A baseband model is often the basis for a digital implementation of a bandpass communications system.

Bandpass vs. equivalent baseband model



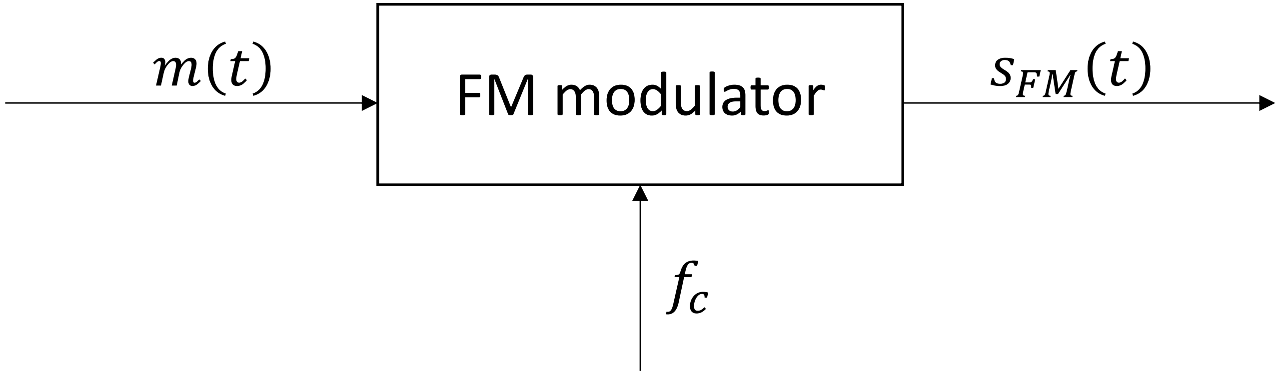


Analog communications: frequency modulation (FM)

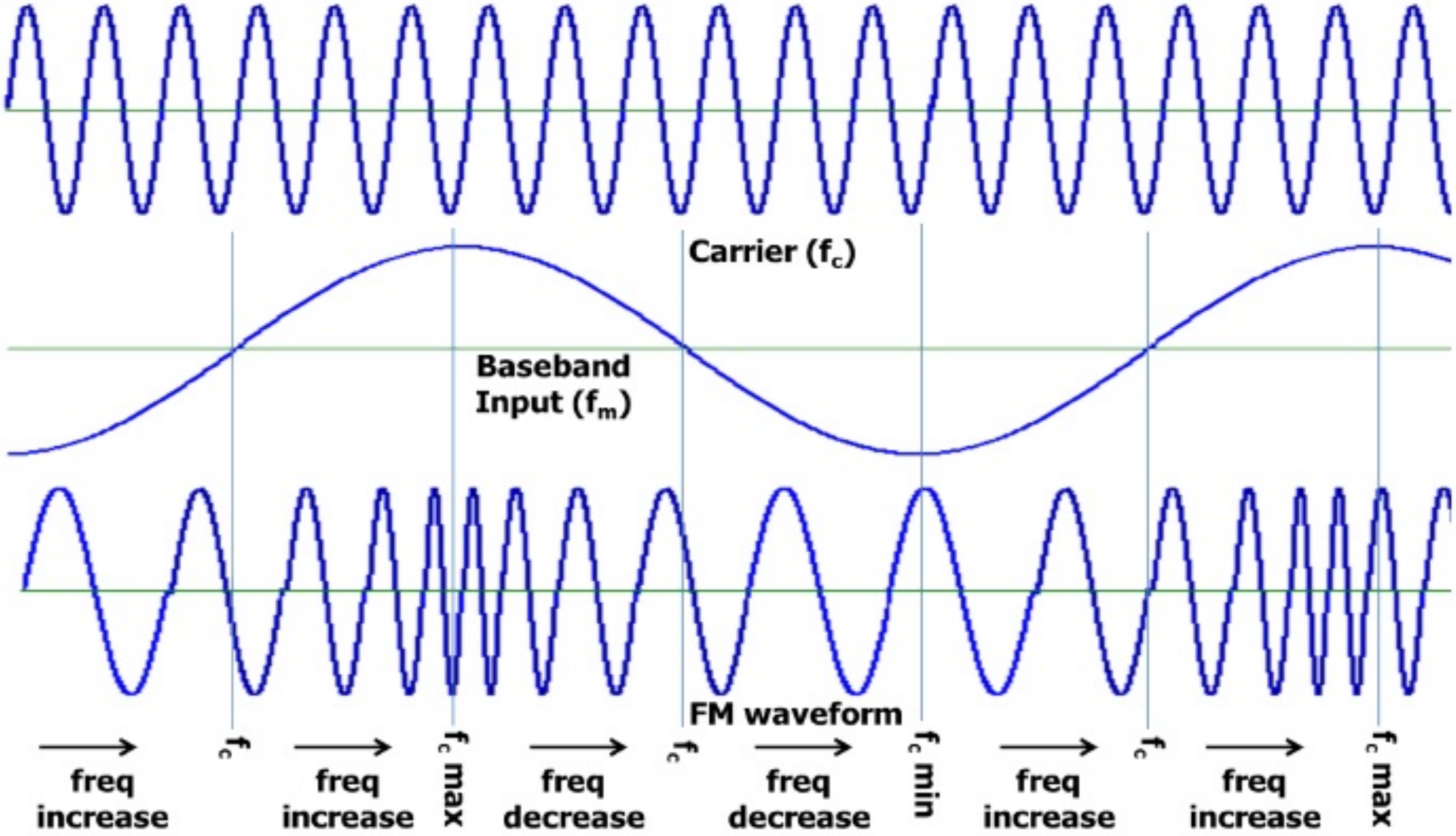
- In the FM modulation, the message is embedded in the signal phase $\phi(t)$

$$s_{FM}(t) = A_c \cos\left(2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(\tau)\, d\tau\right)$$

$$\phi(t) = 2\pi\left(f_c t + 2\pi k_f \int_{-\infty}^{t} m(\tau)\, d\tau\right)$$



Frequency modulation



FM radio

- Advantages:
  - Constant envelope modulation: greatly simplifies amplifier design
  - By properly adjusting FM parameters, it is possible to trade spectral efficiency with energy efficiency
  - Commercial FM transmits an audio signal with bandwidth $B = 15$ kHz over a bandwidth of approx 200 kHz.

FM radio

- The complex envelope of a FM signal is

$$\tilde{s}_{FM}(t) = A_c e^{j2\pi k_f \int_{-\infty}^{t} m(\tau)d\tau}$$

- Frequency deviation of an FM signal

$$f_d(t) = \frac{1}{2\pi}\frac{d}{dt}\phi(t) - f_c = \frac{1}{2\pi}\frac{d}{dt}\tilde{\phi}(t) = k_f m(t)$$

- Maximum frequency deviation

$$\Delta f = \max\{|f_d(t)|\} = k_f \max\{|m(t)|\}$$

- Modulation index $m_f = \frac{\Delta f}{B_m}$

FM signal with a modulating sinusoid

- Let $m(t)$ be a sinusoid

$$m(t) = V_m \cos(2\pi f_m t)$$

- The FM signal is

$$\begin{aligned} s_{FM}(t) &= A_c \cos\left(2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} V_m \cos(2\pi f_m \tau)\, d\tau\right) \\ &= A_c \cos\left(2\pi f_c t + 2\pi k_f V_m \frac{\sin(2\pi f_m t)}{2\pi f_m}\right) \\ &= A_c \cos\left(2\pi f_c t + m_f \sin(2\pi f_m t)\right) \end{aligned}$$

Modulation index

- Complex envelope is

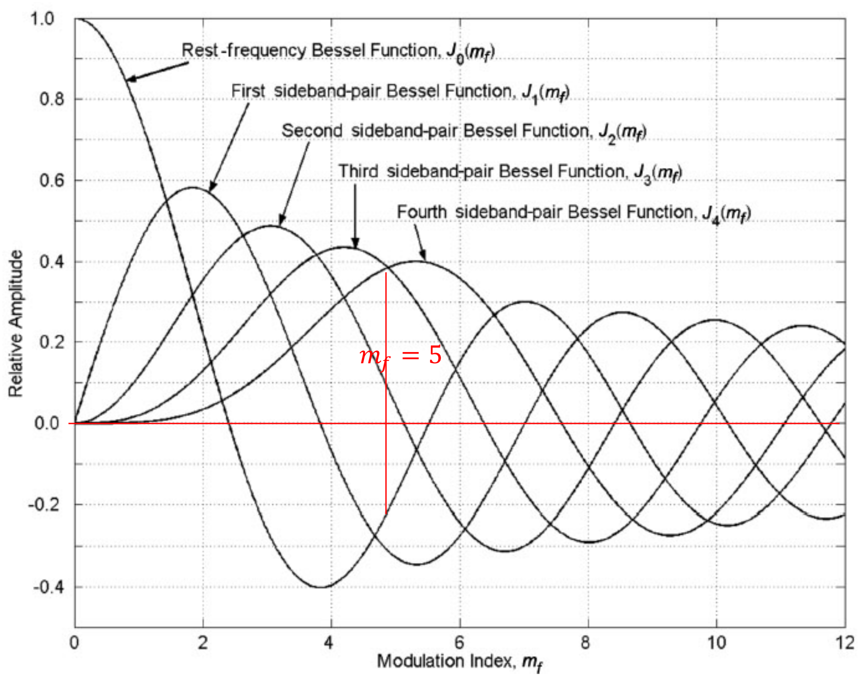
$$\tilde{s}_{FM}(t) = A_c e^{j m_f \sin(2\pi f_m t)}$$

FM signal spectrum

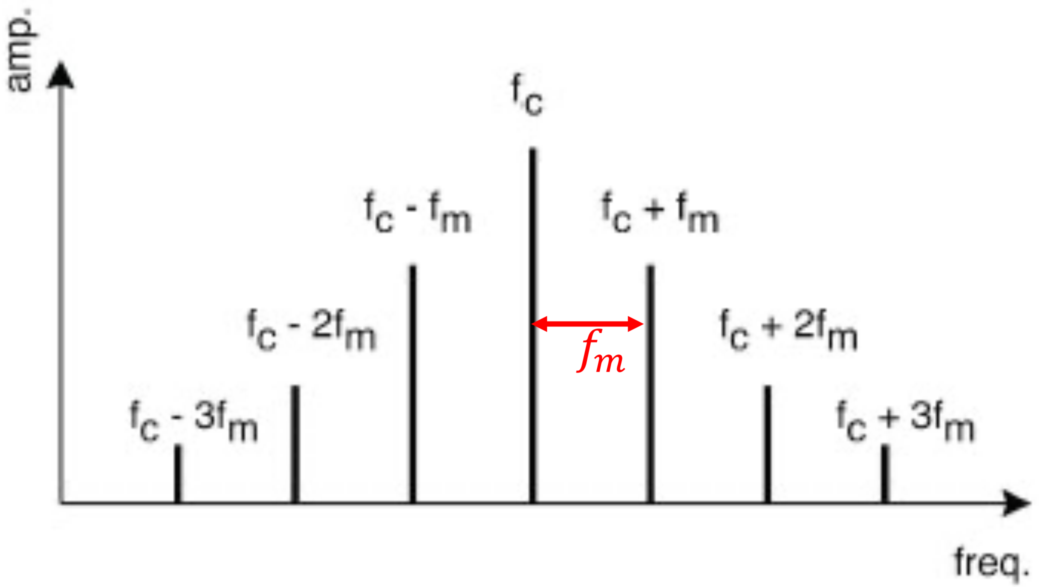
- Expoliting the periodicity of $\tilde{s}_{FM}(t) = A_c e^{j m_f \sin(2\pi f_m t)}$, the complex envelope can be written as a sum of Fourier coefficients

$$\tilde{s}_{FM}(t) = A_c \sum_n \mathrm{J}_n(m_f) e^{j2\pi n f_m t}$$

Bessel function of the first type of order n



$$s_{FM}(t) = \mathrm{Re}\{\tilde{s}_{FM}(t) e^{j2\pi f_0 t}\} = A_c \sum_n \mathrm{J}_n(m_f) \cos(2\pi(f_c + n f_m)t)$$



FM signal spectrum

- It is is impossible to calculate a closed form expression for FM spectrum
- A good approximation is the Carson bandwidth rule
$$B_{FM} \approx 2\left(m_f + 1\right)B = 2(\Delta f + B)$$
- Any frequency modulated signal has an *infinite* number of sidebands and hence an infinite bandwidth but most of the energy (98% or more) is concentrated within the bandwidth defined by Carson's rule.
- In commercial mono FM we have $B_{FM} \approx 180$ kHz
  - $B = 15$ kHz (high quality audio)
  - $\Delta f = 75$ kHz
  - $m_f = 5$

FM receiver

- Neglecting the effect of noise and channel, the complex envelope of the received signal is

$$\tilde{v}(t) = A_c e^{j2\pi k_f \int_{-\infty}^{t} m(\tau)d\tau}$$

- The modulating signal can be recovered by differentiating the phase of $\tilde{v}(t)$

$$\hat{m}(t) = \frac{1}{2\pi k_f}\frac{d}{dt}\angle\tilde{v}(t)$$

Conceptual FM baseband receiver