WiFi at the Physical Layer
How do 802.11 Protocols Work?

A deep dive into the 802.11 protocol family

Who am I?

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About Unimus

Unimus is a multi-vendor system for:

- Network Disaster recovery
- Change Management
- Network Automation
- Configuration Management
- Network Auditing & Compliance

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Note for posterity

If you find this presentation online in a .pdf, please watch the video

Proper explanations to every slide and much more information available

https://www.youtube.com/c/TomasKirnak/videos

Basics & Physics

What is wireless

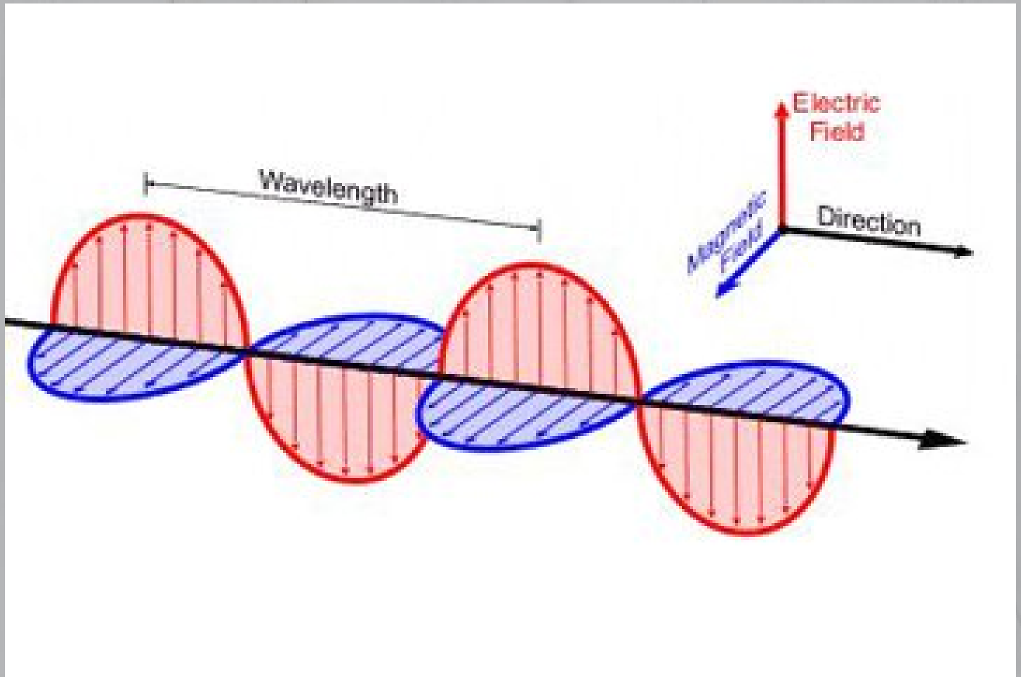
- **Wireless communication** - prenos informácii medzi dvoma alebo viac bodmi ktoré nie sú prepojené elektrickým vodičom.

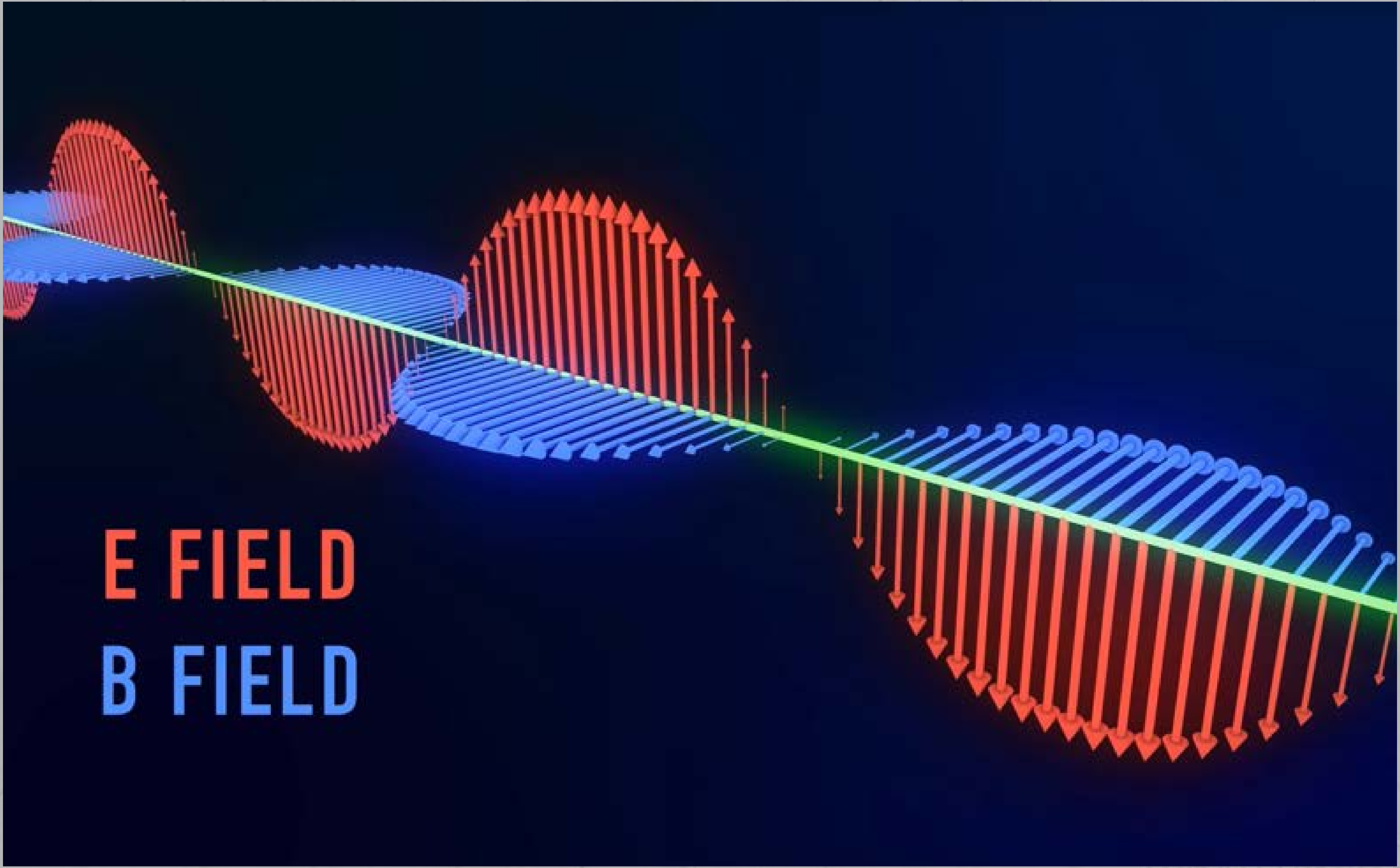
- Dáta prenášame pomocou elektro-magnetických vln
  - Dnes najpoužívaniejšie – pomocou **rádií**

- Iné možnosti:
  - FSO – free space optics

What is EM radiation?

- EM radiation is a form of energy
  - Photons in their “wave” form
- An EM wave has an electric and a magnetic component




E FIELD
B FIELD

Physics that brought us here

- 1865 – Maxwell predicted electromagnetic waves
- 1887 – Hertz generated and detected electromagnetic waves

- 1900 - Planck's Quantum Theory
- 1924 - Louis de Broglie’s Wave-Particle Duality
- 1926 - Schrödinger Equation

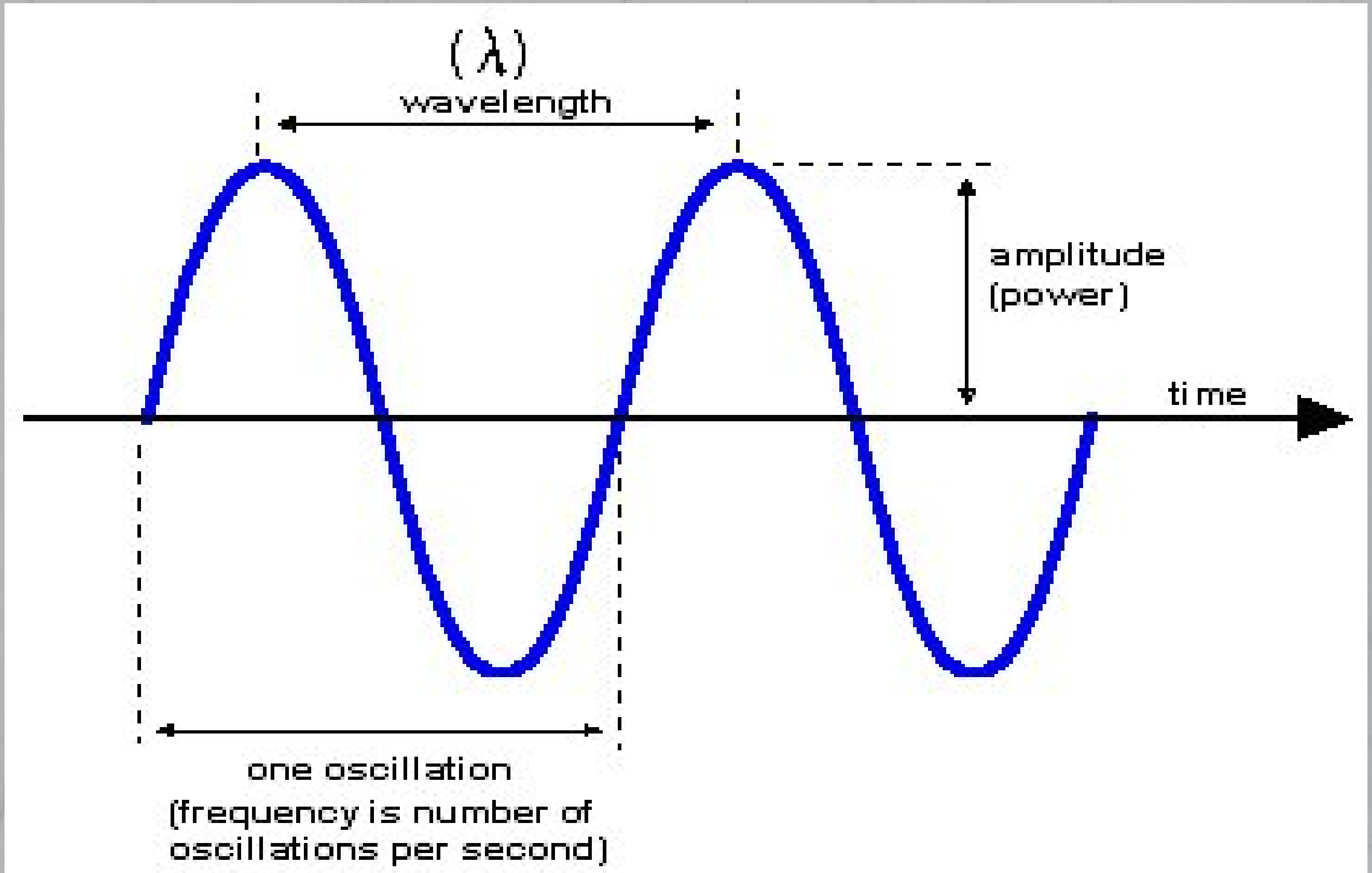
- 1940s - Pauli, Richard Feynman – Quantum Electro Dynamics

WiFi and quantum mechanics

- WiFi is quantum mechanics put into practical technology
- Quantum Electro Dynamics – the only full understood and fully described quantum theory
- QED is a part of Quantum Field Theory

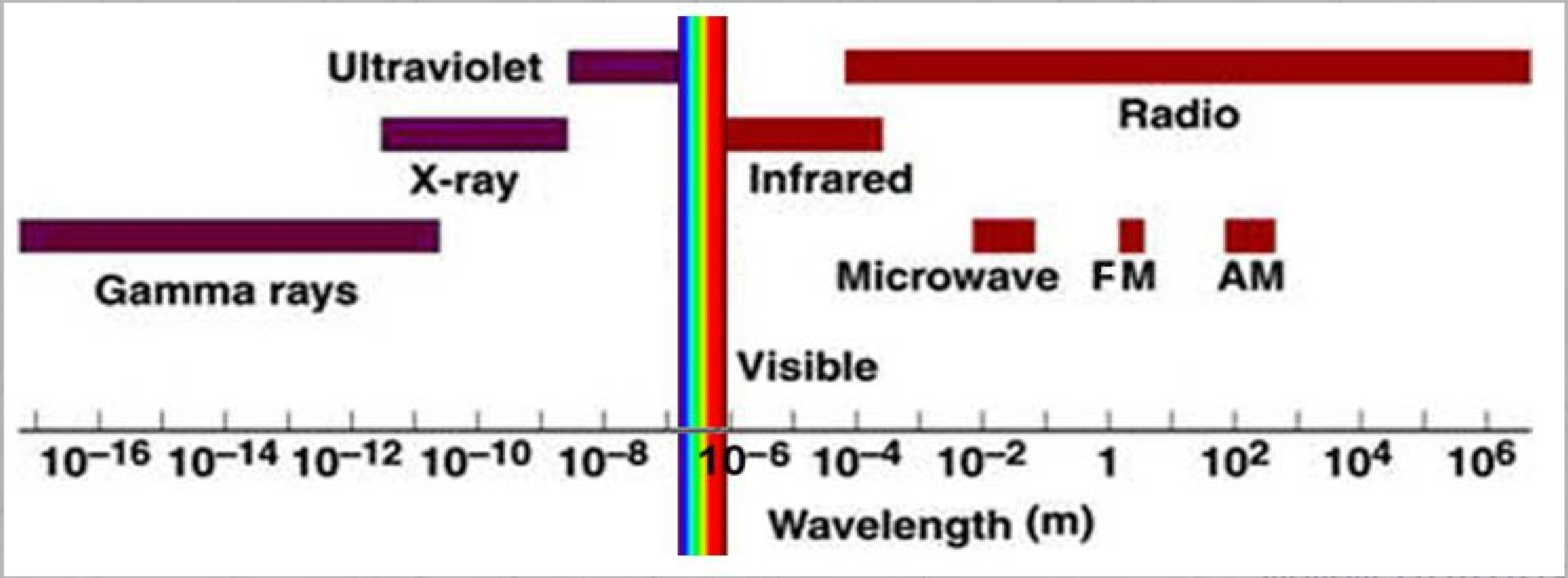
Basic wave physics

- Vlna má:
  - Frekvenciu
  - Vlnovú dĺžku
  - Amplitúdu



Wireless for us

- Budeme hovoriť o bezdrátovéj komunikácii použitím mikrovĺn



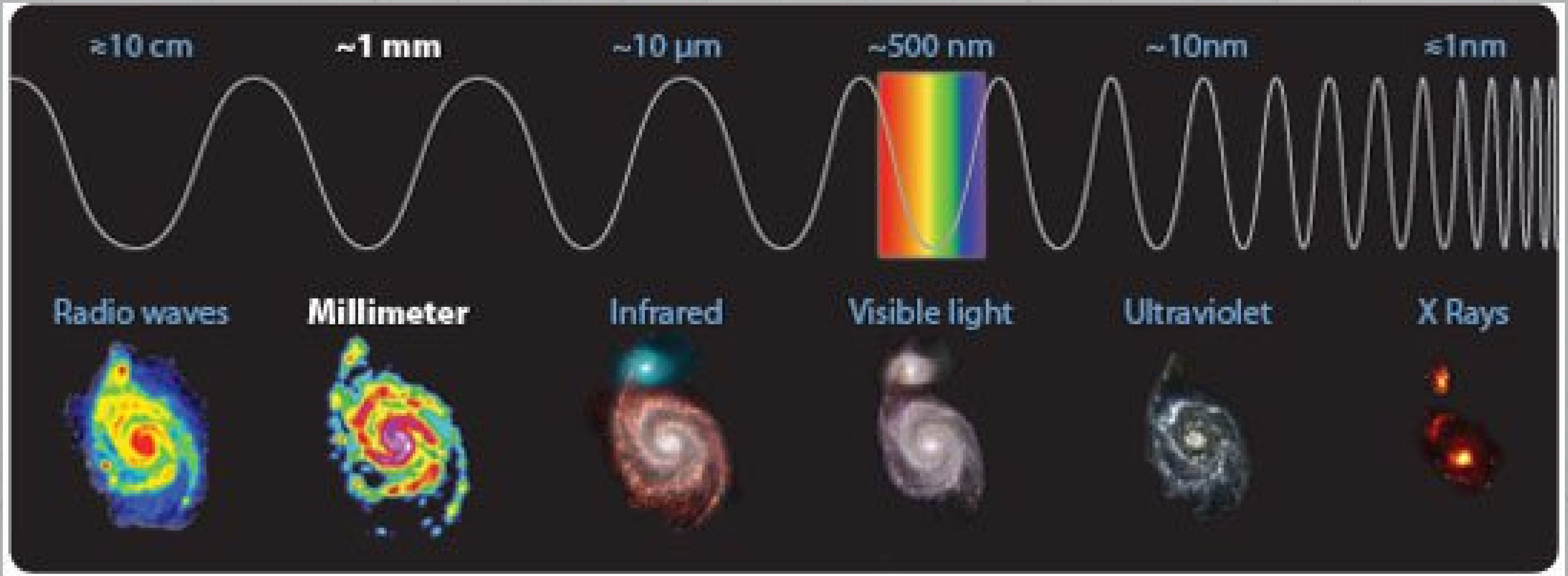
About EM radiation

- EM radiacia v celom spektre je 24/7 vyzarovana slnkom
  - Aj vsetkymi ostatnymi hviezdami vo vesmire

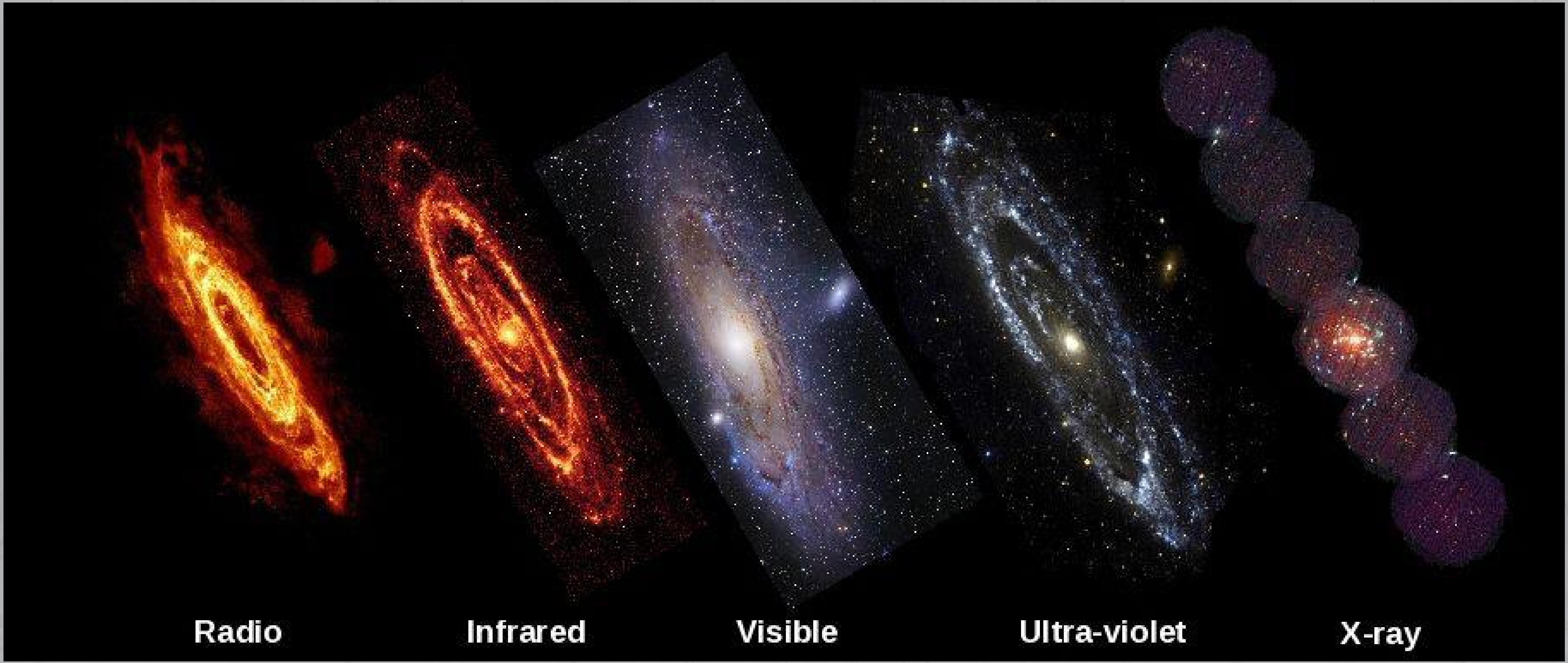
- “Kozmicka” radiacia taktiez konstantne dopada na zem v celom spektre

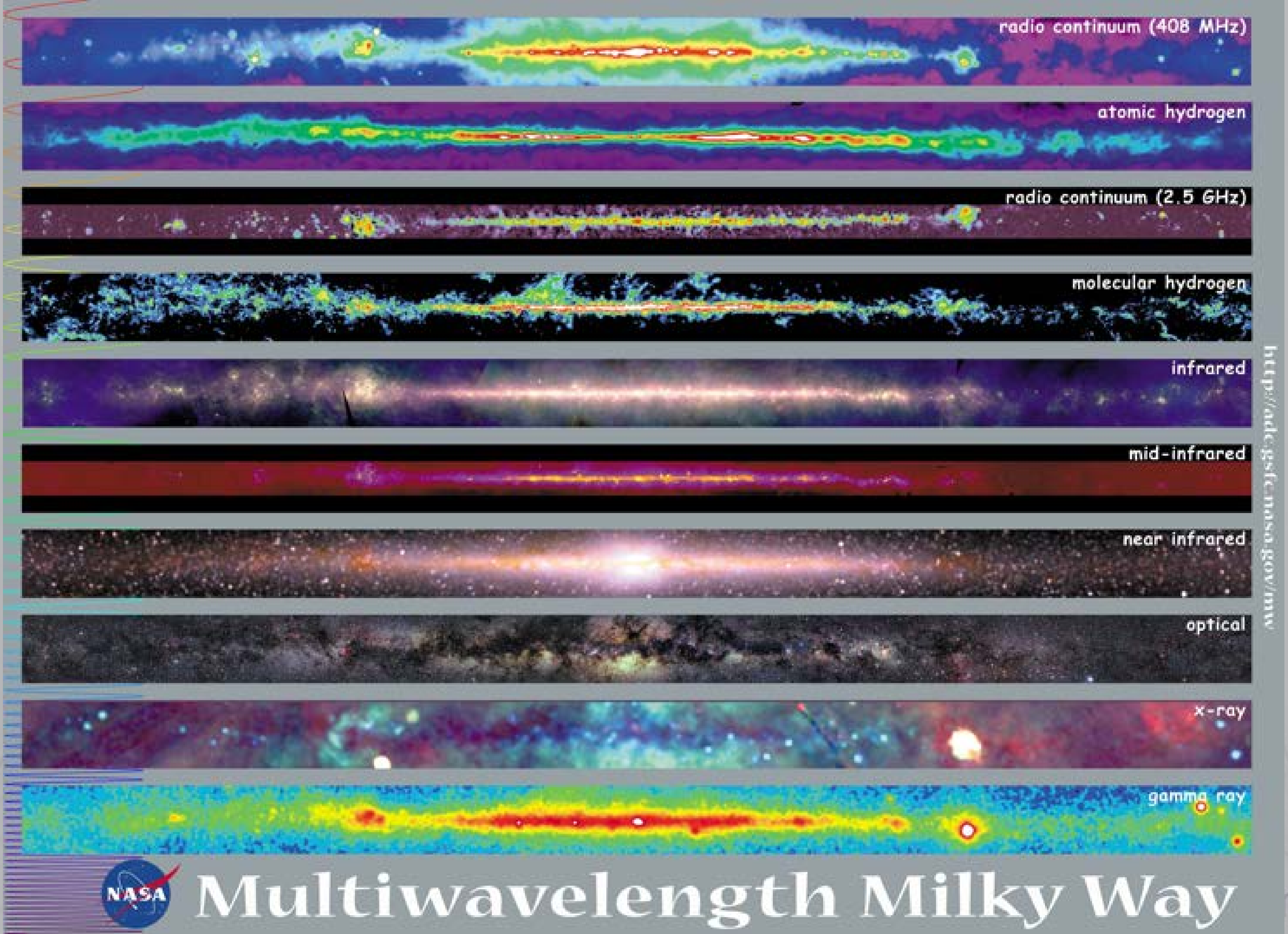
- EM - Light is just a wave that carries energy from a point to a point.

Space radiation



Space radiation - Andromeda




radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

What are we actually using

- Mikrovlny – elektromagnetická radiácia
  - rovnaká ako normálne svetlo, iná frekvencia

- Ne-ionizujúca radiácia – bezpečná
  - Ziadne neziaduce ucinky na zive bunky / DNA
  - minimalna interakcia s pevnou hmotou*

*Each subsance has resonant frequencies

Dangers of EM radiation

- Ionizing (high energy) EM radiation is dangerous because it ionizes atoms
  - It has so much energy it can knock electrons out of atoms

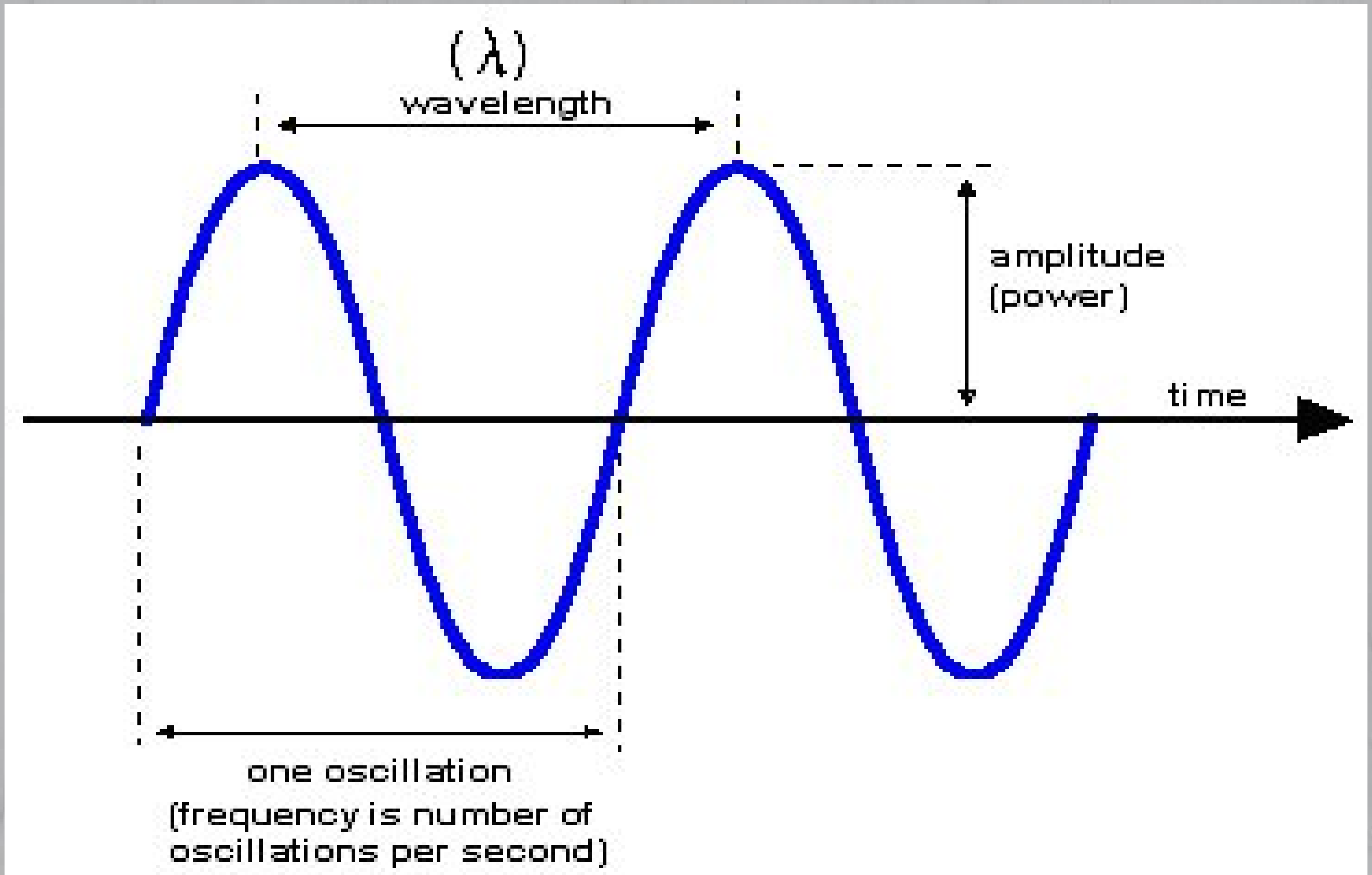
- This ionizes molecules, which damages molecular bonds - damages DNA and other living cells

Why are we even alive

- Earth has an atmosphere and an geomagnetic field.
- These 2 phenomena filter (absorb and reflect) most ionizing radiation hitting our planet from space

Back to basics...

- Vlna má:
  - Frekvenciu
  - Vlnovú dĺžku
  - Amplitúdu



The medium

- All waves travel in a medium
  - for mechanical waves, this can be many things
  - for EM waves, its our space-time

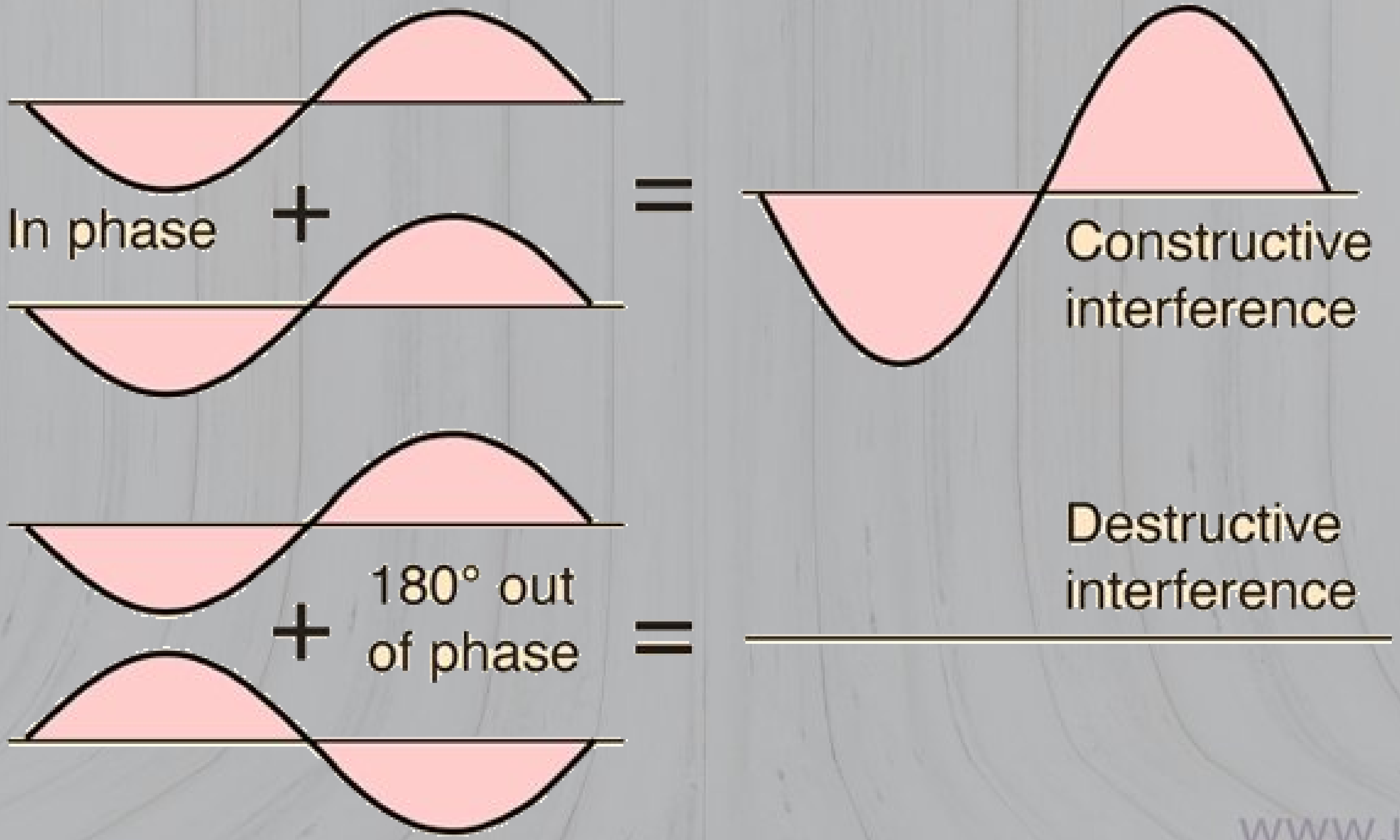
- When we communicate over EM radiation, this means our EM waves share this medium with all other EM waves

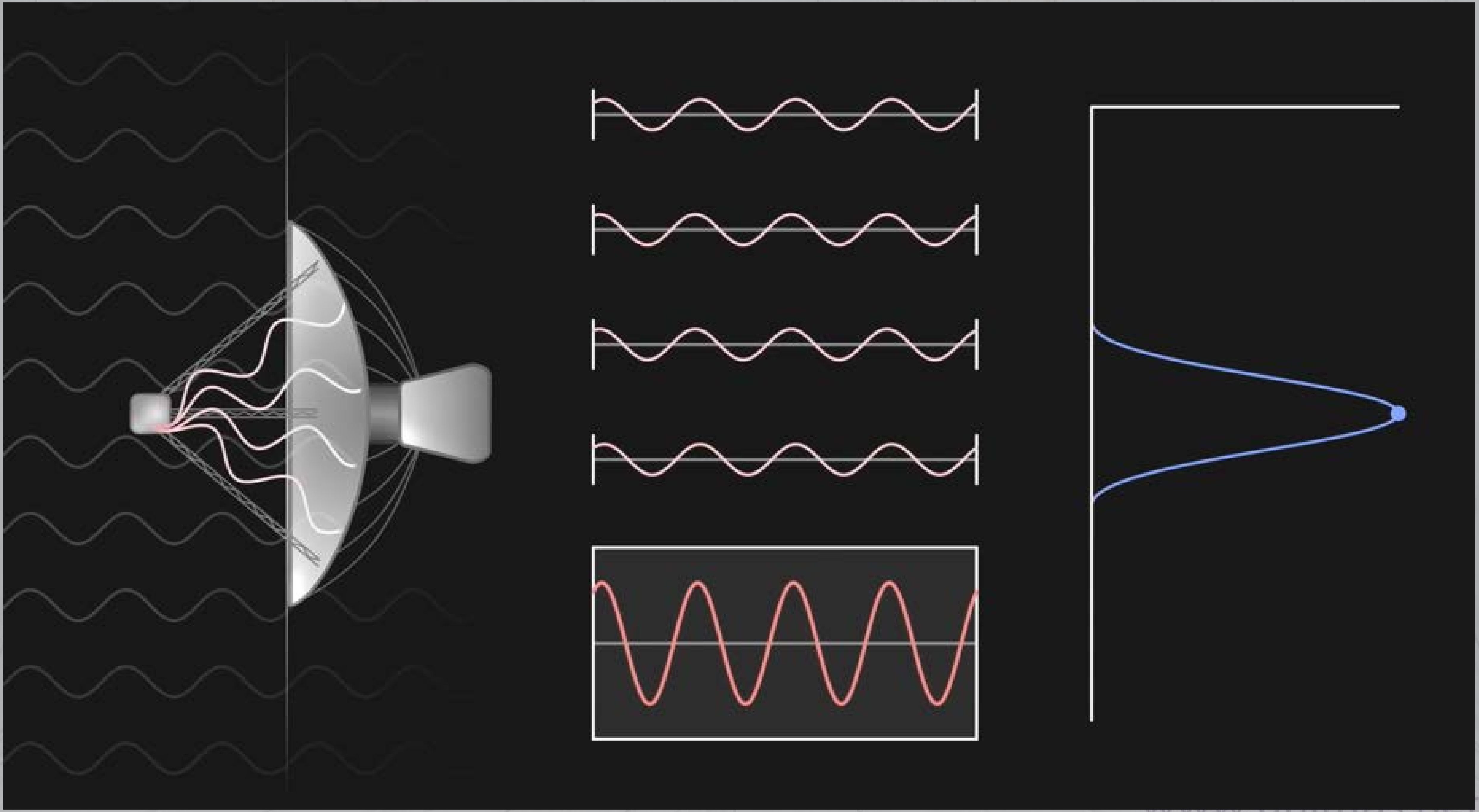
Interference

- All waves on the same frequency (and same polarization) interfere with each other

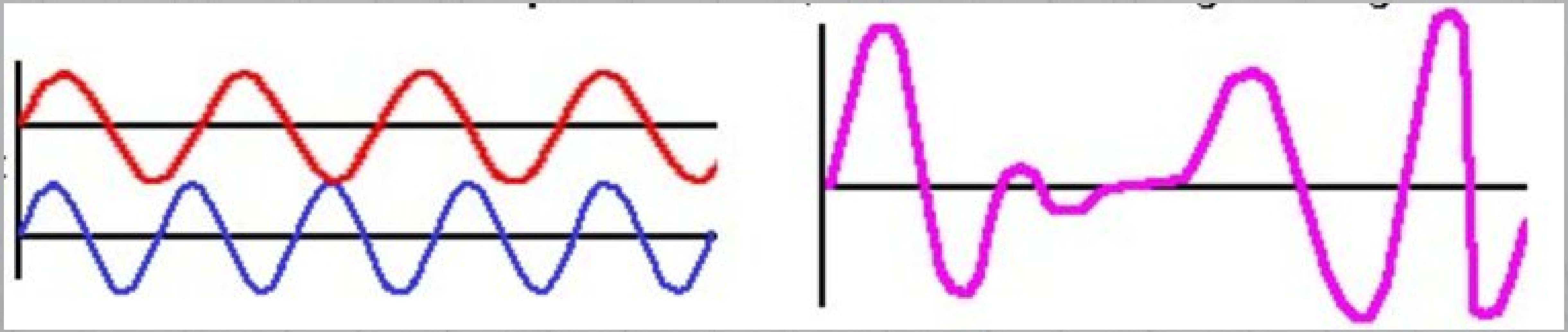
- In physics, this is not really interference, its wave combination…

Basics of interference





Advanced interference



Interference for us

- **Interference** is anything which modifies, or disrupts a signal as it travels along a channel/medium (air, vacuum, copper wire, fiberoptic strand) between a source and a receiver

- Prídavný/ďalší alebo nechcený signál ktorý prichádza s naším dobrým signálom

Interference types

- Electromagnetic interference
  - Aká koľvek iná EM radiácia z akéhokoľvek zdroja na rovnakej frequencii
- Co-channel interference
  - Niekto používa rovnaký kanál (vysvetlené za chvíľku) ako ja, alebo časť môjho kanálu
- Adjacent-channel interference
  - Niekto používa kanál ktorý je veľmi blízko môjmu
- Co-polarization interference
  - Viac o polarizácii za chvíľku...

- A kopa ďalších...

Where is interference from?

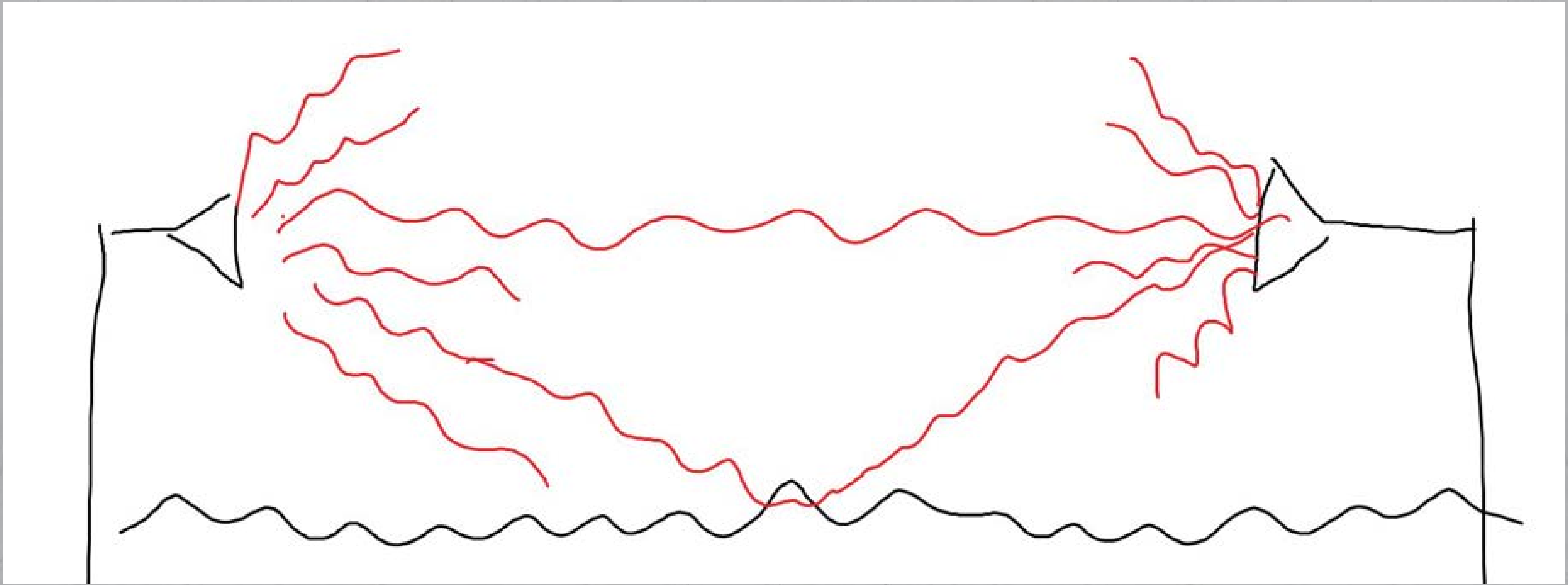
- Self-caused interference
  - Zlý výber mojích vlastných kanálov (toto by sa Vám nikdy nemalo stať)
- Others causing interference
  - Niekto iný používa (alebo práve začal používať) rovnaký kanál ako ja
- Signal cancelation
  - Wireless cez telesá vody
- Space…
  - Kozmická/slnečná radiácia
  - Slnečné erupcie…

Unexpected interference

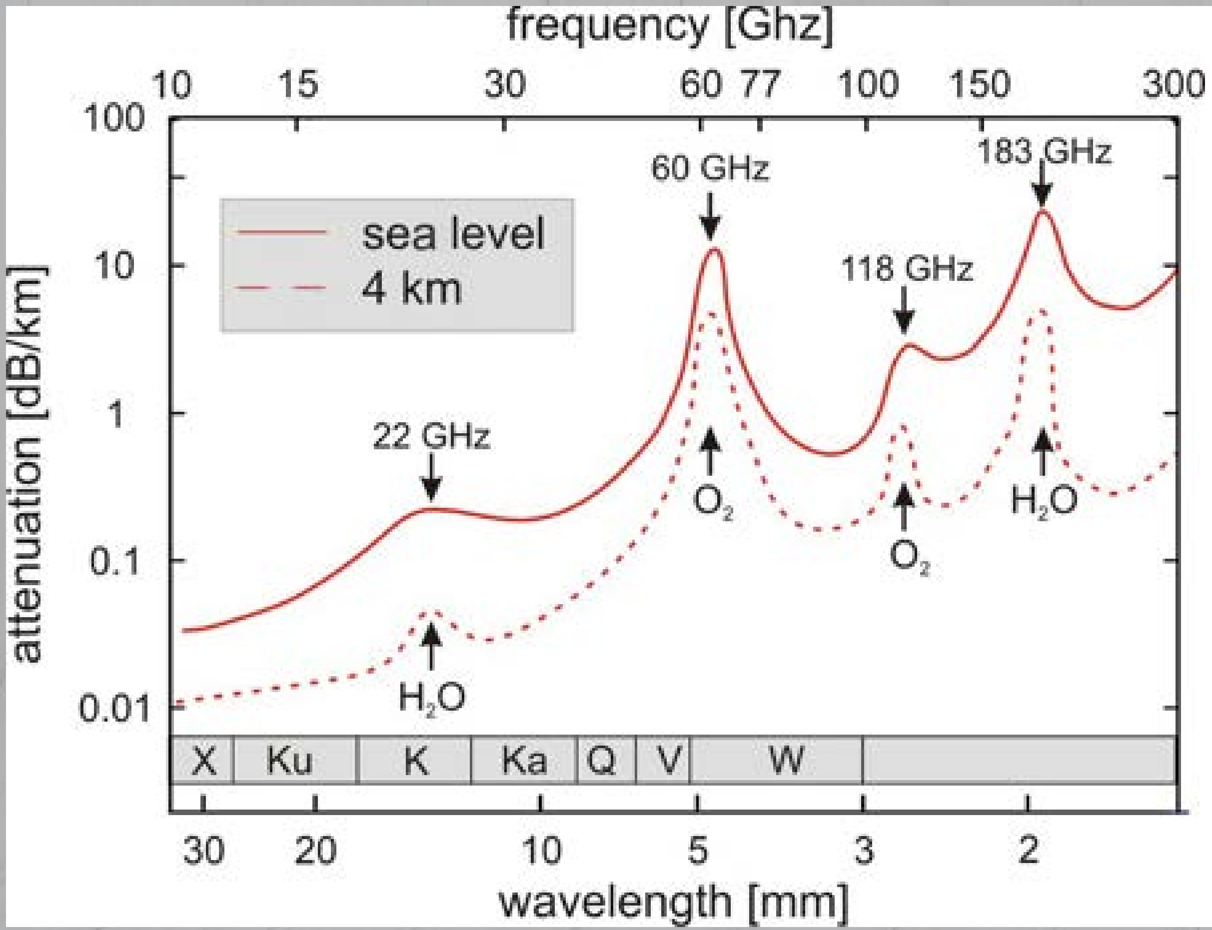
- Signal cancellation over water
- Water reflections after rain

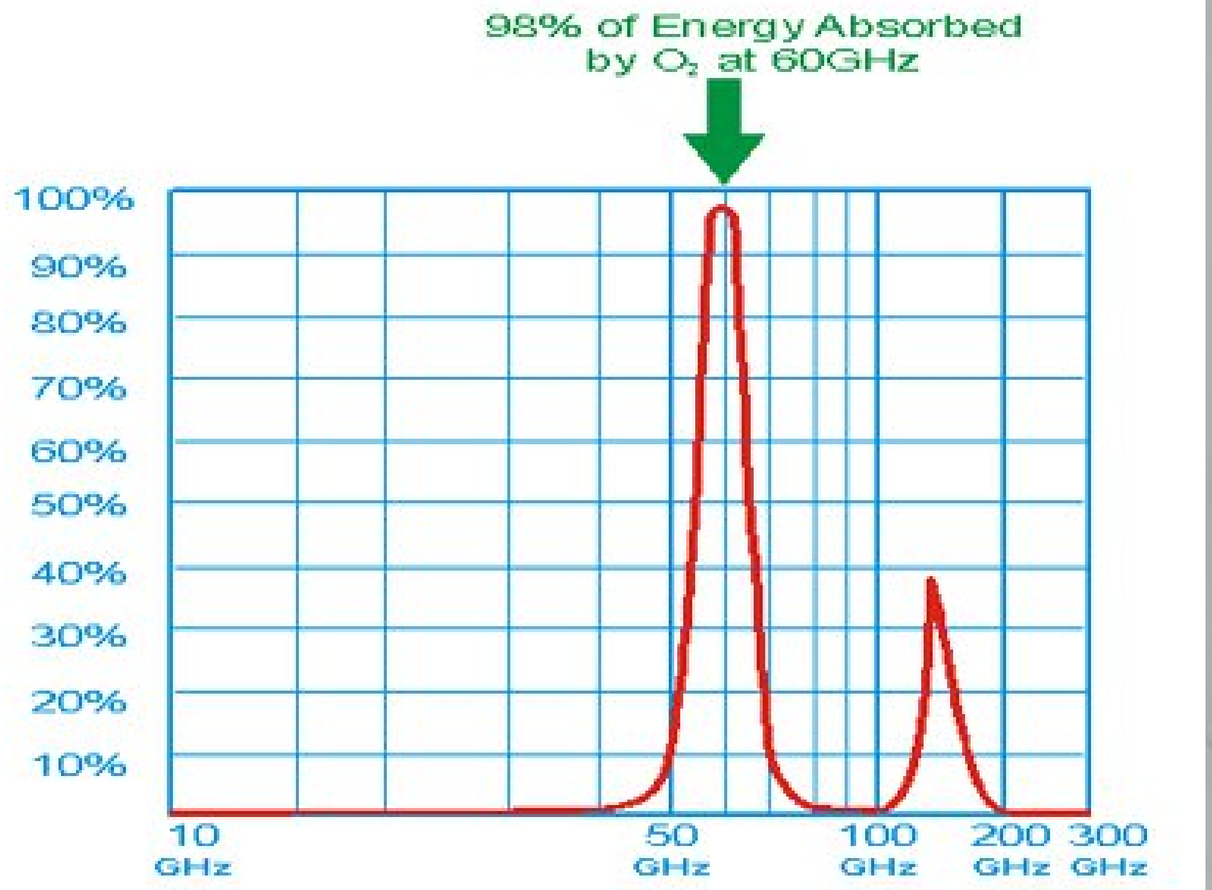
- Oxigen absorbtion bands

Signal cancellation over water



Absorbption bands



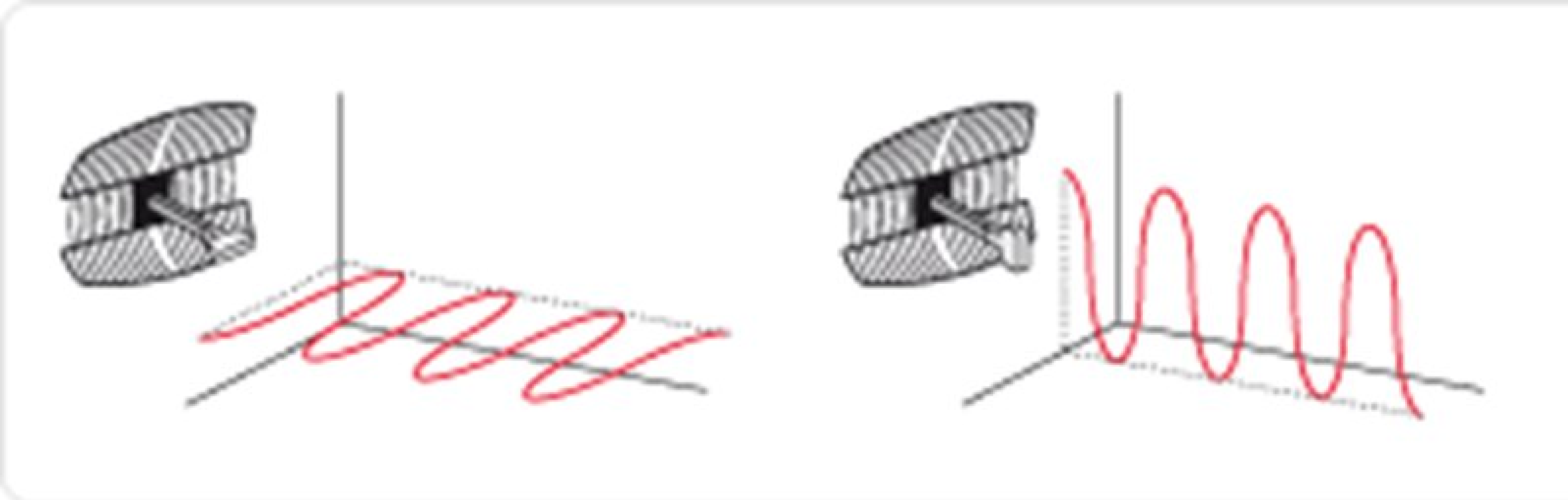


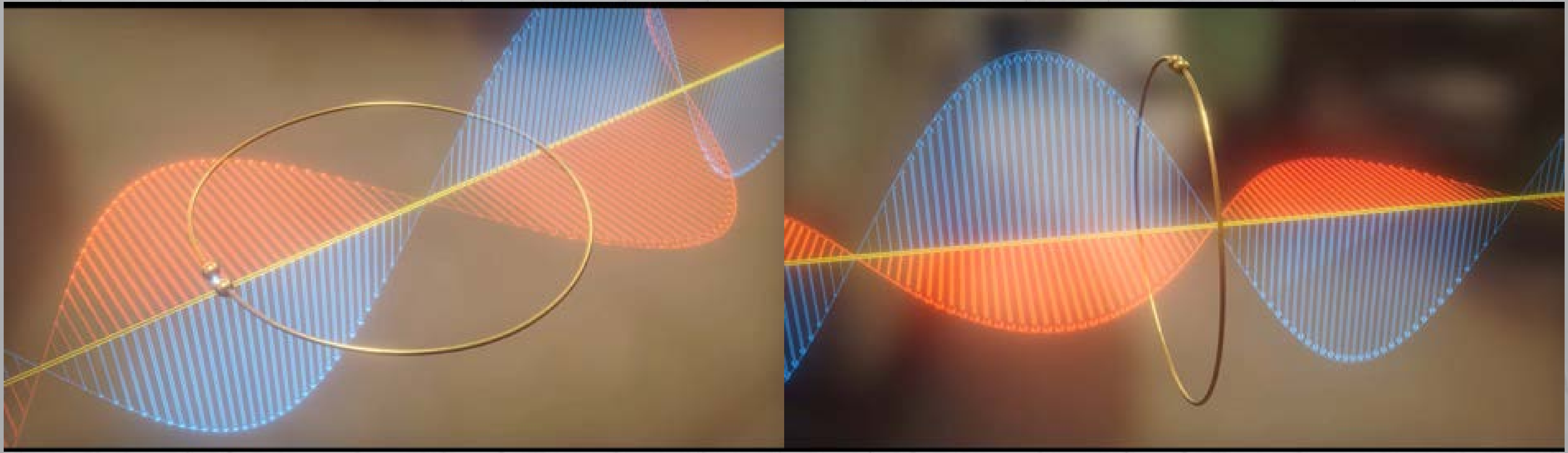
10db/km = 90% loss every 1 km

Wave polarization

- Polarization is the “direction” of the wave
- Wave can have any directional polarization (0°90°etc.)

- Waves with different polarization do not interfere with each other





Progress of technology

- 1887 – Heinrich Hertz:
  - “I do not think that the wireless waves I have discovered will have any practical application.”

- 1895 – first wireless transmissions in Italy (Marconi)
- 1901 – first transatlantic radio transmission
- 1920 – first public Radio Station
- 1978 – GPS
- 1983 – First voice mobile network

Wave polarization and interference

- In perfect situations - waves with different polarization do not interfere with each other
  - This assumes total polarization differential = 0° vs. 90°

- But co-polarization interference is also possible

- This happens when 2 waves are close enough to each other to interfere with each other
  - Example = 0° vs. 15°

Why are we talking about this?

- Using 2 differently polarized waves, and sending different data on each one concurrently, we can double our speed!
  - We call this using multiple spatial streams.

- In reality, wireless antennas do exactly this to increase capacity or a wireless link.

- Modern antennas have multiple arrays internally to leverage this, connectors are marked for example H and V.

Wording clarification

- Ak používame jednu polarizáciu, používame jeden Spatial Stream.

- Spatial stream = wireless chain.
  - Každý vysiela ináč polarizované vlny aby nebola interferencia

Wireless chains example

- Using 2 chains, your card can broadcast 2 independent data streams
  - 2 data streams = 2x data rate

- To avoid self-interference, these signals have to be physically separated

- We have a dual-polarity antenna. We connect each chain to a different polarity on the antenna.
- Using horizontal and vertical polarization, we achieve complete physical separation and avoid self-interference.

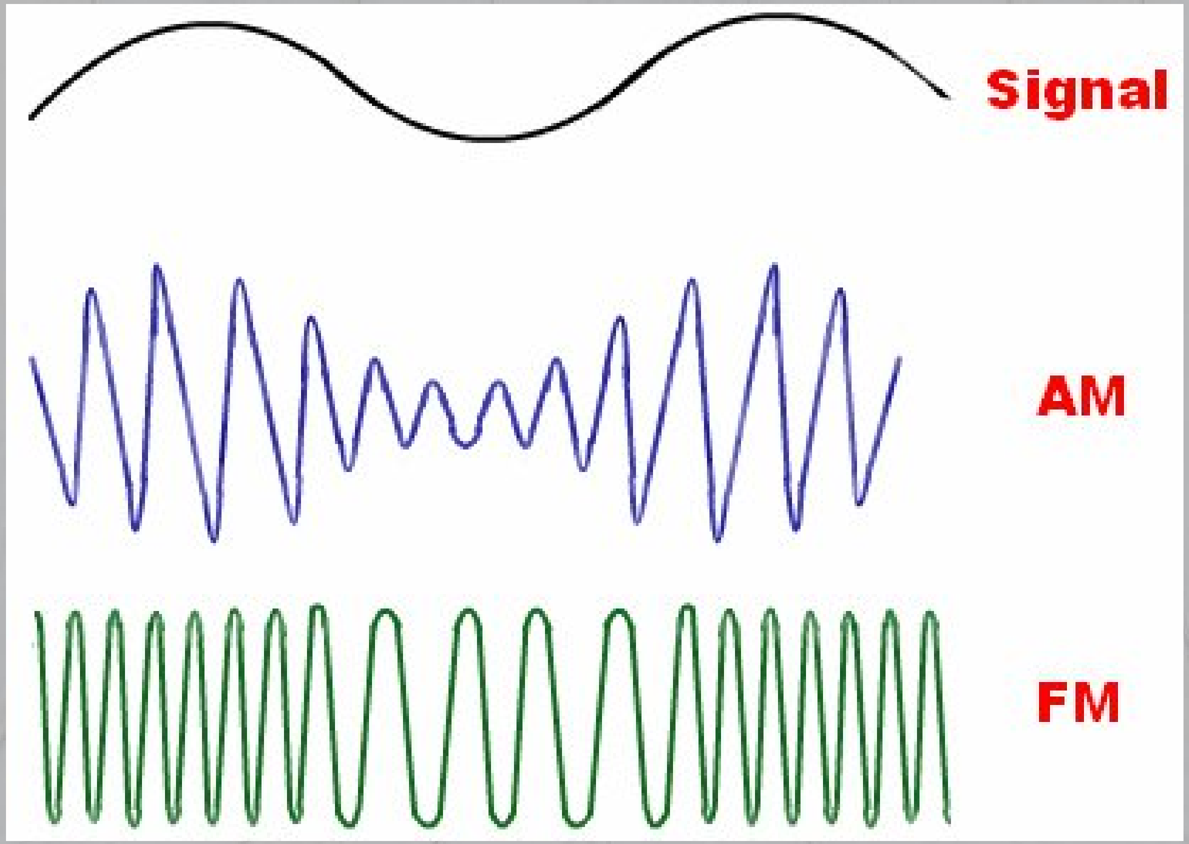
Wireless channel

- A channel is a frequency range needed for communication

- Any frequency range can be considered a channel
  - 2400 – 2402 MHz –2 MHz channel
  - 5820 – 5860 MHz –40 MHz channel

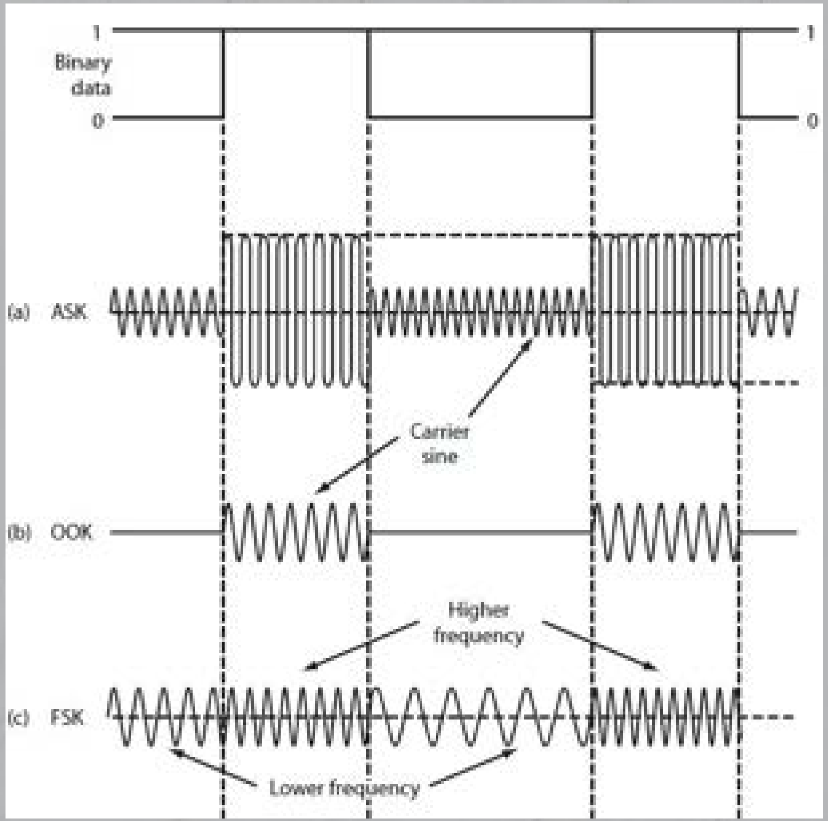
Analog vs. digital

- Wireless signál je analóg-ový



Encoding

- How to represent binary data using analog wireless signal?



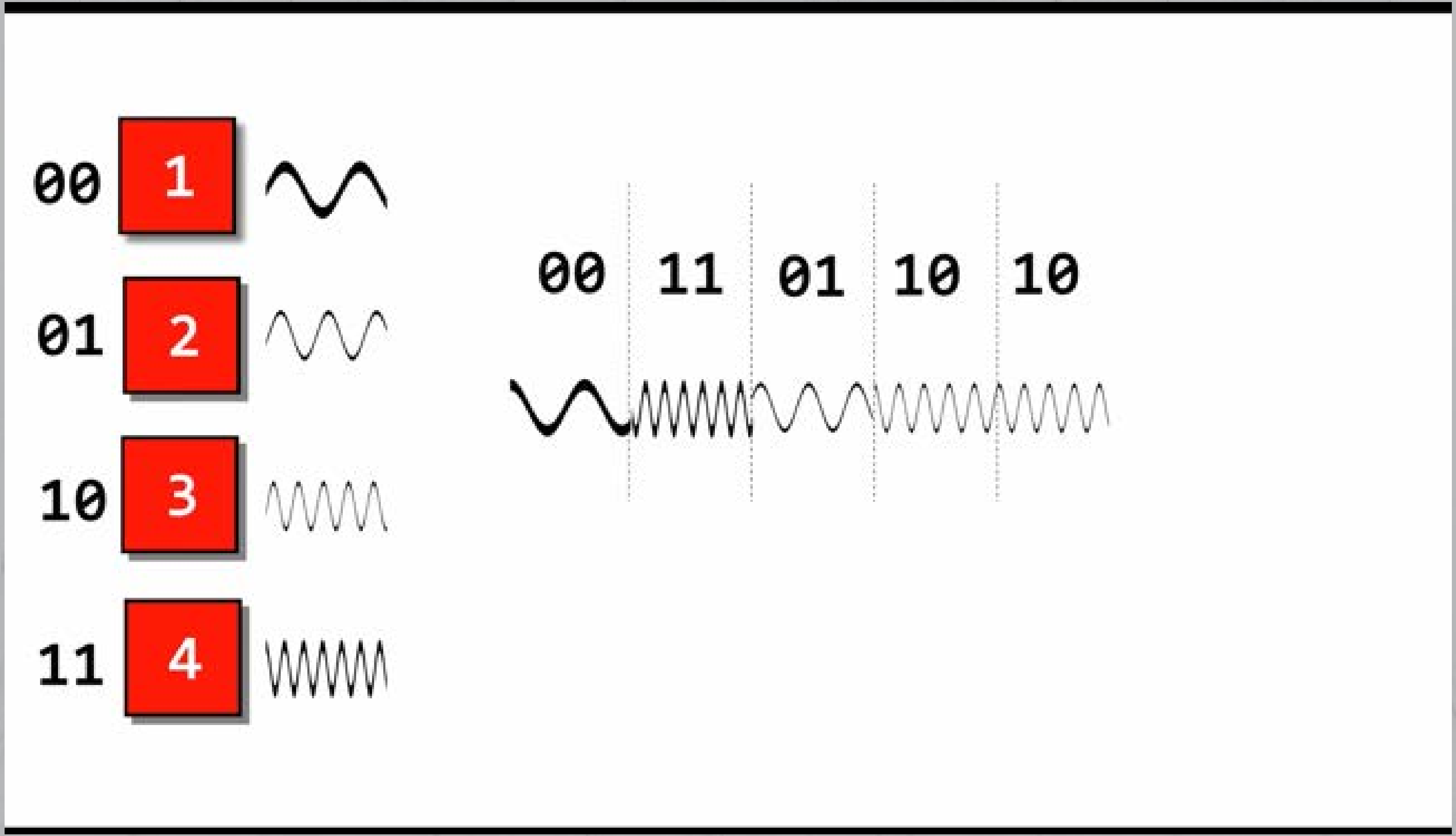
Zdrojové binárne dáta

Použitie amplitúdneho enkódovania

Použitie on/off enkódovania

Enkódovanie na základe frekvenčnej zmeny

Frequency shift keying modulation

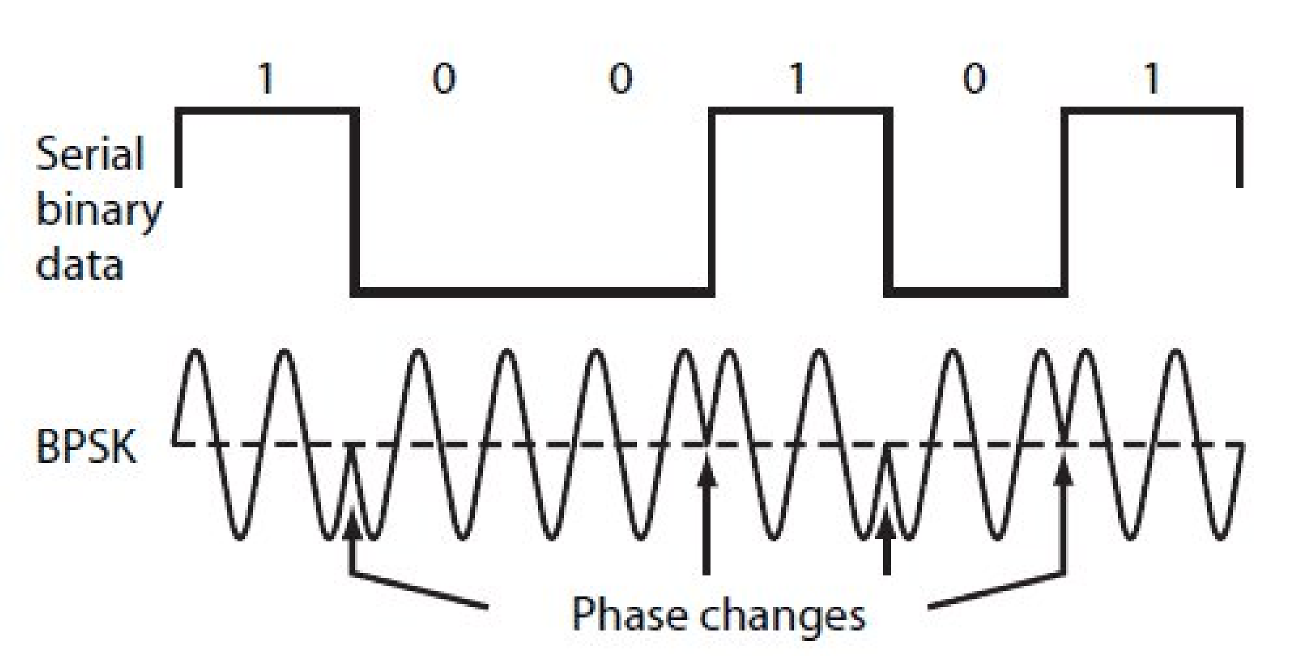


Encoding problems

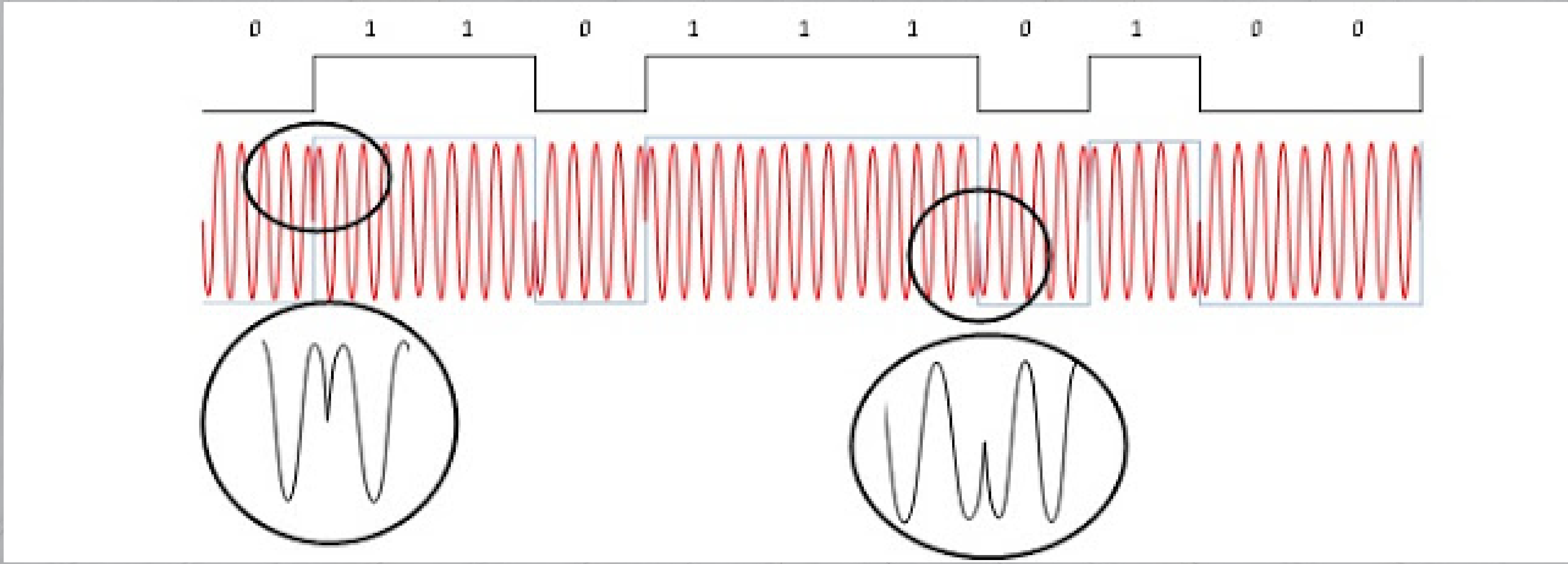
- All of the previously mentioned encoding schemes have their problems:
  - Amplitúdneho enkódovanie by bolo veľmi lahko narušiteľné interferenciou
  - On/off enkódovanie by vyžadovalo nemožne presné časovanie (+ opäť problém s interferenciou)
  - Freq. enkódovanie by si žiadalo extrémnu kontrolu freq. Spktra (+ interferencia...)

Better encoding

- A better option, phase change/reversal encoding
- Same technology used in HDDs
  - In HDDs – magnetic field reversal – flux reversal

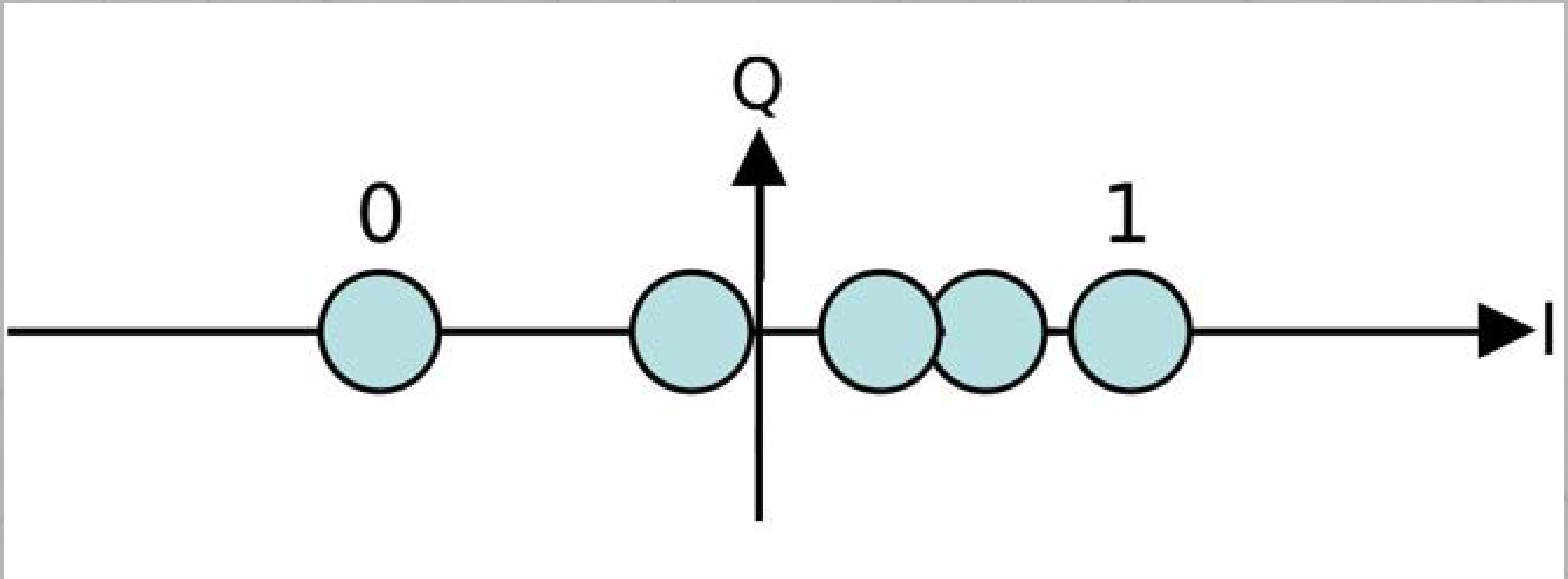


More detailed

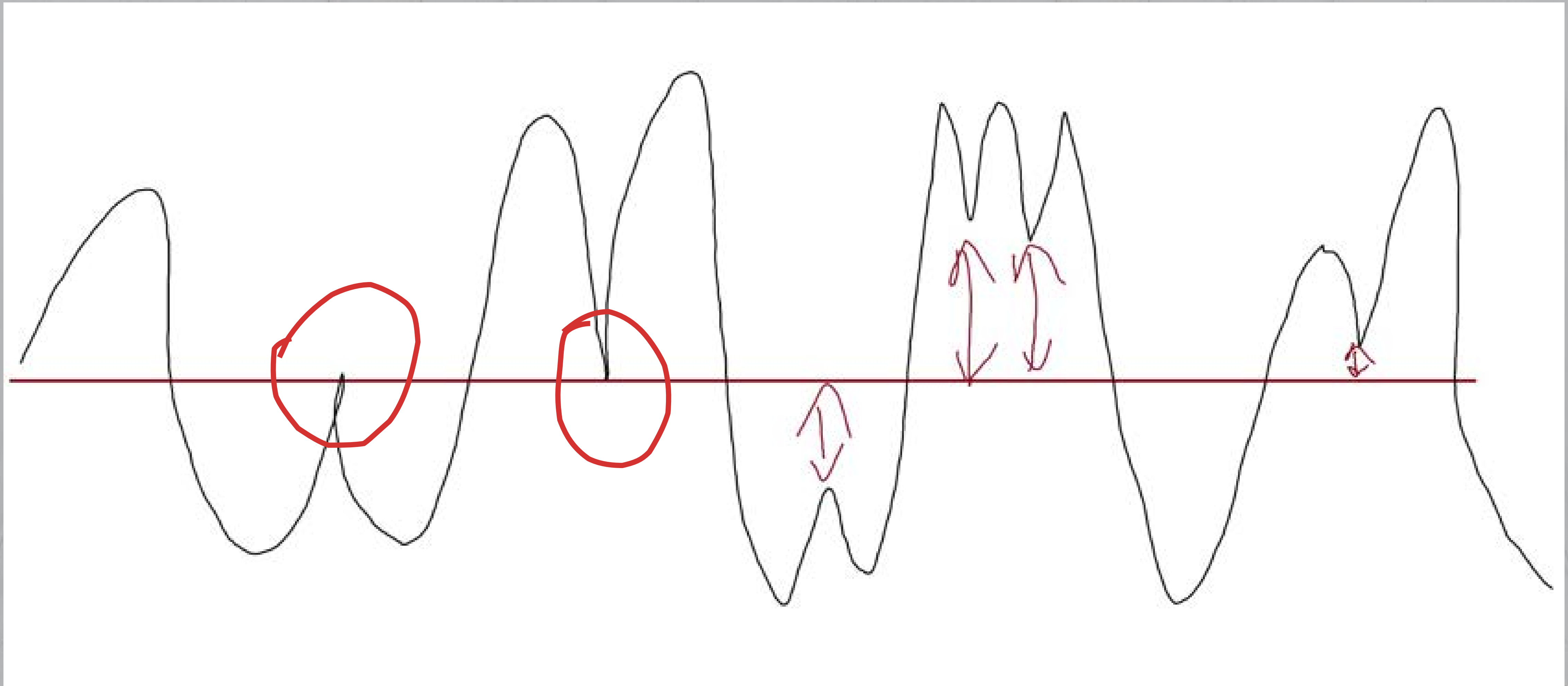


Constellation diagram

- Constellation diagram je reprezentácia signálu modulovaného digitálnou modulačnou schémou.

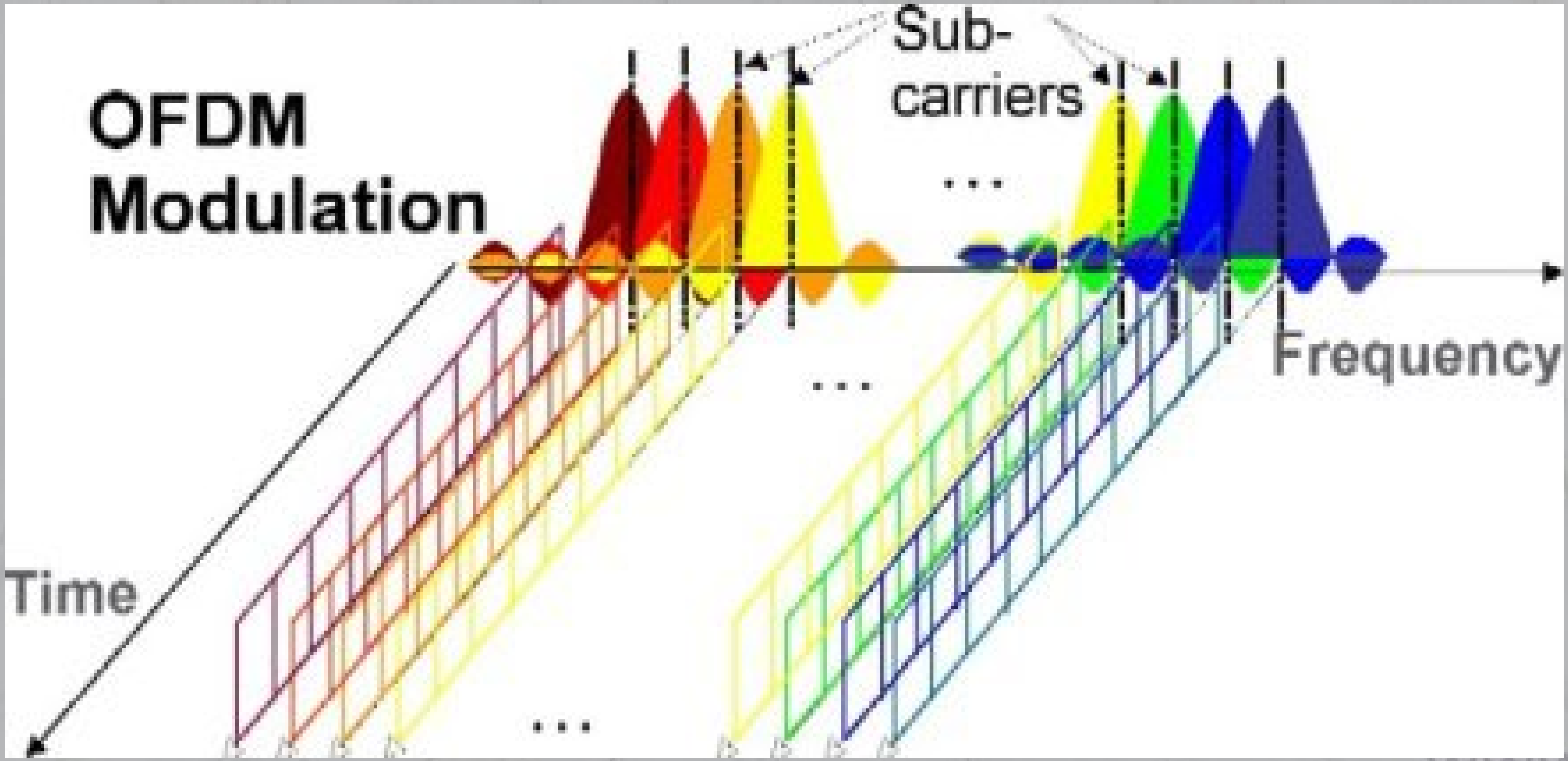


Missmatch example



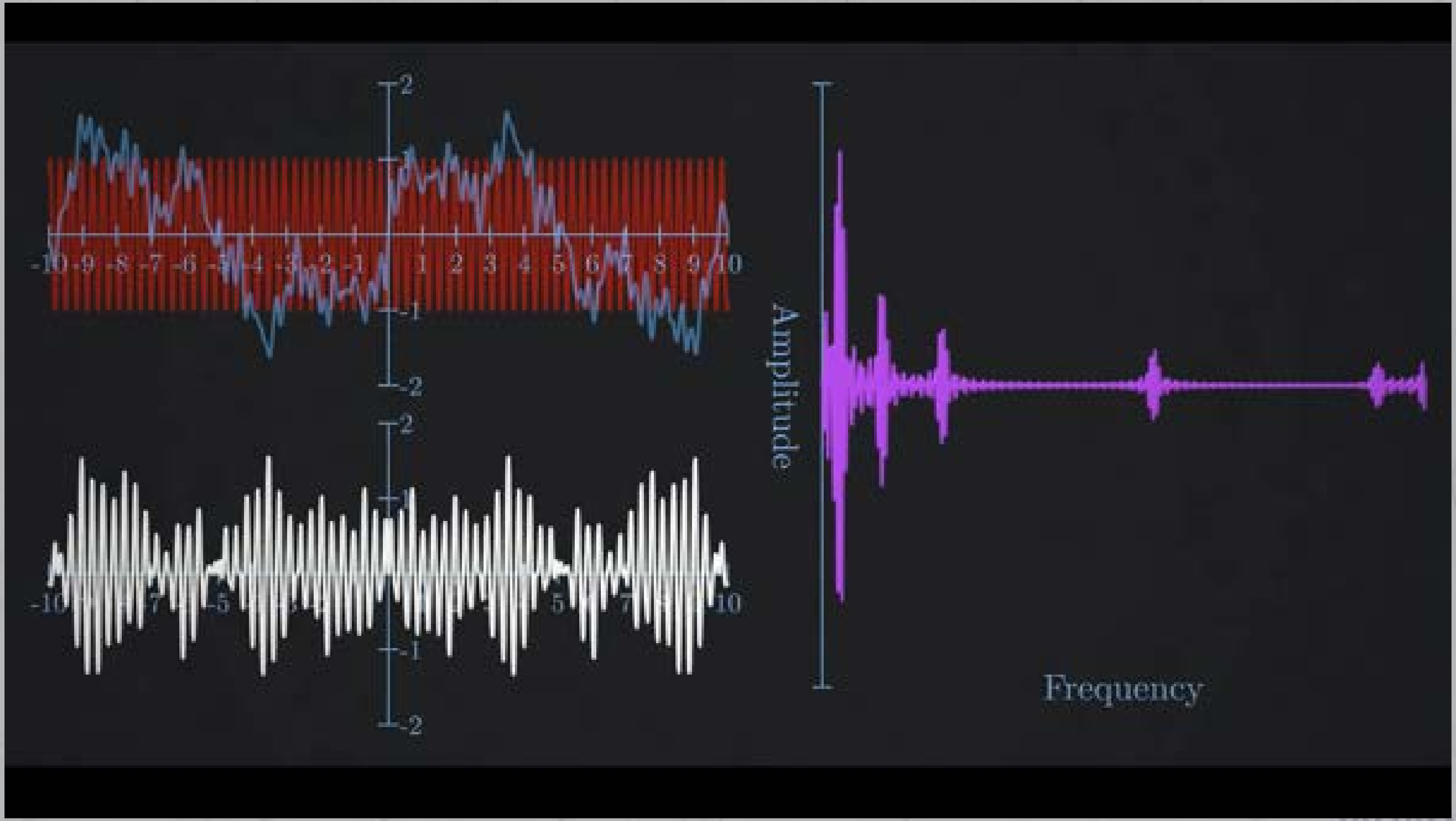
More encoding tricks

- A channel is split into multiple sub-channels, and each sub channel carries data – **OFDM** (Orthogonal Frequency Division Multiplexing)



How does OFDM work?

- Fourier transformations



What encoding means for us

- Pointa
  - Lepšie enkódovanie = lepšia rýchlosť

- Čím menej oscilácií je potrebných pre prenost jedného bit-u, tým viac bitov môžeme preniesť za jednotku času (lepšia rýchlosť)

Even better encoding

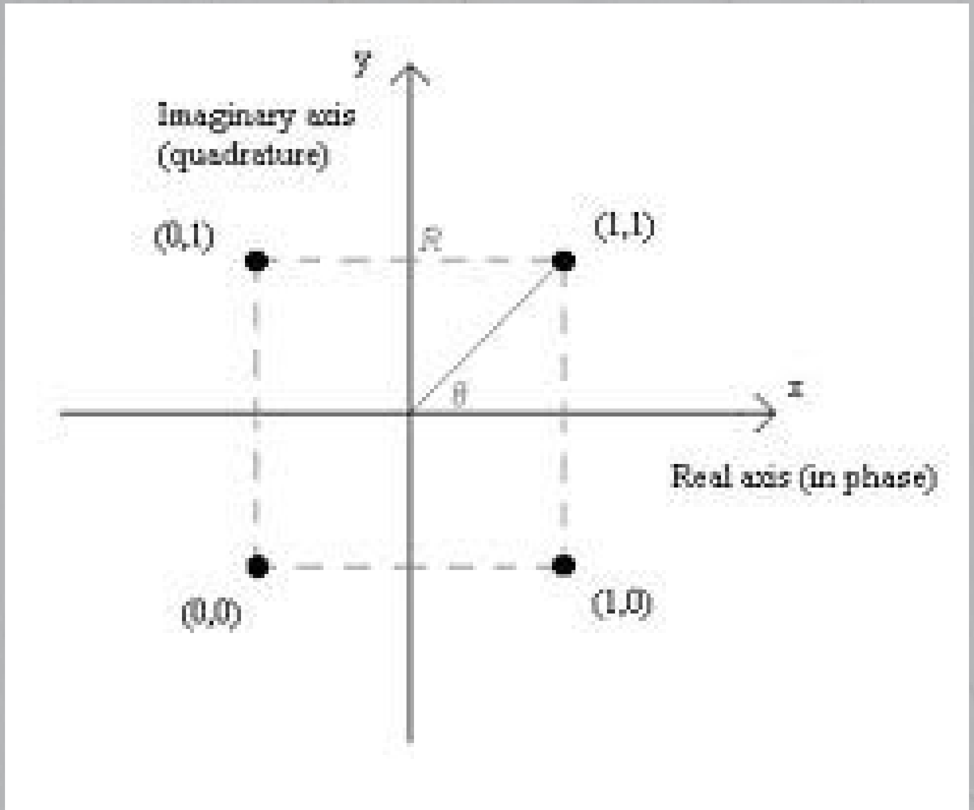
- As technology evolved, some of the previous drawbacks were eliminated.
- Most advanced encoding schemes combine multiple of these techniques to achieve even better encoding rates

- Phase change, amplitude based encoding and channel splitting into sub-carriers is combined in QAM

QAM

- Quadrature Amplitude Modulation

- **4 QAM**
  - splitting the signal
  - into 4 segments

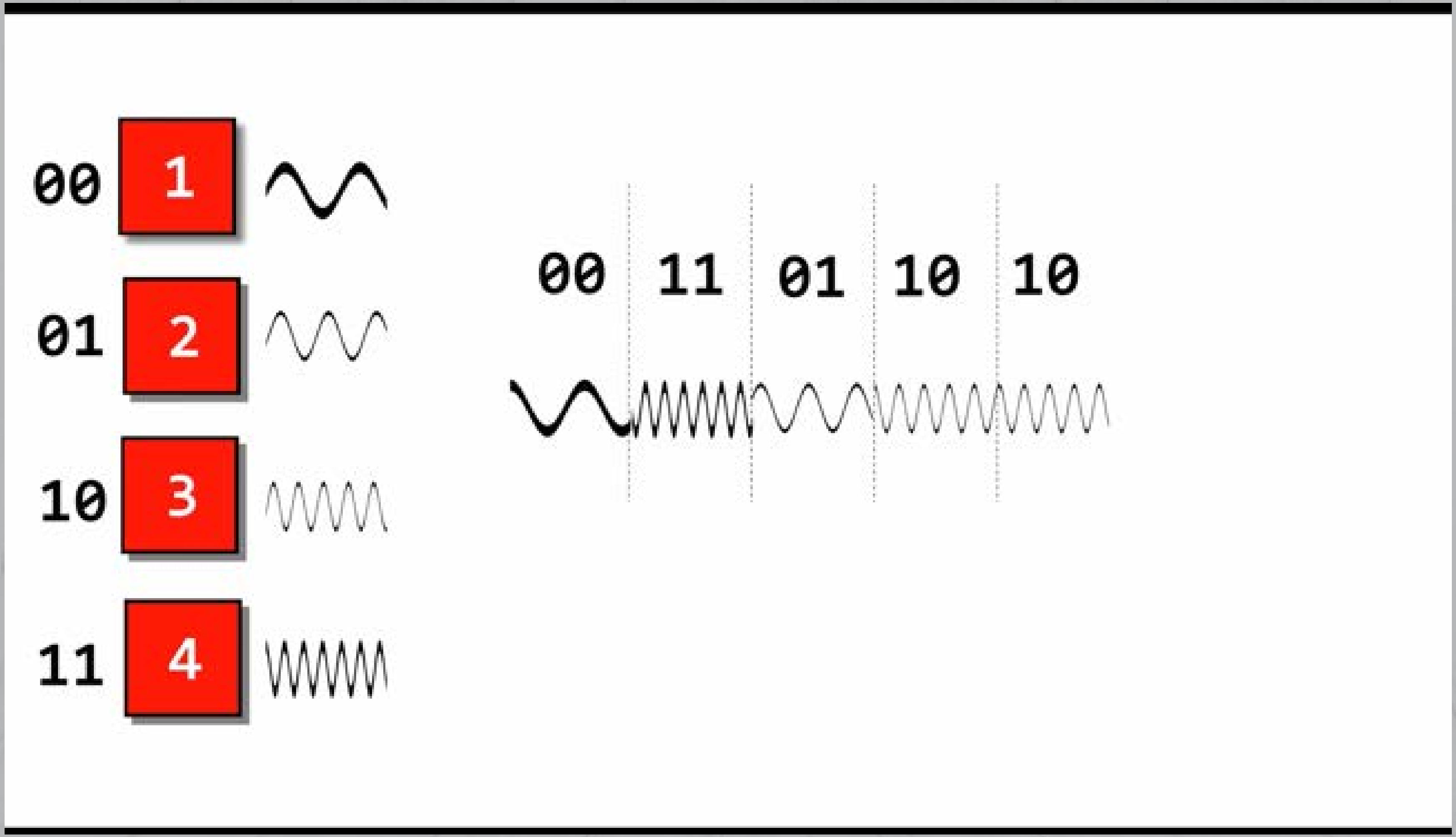


Symbols

- A **symbol** represents the basic unit of information.
- Each symbol is a distinct signal that conveys one or more bits of information.

- In BPSK, 2 symbols – positive or negative phase shift
- This is limiting, so modulations schemes get creative.

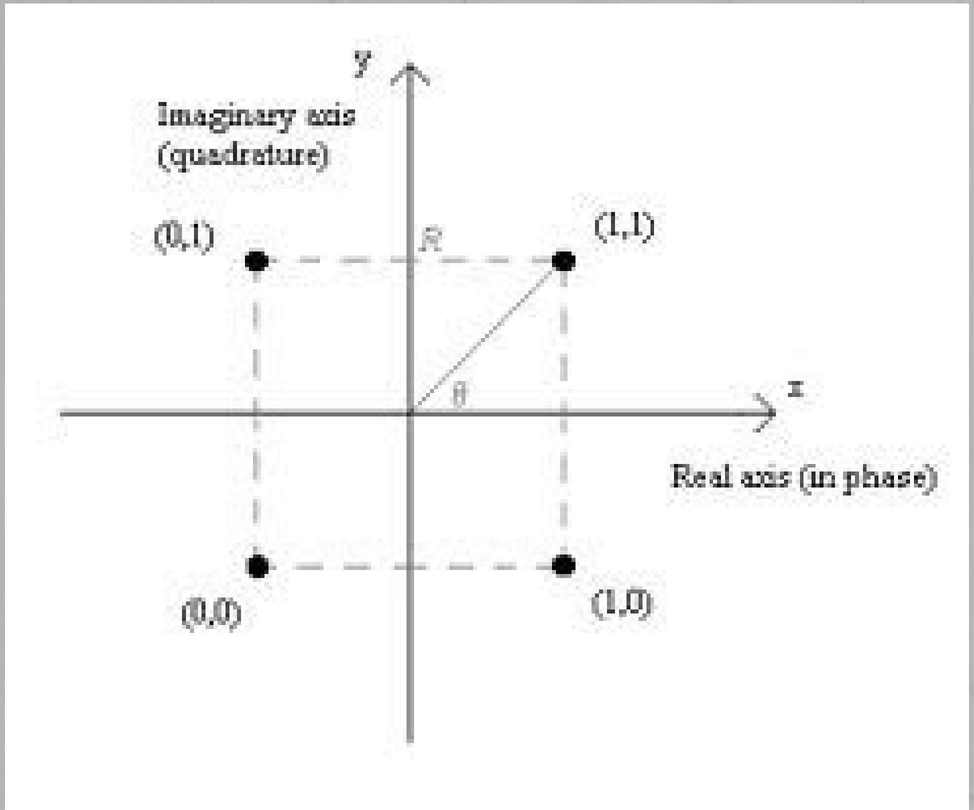
We actually already saw symbols!



QAM simplified

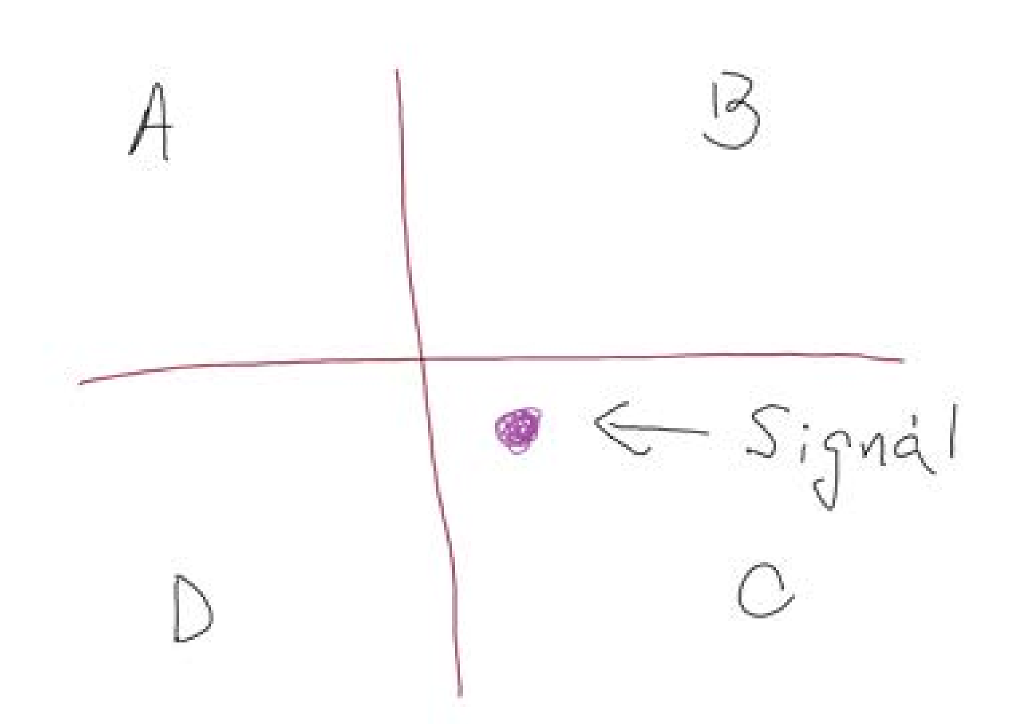
- QAM kombinuje viacero sposobov ako vycitat 4 mozne stavy zo signalu

- 4 symboly
- Prenost 2 bit-ov naraz



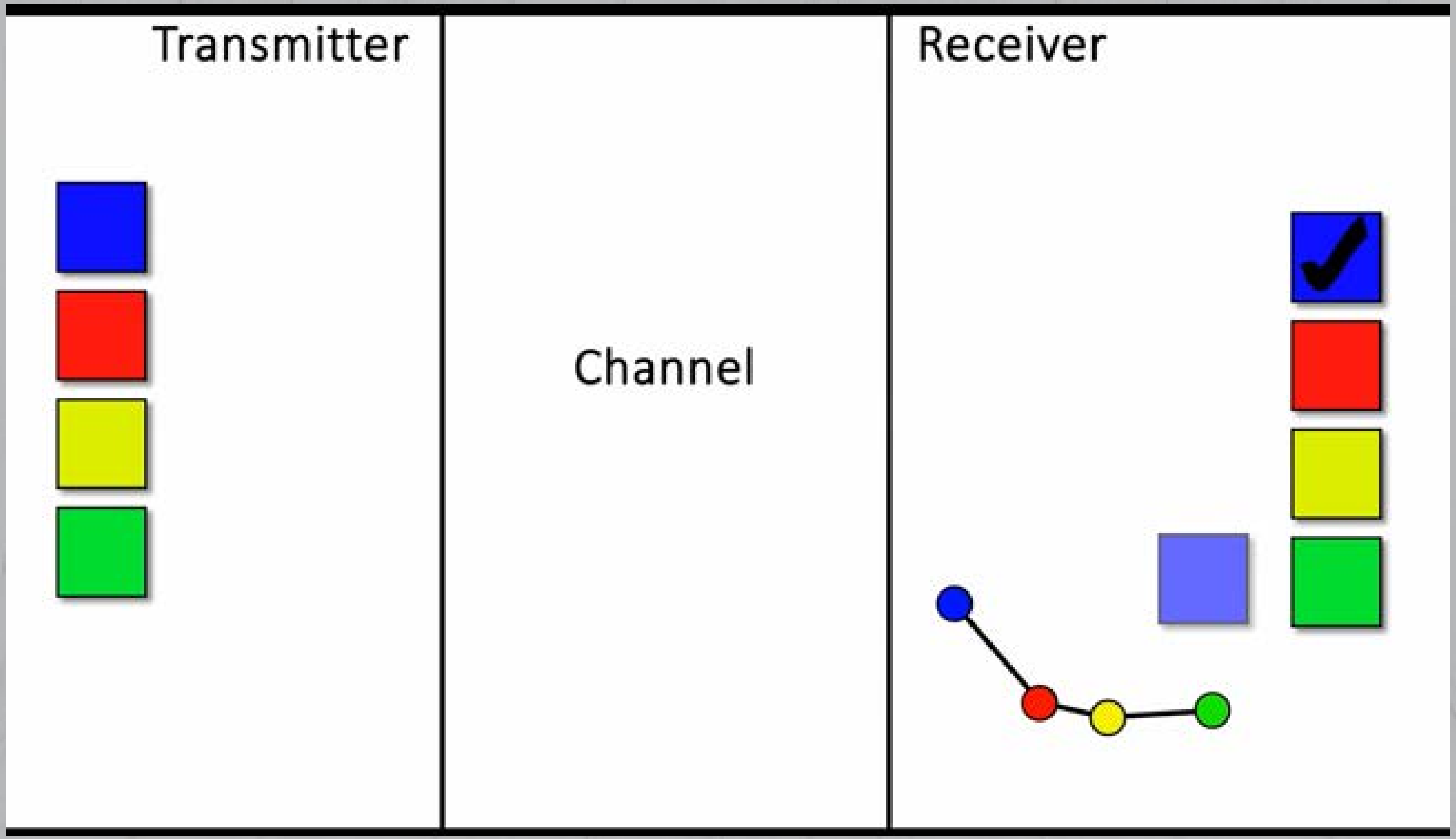
Interference...

- Hovorili sme ze QAM je schopny identifikovat 4 body v signale. Co vsak ked signal nepasuje presne na nejaky bod?



Signal correlation

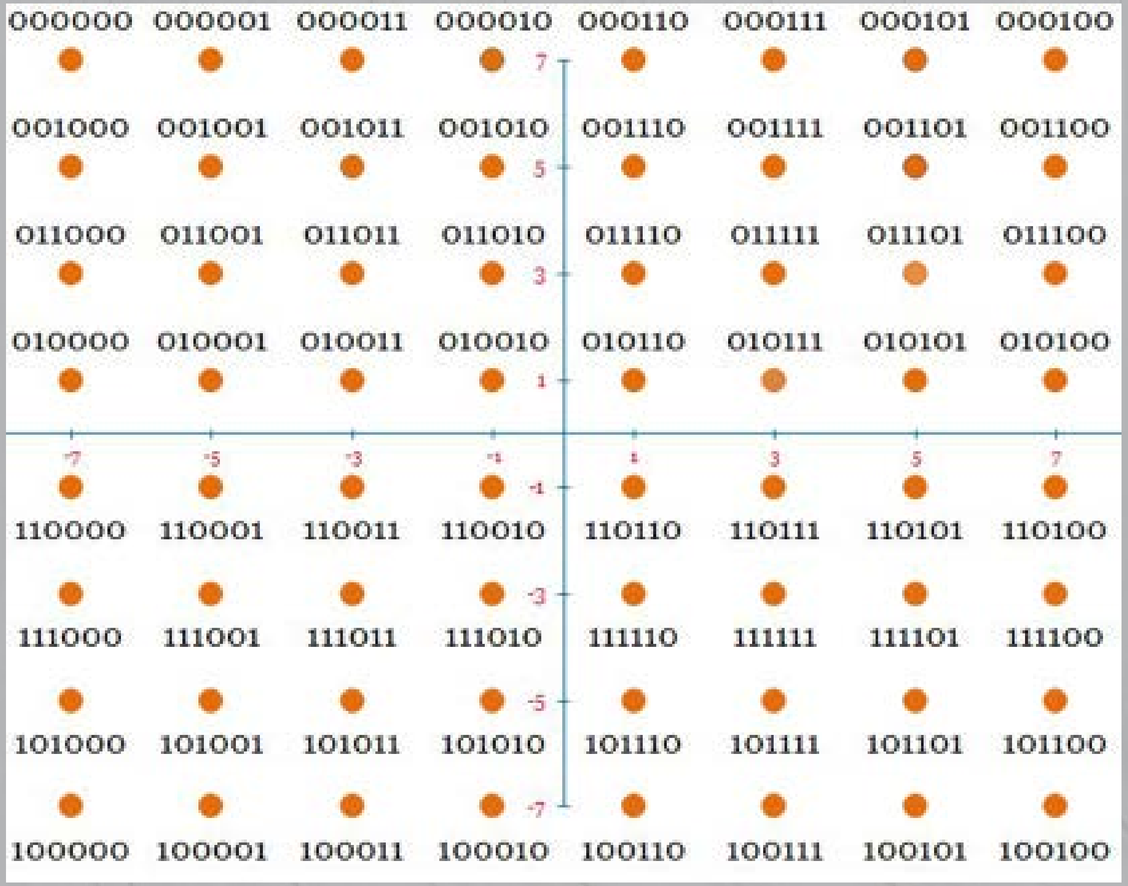
- Text



Better QAM

- **64 QAM**

- Kombinácia rôznych enkódovacích technológii a matematických algoritmov

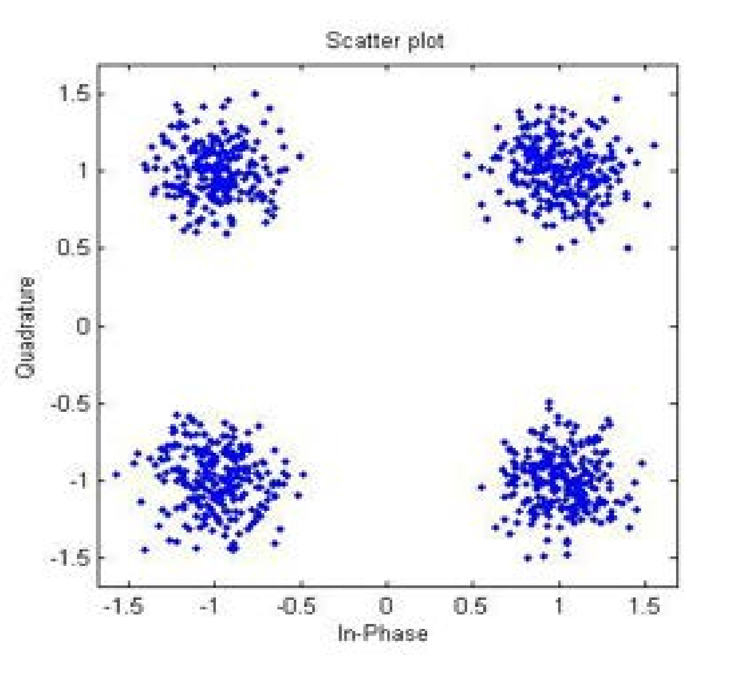


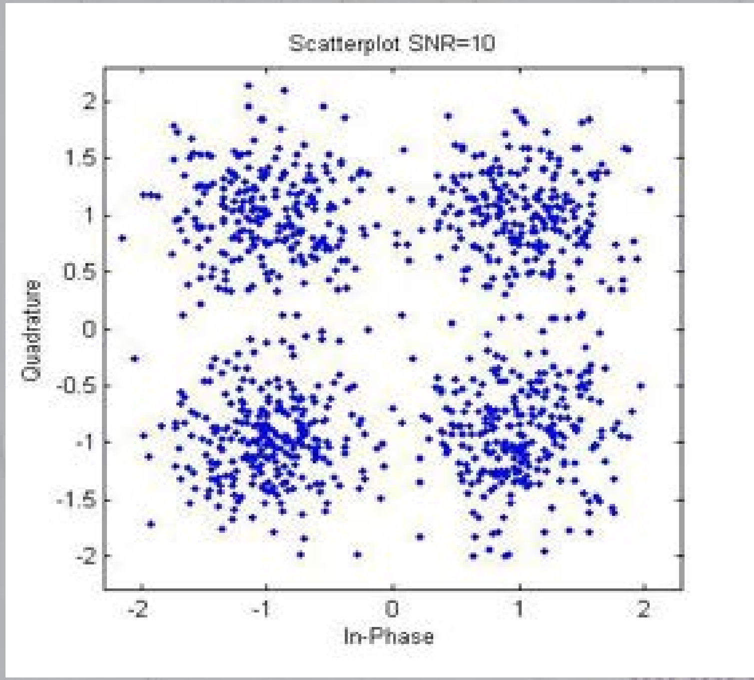
Better QAM

- Actual 64 QAM with -35 and -65 signal strength

Noise vs. encoding

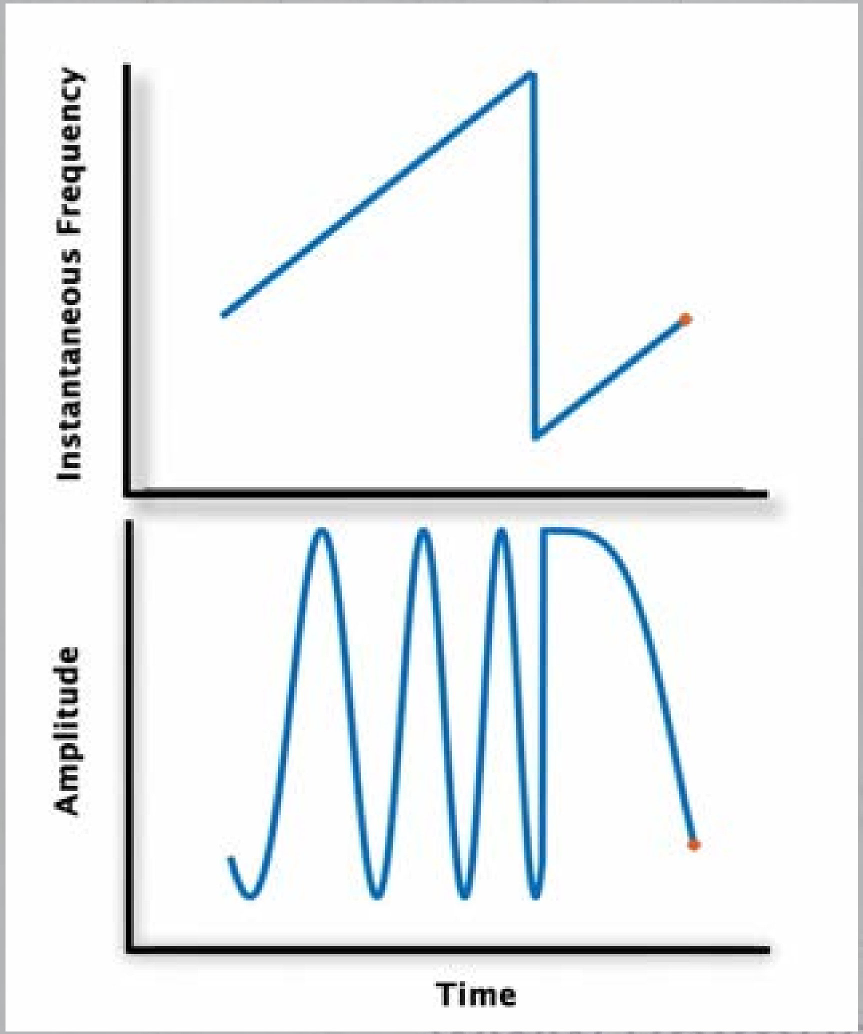
- With higher encoding, we need higher quality signal
- Here is how noise (interference) affects 4QAM





Other interesting encoding

- Many encoding schemas exist.
- For example, LoRa :
  - Frequency Shift Chirp Modulation



What encoding means for us

- Bottom line:
  - For best speed, we need best possible signal strength
  - For best speed, we need least possible interference

- Its possible for better encoding to produce less actual speed – why?

Guard interval

- **Guard interval** (GI) is used to ensure that distinct transmissions do not interfere with one another

- The purpose of the guard interval is to introduce immunity to propagation delays, echoes and reflections

- Lower GI gives better speed, but less protection
- Link with bad signal will therefore choose to run at higher GI – lower speed

Mapping encoding to data rate

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (Mbit/s)			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.50	7.20	13.50	15.00
1	1	QPSK	1/2	13.00	14.40	27.00	30.00
2	1	QPSK	3/4	19.50	21.70	40.50	45.00
3	1	16-QAM	1/2	26.00	28.90	54.00	60.00
4	1	16-QAM	3/4	39.00	43.30	81.00	90.00
5	1	64-QAM	2/3	52.00	57.80	108.00	120.00
6	1	64-QAM	3/4	58.50	65.00	121.50	135.00
7	1	64-QAM	5/6	65.00	72.20	135.00	150.00

Wireless networking standards

Wireless standards

- Physical Layer (Layer 1) štandardy, umožňujú komunikáciu cez EM radiáciu (žiarenie)
- Vrchné layer-y môžu byť čokoľvek (Ethernet na L2, PPPoE na L2, IP na L3, atď.)

Wireless standards

- IEEE 802.11b
  - 2.4GHz frequencia, 11Mbps
- IEEE 802.11g
  - 2.4GHz frequencia, 54Mbps
- IEEE 802.11a
  - 5GHz frequencia, 54Mbps
- IEEE 802.11n
  - 2.4GHz alebo 5GHz, 600Mbps (produkty dostupné na 300Mbps)
- IEEE 802.11ac
  - 5GHz, 6.9Gbps
- IEEE 802.11ax
  - Wifi 6, 9.6Gbps
- IEEE 802.11be
  - Wifi 7, 23Gbps

Compatibility

- All wireless protocols are backwards compatible
- If a client can run a higher protocol then the AP, the client will fall down
- If an AP can run higher protocol then the client, the AP will fall down

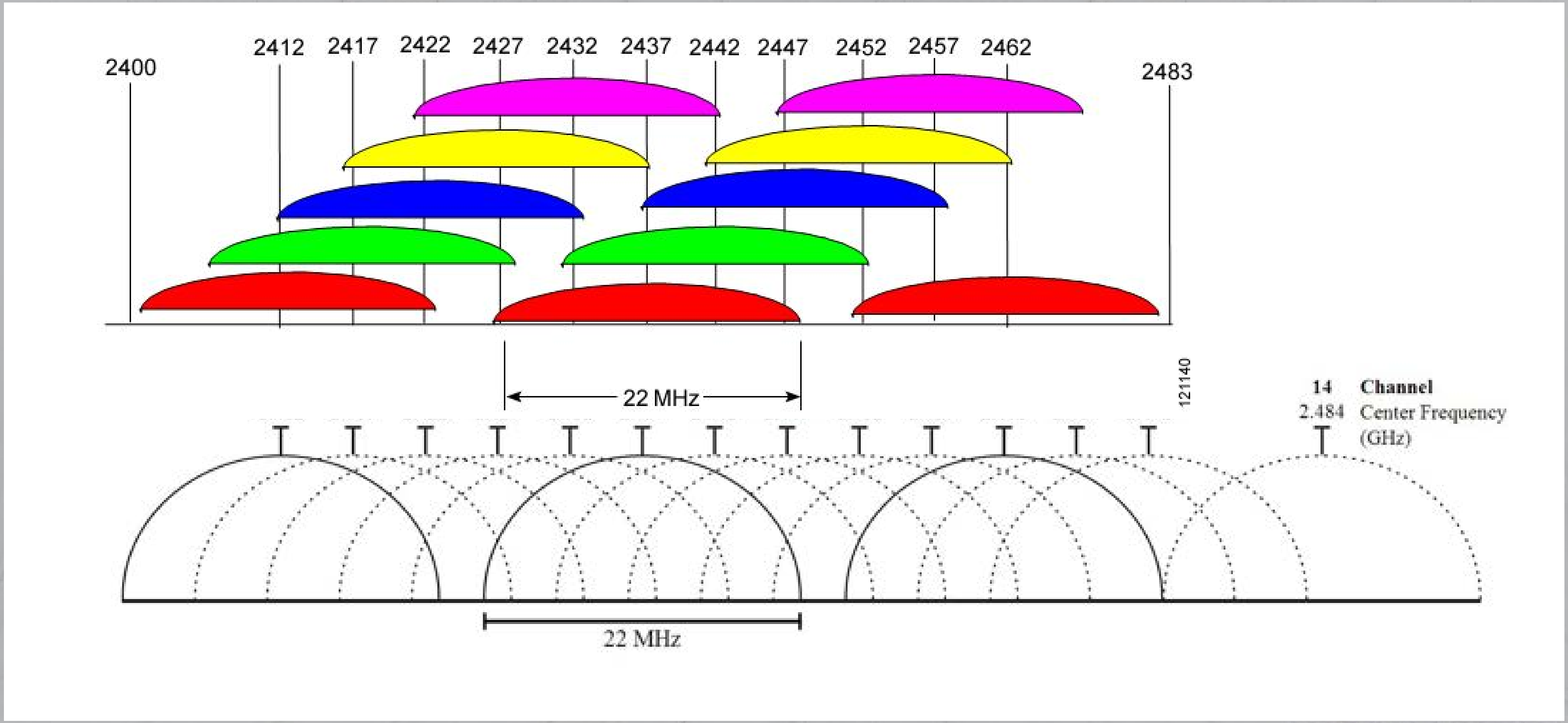
802.11b/g

- 22 MHz potrebných pre komunikáciu – nazývané channel (kanál)

- Frequencia – 2.4 GHz
- Jeden spatial stream

- Podľa regulácií v krajine nasadenia
- 2400 – 2499 MHz

2.4 GHz channels



802.11a

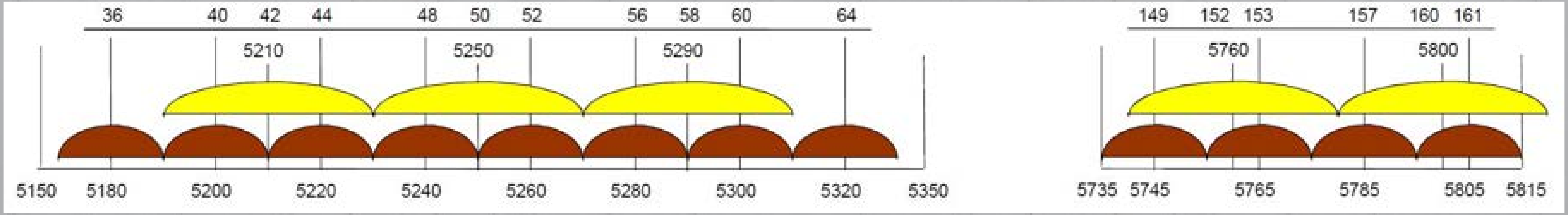
- 22 MHz needed to communicate

- Frequency – 5 GHz
- One spatial stream

- .11a is just a 5GHz implementation of .11b/g

5 GHz channels

- 12x 20 MHz non-overlapping channels
- 5x 40 MHz non-overlapping channels



- May be more depending on your country regulations on free wireless spectrum

802.11n

- 20 MHz potrebných pre komunikáciu
  - Vie združiť 2x 20 MHz kanály do 40 MHz kanálu

- Dual-channel = 2x rýchlosť
- Up to 4 spatial streams = 4x rýchlosť
  - Produkty nikdy neboli dostupne s viac ako 3 – ale 2 je známi .11n 300MBit štandard

- Frequencia – 2.4 GHz alebo 5 GHz

802.11n

- .11n single spatial stream encoding table

MCS index	Spatial streams	Modulation type	Coding rate	Data rate (Mbit/s)			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.50	7.20	13.50	15.00
1	1	QPSK	1/2	13.00	14.40	27.00	30.00
2	1	QPSK	3/4	19.50	21.70	40.50	45.00
3	1	16-QAM	1/2	26.00	28.90	54.00	60.00
4	1	16-QAM	3/4	39.00	43.30	81.00	90.00
5	1	64-QAM	2/3	52.00	57.80	108.00	120.00
6	1	64-QAM	3/4	58.50	65.00	121.50	135.00
7	1	64-QAM	5/6	65.00	72.20	135.00	150.00

802.11ac

- 20 MHz channel as well
  - Can bond for 20/40/80/160 MHz channels

- Octal spatial streams + 256 QAM

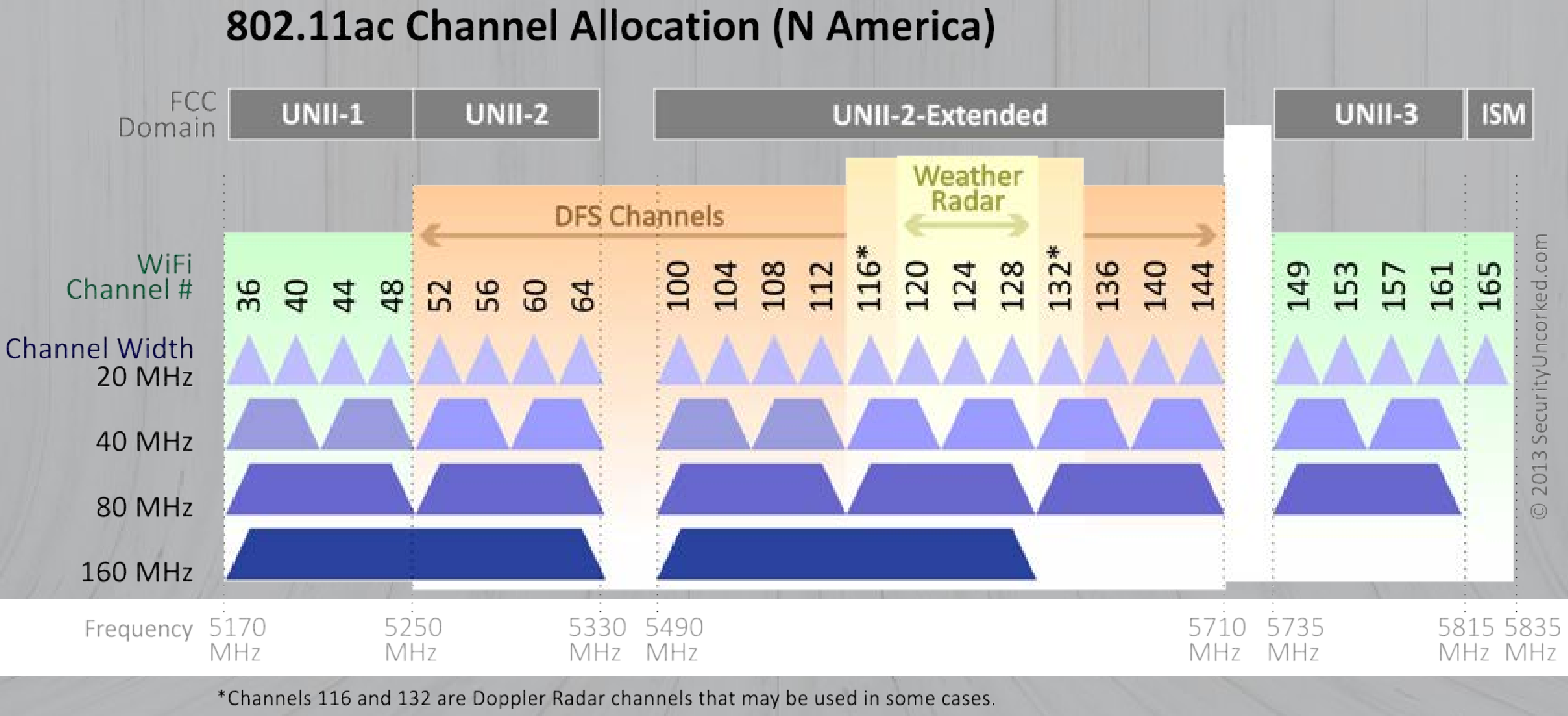
- Frequency – 5 GHz only

802.11ac

- .11ac single spatial stream encoding table

Theoretical throughput for single Spatial Stream (in Mbit/s)										
MCS index	Modulation type	Coding rate	20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			800 ns GI	400 ns GI	800 ns GI	400 ns GI	800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130
2	QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195
3	16-QAM	1/2	26	28.9	54	60	117	130	234	260
4	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390
5	64-QAM	2/3	52	57.8	108	120	234	260	468	520
6	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585
7	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650
8	256-QAM	3/4	78	86.7	162	180	351	390	702	780
9	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7

.11ac channel coverage



Real life

Promises vs. reality

- Data-rates presented in these tables are only "air rates". This is the rate of binary transmit on the wireless interface.

- This number does however not represent real wireless speed which your link will run at.

- Wireless is half-duplex and uses ACKs - CSMA/CA
- Frame corruption can occur due to interference.
- Collisions and re-transmits happen **a lot**

Promises vs. reality

- What to really expect:
  - With standardized wireless (.g/.n/.ac) at maximum (in optimal conditions) 60% of the air-rate can be expected as real L4 udp throughput.
- TCP will be less (due to duplicate ACK-ing)
  - Usually 45-50% as TCP throughput.
- There are options – proprietary protocols

Your homework

Are you ready padavan?

- Here is the full MCS index table for all wireless protocols:
- https://mcsindex.net/

MCS Index				Spatial Stream	Modulation	Coding	OFDM (Prior 11ax)								OFDM & OFDMA (Starting with 11ax)																							
							20MHz		40MHz		80MHz		160MHz		26-tone RU			52-tone RU			106-tone RU			242-tone RU / 20MHz			484-tone RU / 40MHz			996-tone RU / 80MHz			2x996-tone RU / 160MHz			4x996-tone RU / 320 MHz		
HT	VHT	HE	EHT				0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	0.8µs GI	0.4µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI	3.2µs GI	1.6µs GI	0.8µs GI
0	0	0	0	1	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65	0.8	0.9	0.9	1.5	1.7	1.8	3.2	3.5	3.8	7.3	8.1	8.6	14.6	16.3	17.2	30.6	34.0	36.0	61.3	68.1	72.1	122.5	136.1	144.1
1	1	1	1	1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130	1.5	1.7	1.8	3.0	3.3	3.5	6.4	7.1	7.5	14.6	16.3	17.2	29.3	32.5	34.4	61.3	68.1	72.1	122.5	136.1	144.1	245.0	272.2	288.2
2	2	2	2	1	QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195	2.3	2.5	2.6	4.5	5.0	5.3	9.6	10.6	11.3	21.9	24.4	25.8	43.9	48.8	51.6	91.9	102.1	108.1	183.8	204.2	216.2	367.5	408.3	432.4
3	3	3	3	1	16-QAM	1/2	26	28.9	54	60	117	130	234	260	3.0	3.3	3.5	6.0	6.7	7.1	12.8	14.2	15.0	29.3	32.5	34.4	58.5	65.0	68.8	122.5	136.1	144.1	245.0	272.2	288.2	490.0	544.4	576.5
4	4	4	4	1	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390	4.5	5.0	5.3	9.0	10.0	10.6	19.1	21.3	22.5	43.9	48.8	51.6	87.8	97.5	103.2	183.8	204.2	216.2	367.5	408.3	432.4	735.0	816.7	864.7
5	5	5	5	1	64-QAM	2/3	52	57.8	108	120	234	260	468	520	6.0	6.7	7.1	12.0	13.3	14.1	25.5	28.3	30.0	58.5	65.0	68.8	117.0	130.0	137.6	245.0	272.2	288.2	490.0	544.4	576.5	980.0	1088.9	1152.9
6	6	6	6	1	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585	6.8	7.5	7.9	13.5	15.0	15.9	28.7	31.9	33.8	65.8	73.1	77.4	131.6	146.3	154.9	275.6	306.3	324.3	551.3	612.5	648.5	1102.5	1225.0	1297.1
7	7	7	7	1	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650	7.5	8.3	8.8	15.0	16.7	17.6	31.9	35.4	37.5	73.1	81.3	86.0	146.3	162.5	172.1	306.3	340.3	360.3	612.5	680.6	720.6	1225.0	1361.1	1441.2
	8	8	8	1	256-QAM	3/4	78	86.7	162	180	351	390	702	780	9.0	10.0	10.6	18.0	20.0	21.2	38.3	42.5	45.0	87.8	97.5	103.2	175.5	195.0	206.5	367.5	408.3	432.4	735.0	816.7	864.7	1470.0	1633.3	1729.4
	9	9	9	1	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7	10.0	11.1	11.8	20.0	22.2	23.5	42.5	47.2	50.0	97.5	108.3	114.7	195.0	216.7	229.4	408.3	453.7	480.4	816.7	907.4	960.8	1633.3	1814.8	1921.6
		10	10	1	1024-QAM	3/4									11.3	12.5	13.2	22.5	25.0	26.5	47.8	53.1	56.3	109.7	121.9	129.0	219.4	243.8	258.1	459.4	510.4	540.4	918.8	1020.8	1080.9	1837.5	2041.7	2161.8
		11	11	1	1024-QAM	5/6									12.5	13.9	14.7	25.0	27.8	29.4	53.1	59.0	62.5	121.9	135.4	143.4	243.8	270.8	286.8	510.4	567.1	600.5	1020.8	1134.3	1201.0	2041.7	2268.5	2402.0
			12	1	4096-QAM	3/4									13.5	15.0	15.9	27.0	30.0	31.8	57.4	63.8	67.5	131.6	146.3	154.9	263.3	292.5	309.7	551.3	612.5	648.5	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1
			13	1	4096-QAM	5/6									15.0	16.7	17.6	30.0	33.3	35.3	63.8	70.8	75.0	146.3	162.5	172.1	292.5	325.0	344.1	612.5	680.6	720.6	1225.0	1361.1	1441.2	2450.0	2722.2	2882.4
8	0	0	0	2	BPSK	1/2	13	14.4	27	30	58.5	65	117	130	1.5	1.7	1.8	3.0	3.3	3.5	6.4	7.1	7.5	14.6	16.3	17.2	29.3	32.5	34.4	61.3	68.1	72.1	122.5	136.1	144.1	245.0	272.2	288.2
9	1	1	1	2	QPSK	1/2	26	28.9	54	60	117	130	234	260	3.0	3.3	3.5	6.0	6.7	7.1	12.8	14.2	15.0	29.3	32.5	34.4	58.5	65.0	68.8	122.5	136.1	144.1	245.0	272.2	288.2	490.0	544.4	576.5
10	2	2	2	2	QPSK	3/4	39	43.3	81	90	175.5	195	351	390	4.5	5.0	5.3	9.0	10.0	10.6	19.1	21.3	22.5	43.9	48.8	51.6	87.8	97.5	103.2	183.8	204.2	216.2	367.5	408.3	432.4	735.0	816.7	864.7
11	3	3	3	2	16-QAM	1/2	52	57.8	108	120	234	260	468	520	6.0	6.7	7.1	12.0	13.3	14.1	25.5	28.3	30.0	58.5	65.0	68.8	117.0	130.0	137.6	245.0	272.2	288.2	490.0	544.4	576.5	980.0	1088.9	1152.9
12	4	4	4	2	16-QAM	3/4	78	86.7	162	180	351	390	702	780	9.0	10.0	10.6	18.0	20.0	21.2	38.3	42.5	45.0	87.8	97.5	103.2	175.5	195.0	206.5	367.5	408.3	432.4	735.0	816.7	864.7	1470.0	1633.3	1729.4
13	5	5	5	2	64-QAM	2/3	104	115.6	216	240	468	520	936	1040	12.0	13.3	14.1	24.0	26.7	28.2	51.0	56.7	60.0	117.0	130.0	137.6	234.0	260.0	275.3	490.0	544.4	576.5	980.0	1088.9	1152.9	1960.0	2177.8	2305.9
14	6	6	6	2	64-QAM	3/4	117	130	243	270	526.5	585	1053	1170	13.5	15.0	15.9	27.0	30.0	31.8	57.4	63.8	67.5	131.6	146.3	154.9	263.3	292.5	309.7	551.3	612.5	648.5	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1
15	7	7	7	2	64-QAM	5/6	130	144.4	270	300	585	650	1170	1300	15.0	16.7	17.6	30.0	33.3	35.3	63.8	70.8	75.0	146.3	162.5	172.1	292.5	325.0	344.1	612.5	680.6	720.6	1225.0	1361.1	1441.2	2450.0	2722.2	2882.4
	8	8	8	2	256-QAM	3/4	156	173.3	324	360	702	780	1404	1560	18.0	20.0	21.2	36.0	40.0	42.4	76.5	85.0	90.0	175.5	195.0	206.5	351.0	390.0	412.9	735.0	816.7	864.7	1470.0	1633.3	1729.4	2940.0	3266.7	3458.8
	9	9	9	2	256-QAM	5/6	N/A	N/A	360	400	780	866.7	1560	1733.3	20.0	22.2	23.5	40.0	44.4	47.1	85.0	94.4	100.0	195.0	216.7	229.4	390.0	433.3	458.8	816.7	907.4	960.8	1633.3	1814.8	1921.6	3266.7	3629.6	3843.1
		10	10	2	1024-QAM	3/4									22.5	25.0	26.5	45.0	50.0	52.9	95.6	106.3	112.5	219.4	243.8	258.1	438.8	487.5	516.2	918.8	1020.8	1080.9	1837.5	2041.7	2161.8	3675.0	4083.3	4323.5
		11	11	2	1024-QAM	5/6									25.0	27.8	29.4	50.0	55.6	58.8	106.3	118.1	125.0	243.8	270.8	286.8	487.5	541.7	573.5	1020.8	1134.3	1201.0	2041.7	2268.5	2402.0	4083.3	4537.0	4803.9
			12	2	4096-QAM	3/4									27.0	30.0	31.8	54.0	60.0	63.5	114.8	127.5	135.0	263.3	292.5	309.7	526.5	585.0	619.4	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1	4410.0	4900.0	5188.2
			13	2	4096-QAM	5/6									30.0	33.3	35.3	60.0	66.7	70.6	127.5	141.7	150.0	292.5	325.0	344.1	585.0	650.0	688.2	1225.0	1361.1	1441.2	2450.0	2722.2	2882.4	4900.0	5444.4	5764.7
16	0	0	0	3	BPSK	1/2	19.5	21.7	40.5	45	87.8	97.5	175.5	195	2.3	2.5	2.6	4.5	5.0	5.3	9.6	10.6	11.3	21.9	24.4	25.8	43.9	48.8	51.6	91.9	102.1	108.1	183.8	204.2	216.2	367.5	408.3	432.4
17	1	1	1	3	QPSK	1/2	39	43.3	81	90	175.5	195	351	390	4.5	5.0	5.3	9.0	10.0	10.6	19.1	21.3	22.5	43.9	48.8	51.6	87.8	97.5	103.2	183.8	204.2	216.2	367.5	408.3	432.4	735.0	816.7	864.7
18	2	2	2	3	QPSK	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585	6.8	7.5	7.9	13.5	15.0	15.9	28.7	31.9	33.8	65.8	73.1	77.4	131.6	146.3	154.9	275.6	306.3	324.3	551.3	612.5	648.5	1102.5	1225.0	1297.1
19	3	3	3	3	16-QAM	1/2	78	86.7	162	180	351	390	702	780	9.0	10.0	10.6	18.0	20.0	21.2	38.3	42.5	45.0	87.8	97.5	103.2	175.5	195.0	206.5	367.5	408.3	432.4	735.0	816.7	864.7	1470.0	1633.3	1729.4
20	4	4	4	3	16-QAM	3/4	117	130	243	270	526.5	585	1053	1170	13.5	15.0	15.9	27.0	30.0	31.8	57.4	63.8	67.5	131.6	146.3	154.9	263.3	292.5	309.7	551.3	612.5	648.5	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1
21	5	5	5	3	64-QAM	2/3	156	173.3	324	360	702	780	1404	1560	18.0	20.0	21.2	36.0	40.0	42.4	76.5	85.0	90.0	175.5	195.0	206.5	351.0	390.0	412.9	735.0	816.7	864.7	1470.0	1633.3	1729.4	2940.0	3266.7	3458.8
22	6	6	6	3	64-QAM	3/4	175.5	195	364.5	405	N/A	N/A	1579.5	1755	20.3	22.5	23.8	40.5	45.0	47.6	86.1	95.6	101.3	197.4	219.4	232.3	394.9	438.8	464.6	826.9	918.8	972.8	1653.8	1837.5	1945.6	3307.5	3675.0	3891.2
23	7	7	7	3	64-QAM	5/6	195	216.7	405	450	877.5	975	1755	1950	22.5	25.0	26.5	45.0	50.0	52.9	95.6	106.3	112.5	219.4	243.8	258.1	438.8	487.5	516.2	918.8	1020.8	1080.9	1837.5	2041.7	2161.8	3675.0	4083.3	4323.5
	8	8	8	3	256-QAM	3/4	234	260	486	540	1053	1170	2106	2340	27.0	30.0	31.8	54.0	60.0	63.5	114.8	127.5	135.0	263.3	292.5	309.7	526.5	585.0	619.4	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1	4410.0	4900.0	5188.2
	9	9	9	3	256-QAM	5/6	260	288.9	540	600	1170	1300	N/A	N/A	30.0	33.3	35.3	60.0	66.7	70.6	127.5	141.7	150.0	292.5	325.0	344.1	585.0	650.0	688.2	1225.0	1361.1	1441.2	2450.0	2722.2	2882.4	4900.0	5444.4	5764.7
		10	10	3	1024-QAM	3/4									33.8	37.5	39.7	67.5	75.0	79.4	143.4	159.4	168.8	329.1	365.6	387.1	658.1	731.3	774.3	1378.1	1531.3	1621.3	2756.3	3062.5	3242.6	5512.5	6125.0	6485.3
		11	11	3	1024-QAM	5/6									37.5	41.7	44.1	75.0	83.3	88.2	159.4	177.1	187.5	365.6	406.3	430.1	731.3	812.5	860.3	1531.3	1701.4	1801.5	3062.5	3402.8	3602.9	6125.0	6805.6	7205.9
			12	3	4096-QAM	3/4									40.5	45.0	47.6	81.0	90.0	95.3	172.1	191.3	202.5	394.9	438.8	464.6	789.8	877.5	929.1	1653.8	1837.5	1945.6	3307.5	3675.0	3891.2	6615.0	7350.0	7782.4
			13	3	4096-QAM	5/6									45.0	50.0	52.9	90.0	100.0	105.9	191.3	212.5	225.0	438.8	487.5	516.2	877.5	975.0	1032.4	1837.5	2041.7	2161.8	3675.0	4083.3	4323.5	7350.0	8166.7	8647.1
24	0	0	0	4	BPSK	1/2	26	28.9	54	60	117	130	234	260	3.0	3.3	3.5	6.0	6.7	7.1	12.8	14.2	15.0	29.3	32.5	34.4	58.5	65.0	68.8	122.5	136.1	144.1	245.0	272.2	288.2	490.0	544.4	576.5
25	1	1	1	4	QPSK	1/2	52	57.8	108	120	234	260	468	520	6.0	6.7	7.1	12.0	13.3	14.1	25.5	28.3	30.0	58.5	65.0	68.8	117.0	130.0	137.6	245.0	272.2	288.2	490.0	544.4	576.5	980.0	1088.9	1152.9
26	2	2	2	4	QPSK	3/4	78	86.7	162	180	351	390	702	780	9.0	10.0	10.6	18.0	20.0	21.2	38.3	42.5	45.0	87.8	97.5	103.2	175.5	195.0	206.5	367.5	408.3	432.4	735.0	816.7	864.7	1470.0	1633.3	1729.4
27	3	3	3	4	16-QAM	1/2	104	115.6	216	240	468	520	936	1040	12.0	13.3	14.1	24.0	26.7	28.2	51.0	56.7	60.0	117.0	130.0	137.6	234.0	260.0	275.3	490.0	544.4	576.5	980.0	1088.9	1152.9	1960.0	2177.8	2305.9
28	4	4	4	4	16-QAM	3/4	156	173.3	324	360	702	780	1404	1560	18.0	20.0	21.2	36.0	40.0	42.4	76.5	85.0	90.0	175.5	195.0	206.5	351.0	390.0	412.9	735.0	816.7	864.7	1470.0	1633.3	1729.4	2940.0	3266.7	3458.8
29	5	5	5	4	64-QAM	2/3	208	231.1	432	480	936	1040	1872	2080	24.0	26.7	28.2	48.0	53.3	56.5	102.0	113.3	120.0	234.0	260.0	275.3	468.0	520.0	550.6	980.0	1088.9	1152.9	1960.0	2177.8	2305.9	3920.0	4355.6	4611.8
30	6	6	6	4	64-QAM	3/4	234	260	486	540	1053	1170	2106	2340	27.0	30.0	31.8	54.0	60.0	63.5	114.8	127.5	135.0	263.3	292.5	309.7	526.5	585.0	619.4	1102.5	1225.0	1297.1	2205.0	2450.0	2594.1	4410.0	4900.0	5188.2
31	7	7	7	4	64-QAM	5/6	260	288.9	540	600	1170	1300	2340	2600	30.0	33.3	35.3	60.0	66.7	70.6	127.5	141.7	150.0	292.5	325.0	344.1	585.0	650.0	688.2	1225.0	1361.1	1441.2	2450.0	2722.2	2882.4	4900.0	5444.4	5764.7
	8	8	8	4	256-QAM	3/4	312	346.7	648	720	1404	1560	2808	3120	36.0	40.0	42.4	72.0	80.0	84.7	153.0	170.0	180.0	351.0	390.0	412.9	702.0	780.0	825.9	1470.0	1633.3	1729.4	2940.0	3266.7	3458.8	5880.0	6533.3	6917.6
	9	9	9	4	256-QAM	5/6	N/A	N/A	720	800	1560	1733.3	3120	3466.7	40.0	44.4	47.1	80.0	88.9	94.1	170.0	188.9	200.0	390.0	433.3	458.8	780.0	866.7	917.6	1633.3	1814.8	1921.6	3266.7	3629.6	3843.1	6533.3	7259.3	7686.3
		10	10	4	1024-QAM	3/4									45.0	50.0	52.9	90.0	100.0	105.9	191.3	212.5	225.0	438.8	487.5	516.2	877.5	975.0	1032.4	1837.5	2041.7	2161.8	3675.0	4083.3	4323.5	7350.0	8166.7	8647.1
		11	11	4	1024-QAM	5/6									50.0	55.6	58.8	100.0	111.1	117.6	212.5	236.1	250.0	487.5	541.7	573.5	975.0	1083.3	1147.1	2041.7	2268.5	2402.0	4083.3	4537.0	4803.9	8166.7	9074.1	9607.8
			12	4	4096-QAM	3/4									54.0	60.0	63.5	108.0	120.0	127.1	229.5	255.0	270.0	526.5	585.0	619.4	1053.0	1170.0	1238.8	2205.0	2450.0	2594.1	4410.0	4900.0	5188.2	8820.0	9800.0	10376.5
			13	4	4096-QAM	5/6									60.0	66.7	70.6	120.0	133.3	141.2	255.0	283.3	300.0	585.0	650.0	688.2	1170.0	1300.0	1376.5	2450.0	2722.2	2882.4	4900.0	5444.4	5764.7	9800.0	10888.9	11529.4

That's it, thank you!

Q&A session