

Principles of Communications

ECS 332

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4.6 QAM



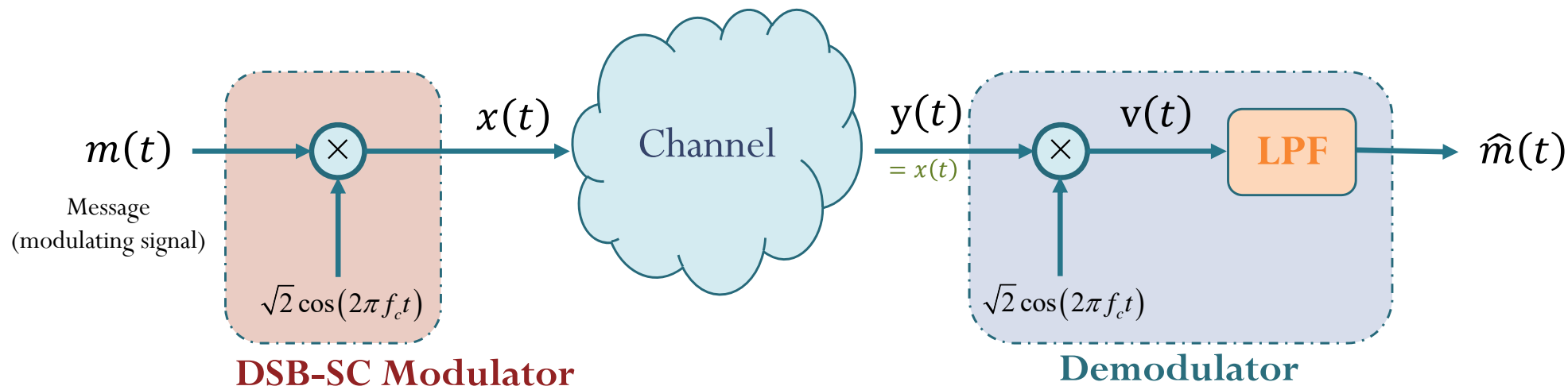
Office Hours:

Check Google Calendar on the course website.

Dr.Prapun's Office:

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BKD

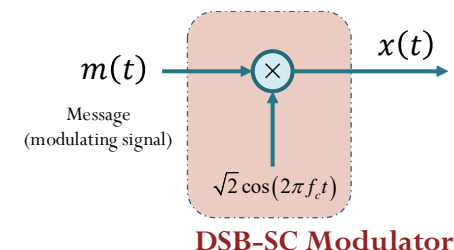
DSB-SC Modem



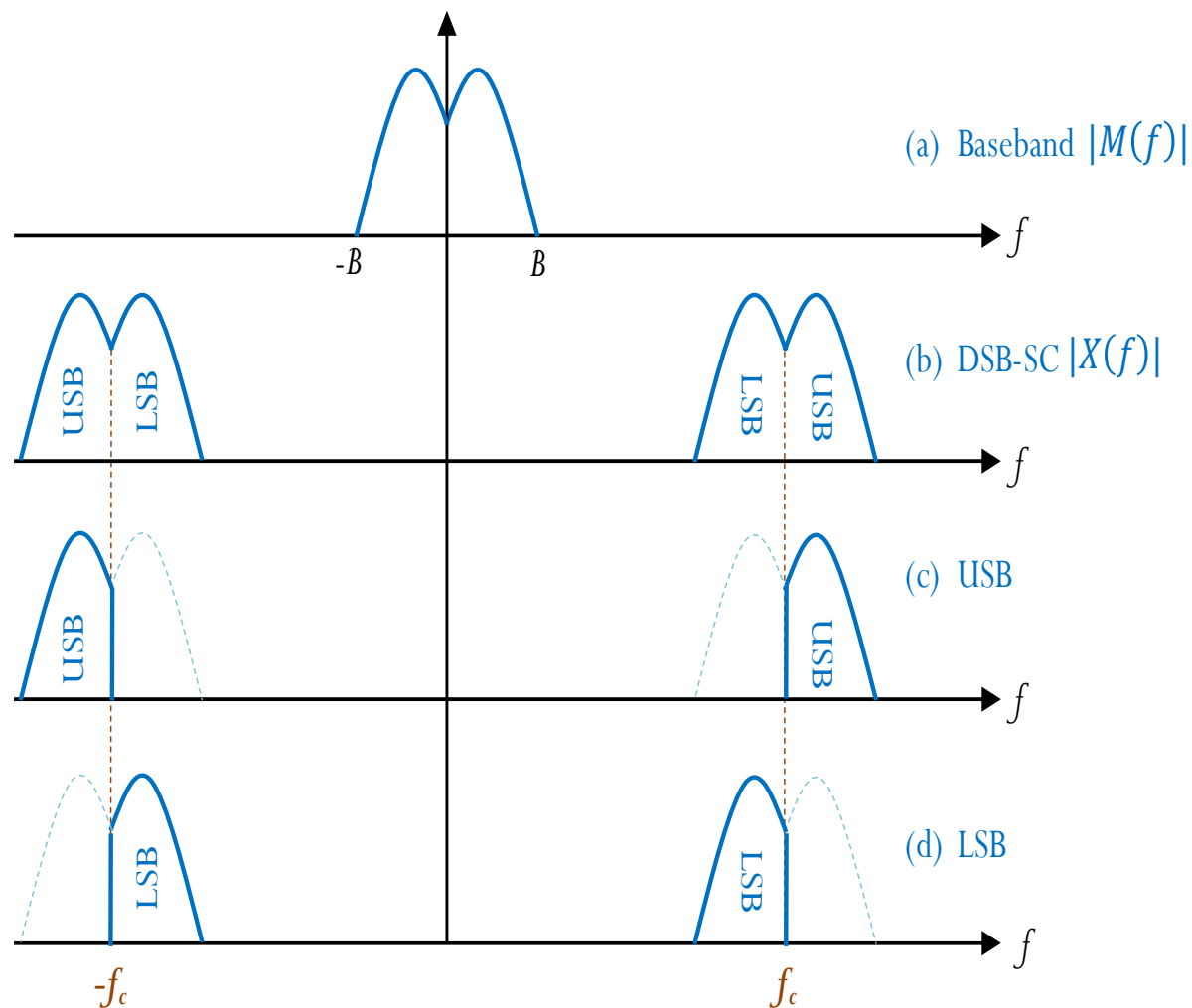
[4.8] Implementation issues:

Problem	Solutions
Modulator construction	Square mod [4.56]; SW mod [4.58],
Demodulator construction; Synchronization between the two (local) carriers/oscillators	AM (Additional carrier component is transmitted) + Rectifier/Envelope Detector [4.71-4.72]
Spectral inefficiency	[Sec. 4.6] Bandwidth-Efficient Mod.

DSB = double sidebands



- [2.30] When $m(t)$ is real-valued, its spectrum $M(f)$ has **conjugate symmetry**.
- [4.9] With such message, the corresponding modulated signal's spectrum $X(f)$ will also inherit the symmetry but now centered at f_c (instead of at 0).
- The portion that lies above f_c is known as the **upper sideband (USB)** and the portion that lies below f_c is known as the **lower sideband (LSB)**.
- Similarly, the spectrum centered at $-f_c$ has upper and lower sidebands.



[Figure 31 in Example 4.80]

HW 5 — Due: Not Due

Solution

Lecturer: Prapun Suksumpong, Ph.D.

Problem 4. This question starts with a *square-modulator* for DSB-SC. Then, the use of the square-operation block is further explored on the receiver side of the system. [Doerschuk, 2008, Cornell ECE 320]

- (a) Let $x(t) = A_c m(t)$ where $m(t) \xleftrightarrow{\mathcal{F}} M(f)$ is bandlimited to B , i.e., $|M(f)| = 0$ for $|f| > B$. Consider the block diagram shown in Figure 5.3.

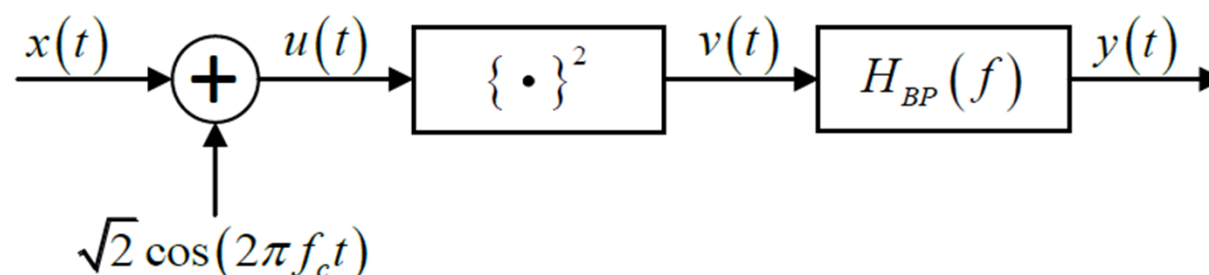


Figure 5.3: Block diagram for Problem 4a

Assume $f_c \gg B$ and

$$H_{BP}(f) = \begin{cases} 1, & |f - f_c| \leq B \\ 1, & |f + f_c| \leq B \\ 0, & \text{otherwise.} \end{cases}$$

HW 5 — Due: Not Due

Solution*Lecturer: Prapun Suksumpong, Ph.D.*

Problem 6. Consider a signal $g(t)$. Recall that $|G(f)|^2$ is called the **energy spectral density** of $g(t)$. Integrating the energy spectral density over all frequency gives the signal's total energy. Furthermore, the energy contained in the frequency band I can be found from the integral $\int_I |G(f)|^2 df$ where the integration is over the frequencies in band I . In particular, if the band is simply an interval of frequency from f_1 to f_2 , then the energy contained in this band is given by

$$\int_{f_1}^{f_2} |G(f)|^2 df. \quad (5.1)$$

In this problem, assume

$$g(t) = 1[-1 \leq t \leq 1].$$

(a) Find the (total) energy of $g(t)$.

$$E_g = \int_{-\infty}^{\infty} |g(t)|^2 dt = \int_{-\infty}^{\infty} (1[-1 \leq t \leq 1])^2 dt = \int_{-1}^1 1 dt = 2.$$

HW 5 — Due: Not Due

Solution*Lecturer: Prapun Suksumpong, Ph.D.*

- (b) Figure 5.7 define the main lobe of a sinc pulse. It is well-known that the main lobe of the sinc function contains about 90% of its total energy. Check this fact by first computing the energy contained in the frequency band occupied by the main lobe and then compare with your answer from part (a).

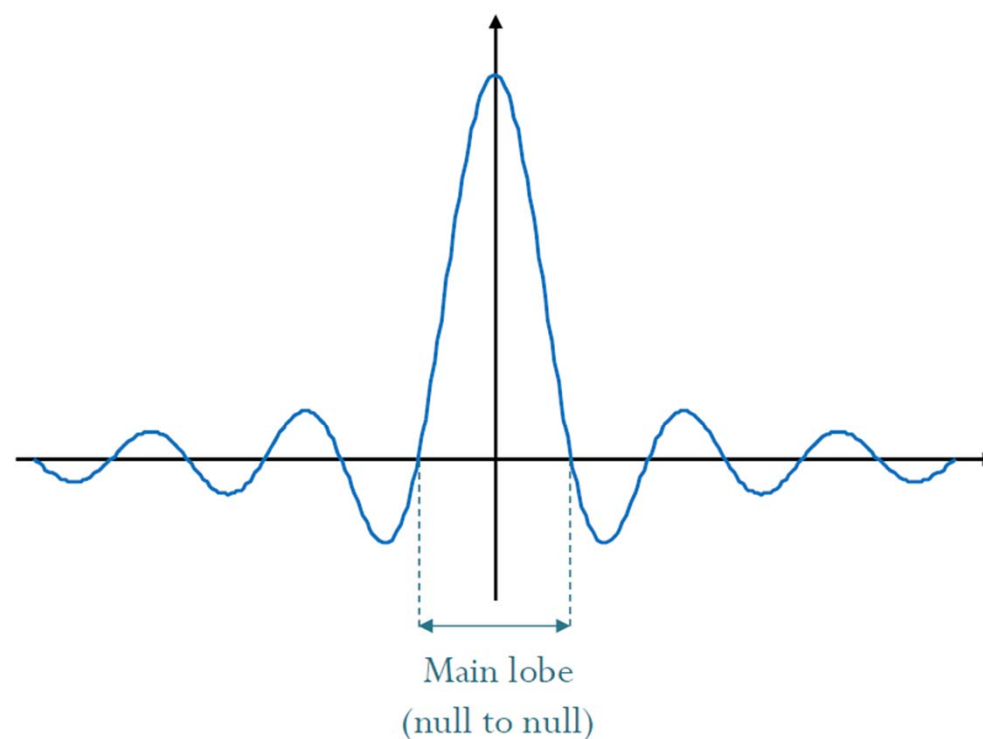


Figure 5.7: Main lobe of a sinc pulse

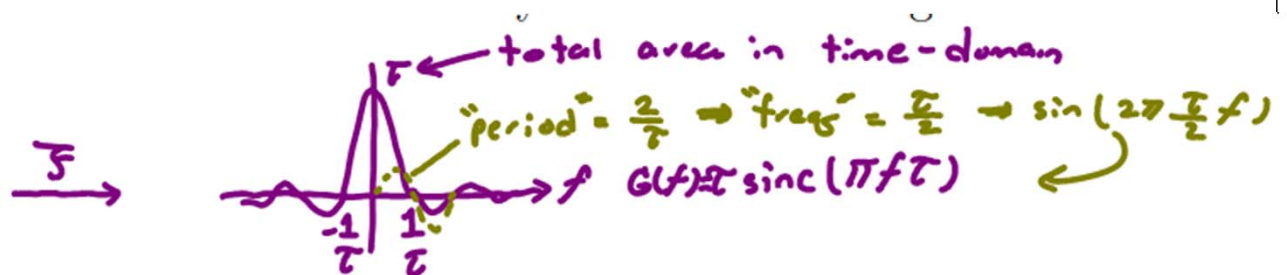
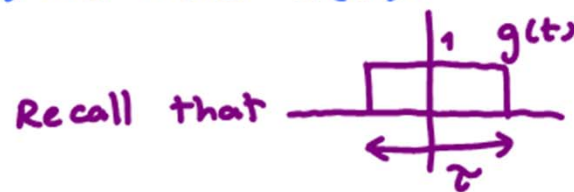
HW 5 — Due: Not Due

Solution

Lecturer: Prapun Suksumpong, Ph.D.

- (b) Figure 5.7 define the main lobe of a sinc pulse. It is well-known that the main lobe of the sinc function contains about 90% of its total energy. Check this fact by first computing the energy contained in the frequency band occupied by the main lobe and then compare with your answer from part (a).

First, we need $G(f)$.



Here, $\tau = 2$. So, $G(f) = 2 \text{sinc}(2\pi f)$

The main lobe occupies an interval of frequency from $f_1 = -\frac{1}{\tau} = -\frac{1}{2}$ to $f_2 = +\frac{1}{\tau} = +\frac{1}{2}$.

So, the energy contained in the band $B = [f_1, f_2]$ is given by $\int_{-1/2}^{1/2} (2 \text{sinc}(2\pi f))^2 df \approx 1.9056$

Compared with the answer from part (a), this is $\approx 90\%$ of the total energy. ↑ MATLAB

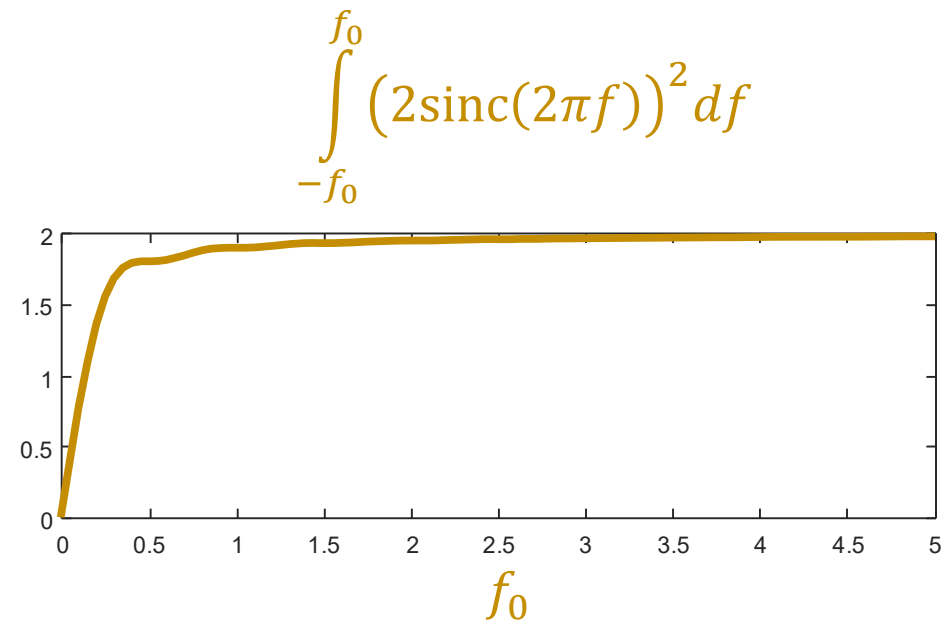
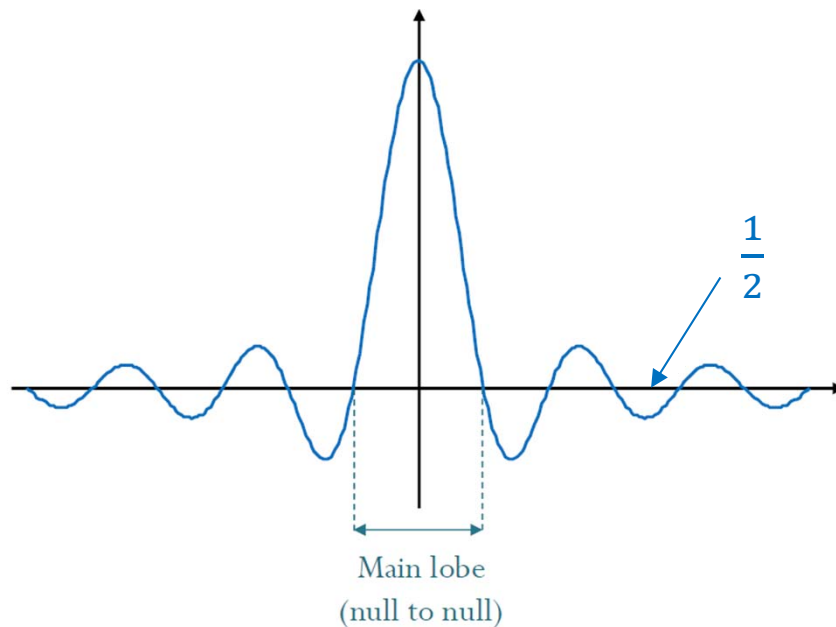
HW 5 — Due: Not Due

Solution

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- (c) Suppose we want to include more energy by considering wider frequency band. Let this band be the interval $I = [-f_0, f_0]$. Find the minimum value of f_0 that allows the band to capture at least 99% of the total energy in $g(t)$.

Using MATLAB, we can look at the fraction of energy as a function of f_0 . We found that at around $f_0 \approx 5.1$, the fraction begins to exceed 99%.



IEEE 802.11ac

From Wikipedia, the free encyclopedia

IEEE 802.11ac is a wireless networking standard in the IEEE 802.11 family, providing high-throughput Wi-Fi based on the IEEE 802.11n standard. It was approved by IEEE in December 2013 and is backward compatible with IEEE 802.11n. It is a subset of IEEE 802.11ax.

- 1 Overview
- 2 Features
- 3 Use cases and configurations
- 4 Physical layer
- 5 Channel access
- 6 Modulation
- 7 Security
- 8 Power
- 9 Coexistence
- 10 Security

New technologies (edit)

The standard introduces several new technologies:

- Beamforming** - Uses multiple antennas to focus signals on specific devices, increasing range and throughput.
- Channel bonding** - Combines two adjacent 20 MHz channels into a 40 MHz channel to double the data rate.
- Multi-user MIMO (MU-MIMO)** - Allows multiple users to receive data simultaneously, increasing network capacity.
- Long Guard Intervals (LGI)** - Improves performance in multipath environments by extending the guard interval between OFDM symbols.
- Channel state information (CSI) feedback** - Allows the transmitter to adapt to the current channel conditions for better performance.

Features (edit)

- Support for up to 8 spatial streams (SU-MIMO) and 80 MHz channels.
- Support for up to 256-QAM modulation.
- Support for up to 30 users per access point (MU-MIMO).
- Support for up to 80 MHz channels.
- Support for up to 256-QAM modulation.
- Support for up to 30 users per access point (MU-MIMO).

Example configurations (edit)

Scenario	Channel width	MCS	Approximate throughput
Downstream 802.11ac 80 MHz	80 MHz	MCS 8	433 Mbps
Downstream 802.11ac 40 MHz	40 MHz	MCS 8	216 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 8	108 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 9	130 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 10	152 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 11	174 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 12	196 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 13	218 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 14	240 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 15	262 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 16	284 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 17	306 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 18	328 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 19	350 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 20	372 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 21	394 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 22	416 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 23	438 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 24	460 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 25	482 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 26	504 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 27	526 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 28	548 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 29	570 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 30	592 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 31	614 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 32	636 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 33	658 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 34	680 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 35	702 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 36	724 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 37	746 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 38	768 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 39	790 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 40	812 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 41	834 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 42	856 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 43	878 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 44	900 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 45	922 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 46	944 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 47	966 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 48	988 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 49	1010 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 50	1032 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 51	1054 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 52	1076 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 53	1098 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 54	1120 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 55	1142 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 56	1164 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 57	1186 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 58	1208 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 59	1230 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 60	1252 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 61	1274 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 62	1296 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 63	1318 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 64	1340 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 65	1362 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 66	1384 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 67	1406 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 68	1428 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 69	1450 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 70	1472 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 71	1494 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 72	1516 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 73	1538 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 74	1560 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 75	1582 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 76	1604 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 77	1626 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 78	1648 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 79	1670 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 80	1692 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 81	1714 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 82	1736 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 83	1758 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 84	1780 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 85	1802 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 86	1824 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 87	1846 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 88	1868 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 89	1890 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 90	1912 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 91	1934 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 92	1956 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 93	1978 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 94	2000 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 95	2022 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 96	2044 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 97	2066 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 98	2088 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 99	2110 Mbps
Downstream 802.11ac 20 MHz	20 MHz	MCS 100	2132 Mbps

Data rates and speed (edit)

The standard introduces several new technologies:

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IEEE 802.11ac is a **wireless networking** standard in the **802.11** family. The standard was developed in the **IEEE Standards Association** and is retroactively labelled as **Wi-Fi 5** by **Wi-Fi Alliance**.^{[3][4]}

Data rates and speed [edit]

MCS index ^[a]	Spatial Streams	Modulation type	Coding rate
0	1	BPSK	1/2
1	1	QPSK	1/2
2	1	QPSK	3/4
3	1	16-QAM	1/2
4	1	16-QAM	3/4
5	1	64-QAM	2/3
6	1	64-QAM	3/4
7	1	64-QAM	5/6
8	1	256-QAM	3/4
9	1	256-QAM	5/6
0	2	BPSK	1/2
1	2	QPSK	1/2
2	2	QPSK	3/4
3	2	16-QAM	1/2
4	2	16-QAM	3/4
5	2	64-QAM	2/3
6	2	64-QAM	3/4
7	2	64-QAM	5/6
8	2	256-QAM	3/4
9	2	256-QAM	5/6

LTE



1x20MHz CA
2x2 MIMO
64 QAM DL

100Mbps ↓ 150Mbps ↓

CAT3 CAT4

2008/9: Rel. 8/9



2x20MHz CA
2x2 MIMO
64 QAM DL

3x20MHz CA
2x2 MIMO
64 QAM DL

300Mbps ↓ 600Mbps ↓

CAT6 CAT11/12

2011/12: Rel. 10/11



>5x20 MHz CA
4x4 MIMO
256 QAM DL
LAA
CBRS
Public Safety

1.2Gbps ↓

CAT16/18

2014/15: Rel. 13/14



Massive MIMO
1024 QAM DL
mmWave
URLL

20Gbps ↓

CAT "X"

2018/19: Rel. 15/16

Three Forms of QAM

Emphasize that there are two messages

$$\begin{aligned} 1 \quad x_{\text{QAM}}(t) &= 3\sqrt{2} \cos(2\pi f_c t) + 4\sqrt{2} \sin(2\pi f_c t) \\ &\Leftrightarrow 3\sqrt{2} \angle 0^\circ + 4\sqrt{2} \angle -90^\circ \approx 5\sqrt{2} \angle -53^\circ \\ 2 \quad &\Leftrightarrow 5\sqrt{2} \cos(2\pi f_c t + (-53^\circ)) \end{aligned}$$

Emphasize that the messages are embedded in both amplitude and phase of the carrier

$$\begin{aligned} e^{jx} &= \cos(x) + j \sin(x) \\ \cos(x) &= \{e^{jx}\} \end{aligned}$$

$$\begin{aligned} -je^{jx} &= -j \cos(x) + \sin(x) \\ \sin(x) &= \{-je^{jx}\} \end{aligned}$$

$$\begin{aligned} 3 \quad x_{\text{QAM}}(t) &= 3\sqrt{2} \operatorname{Re}\{e^{j2\pi f_c t}\} + 4\sqrt{2} \operatorname{Re}\{-je^{j2\pi f_c t}\} \\ &= \sqrt{2} \operatorname{Re}\{(3 - 4j)e^{j2\pi f_c t}\} \end{aligned}$$

Emphasize the use of the combined complex-valued representation of the two messages.

Three Forms of QAM

Emphasize that there are two messages

$$\begin{aligned} 1 \quad x_{\text{QAM}}(t) &= m_1(t)\sqrt{2} \cos(2\pi f_c t) + m_2(t)\sqrt{2} \sin(2\pi f_c t) \\ &\Leftrightarrow m_1(t)\sqrt{2} \angle 0^\circ + m_2(t)\sqrt{2} \angle -90^\circ \\ &= E(t)\sqrt{2} \angle \phi(t) \end{aligned}$$

Emphasize that the messages are embedded in both amplitude and phase of the carrier

$$2 \quad \Leftrightarrow \sqrt{2}E(t) \cos(2\pi f_c t + \phi(t))$$

$$\begin{aligned} e^{jx} &= \cos(x) + j \sin(x) \\ \cos(x) &= \{e^{jx}\} \end{aligned}$$

$$\begin{aligned} -je^{jx} &= -j \cos(x) + \sin(x) \\ \sin(x) &= \{-je^{jx}\} \end{aligned}$$

$$\begin{aligned} 3 \quad x_{\text{QAM}}(t) &= m_1(t)\sqrt{2} \operatorname{Re}\{e^{j2\pi f_c t}\} + m_2(t)\sqrt{2} \operatorname{Re}\{-je^{j2\pi f_c t}\} \\ &= \sqrt{2} \operatorname{Re}\{(m_1(t) - jm_2(t))e^{j2\pi f_c t}\} \end{aligned}$$

Emphasize the use of the combined complex-valued representation of the two messages.