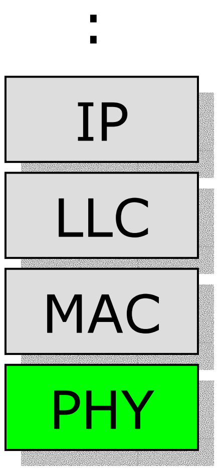
Contents

Physical layer (PHY)

IEEE 802.11 (in 1999) originally defined three alternatives: DSSS (Direct Sequence Spread Spectrum), FHSS (Frequency Hopping) and IR (Infrared). However, the 802.11 PHY never took off.

802.11b defines DSSS operation which builds on (and is backward compatible with) the 802.11 DSSS alternative.

802.11a and 802.11g use OFDM (Orthogonal Frequency Division Multiplexing) which is very different from DSSS.



Operating channels for 802.11b

Channel 1	2.412 GHz
Channel 2	2.417 GHz
Channel 3	2.422 GHz
:	:
Channel 10	2.457 GHz
Channel 11	2.462 GHz
Channel 12	2.467 GHz
Channel 13	2.472 GHz
Channel 14 (only used in Japan)	2.484 GHz

ISM frequency band:
2.4 … 2.4835 GHz

Channel spacing = 5 MHz

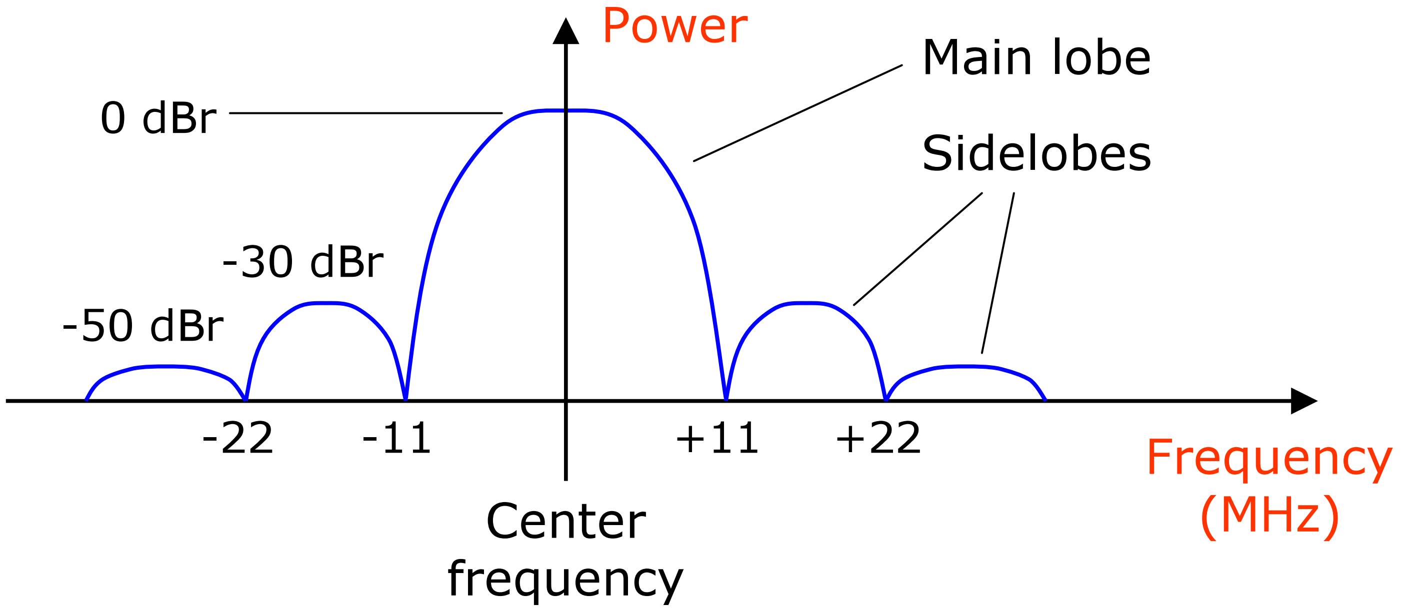
Not all channels can be used at the same time!

Channels used in different regulatory domains

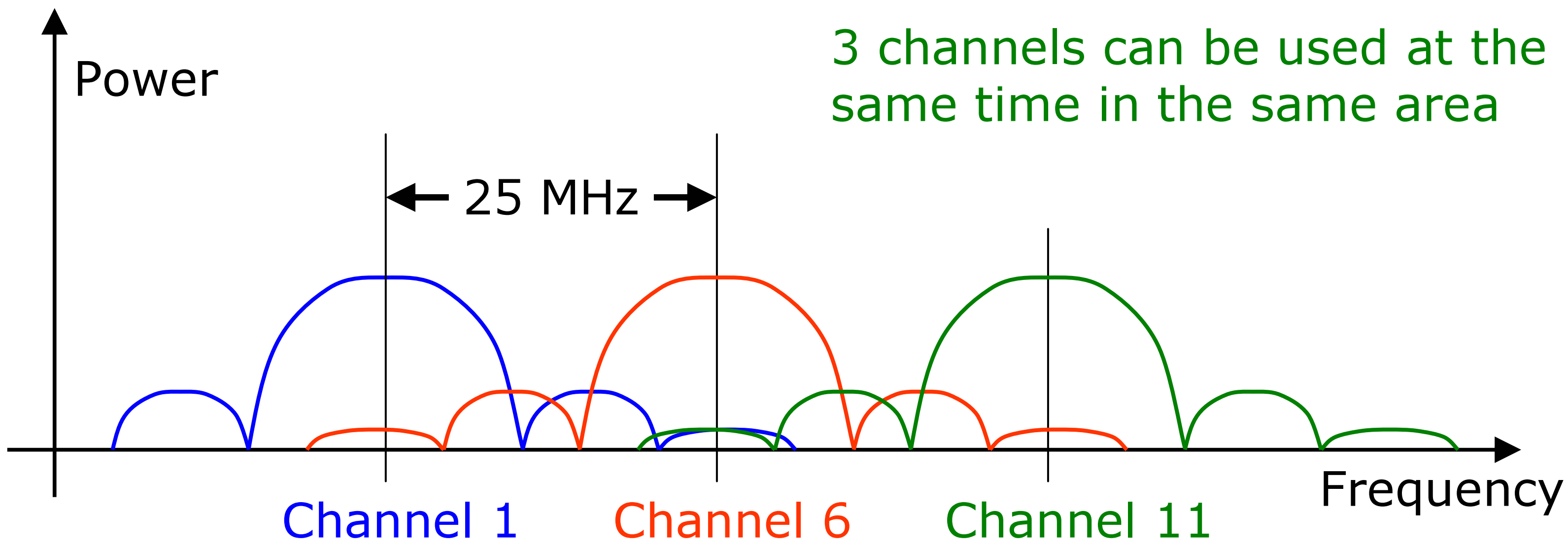
Regulatory domain	Allowed channels
US (FCC) / Canada	1 to 11
France	10 to 13
Spain	10 to 11
Europe (ETSI)	1 to 13
Japan	14

Most 802.11b products use channel 10 as the default operating channel

Energy spread of 11 Mchip/s sequence



Channel separation in 802.11b networks



More channels at the same time => severe spectral overlapping

Bit rates and modulation in 802.11b

Modulation	Bit rate	
DBPSK	1 Mbit/s	Defined in 802.11
DQPSK	2 Mbit/s	
CCK	5.5 Mbit/s	Defined in 802.11b
CCK	11 Mbit/s	

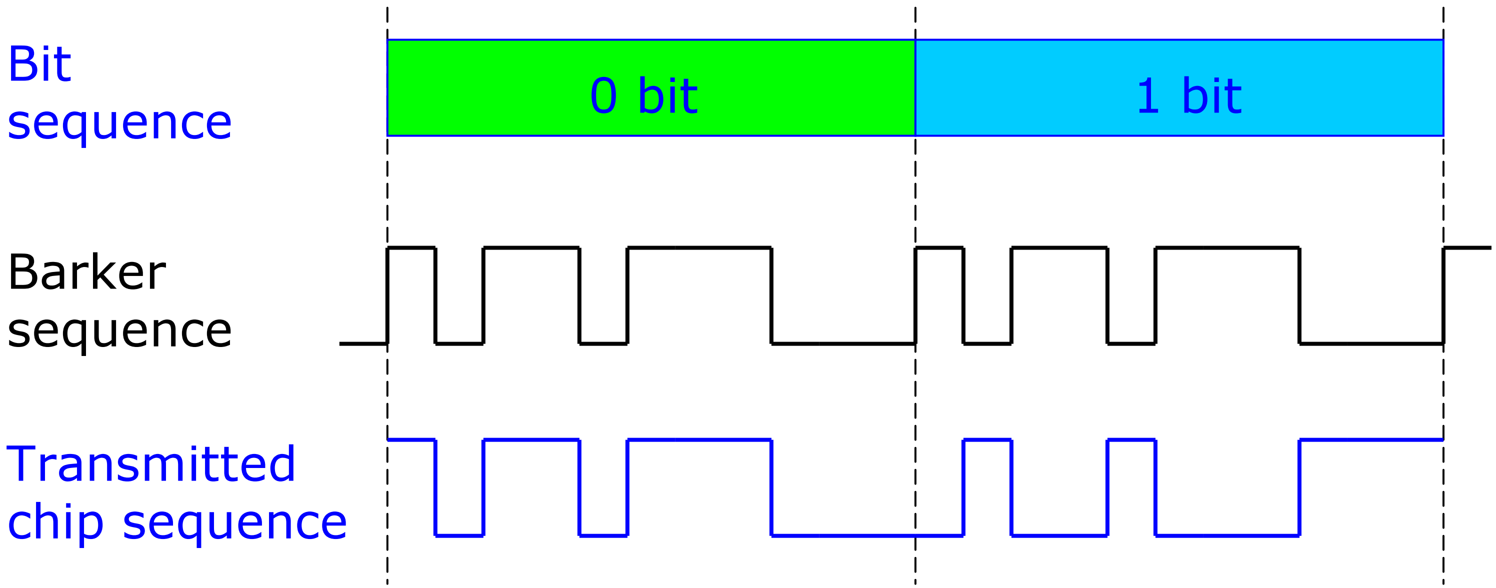
DB/QPSK = Differential Binary/Quaternary PSK

CCK = Complementary Code Keying

Automatic fall-back to a lower bit rate if channel becomes bad

Encoding with 11-chip Barker sequence

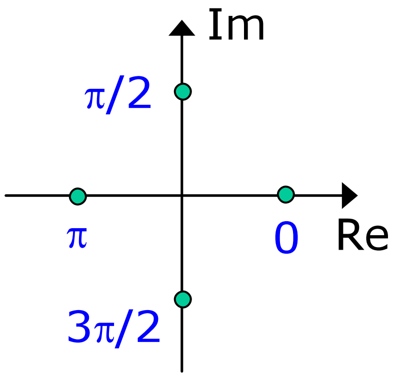
(Used only at 1 and 2 Mbit/s, CCK is used at higher bit rates)



Differential quadrature phase shift keying

(Used at the higher bit rates in one form or another)

QPSK symbols in the complex plane:



DQPSK encoding table	
Bit pattern	Phase shift w.r.t. previous symbol
00	0
01	$\pi/2$
11	π
10	$3\pi/2$

Why 1 or 2 Mbit/s ?

Chip rate = 11 Mchips/s

Duration of one chip = 1/11 μs

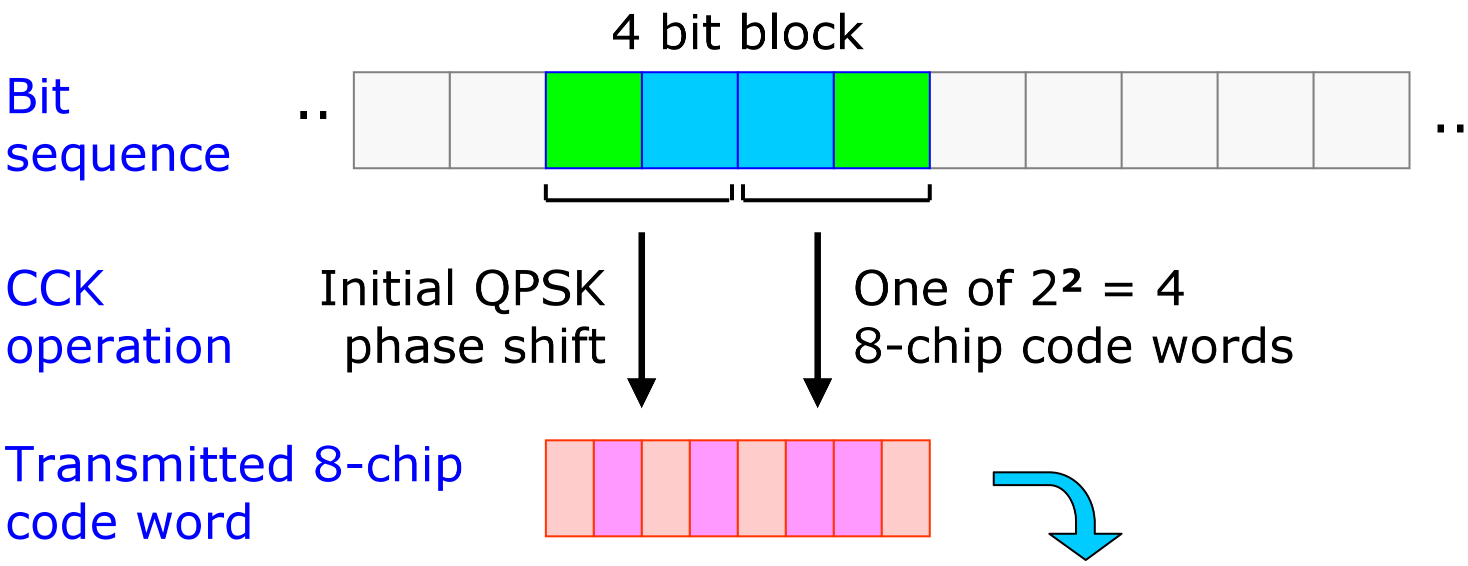
Duration of 11 chip Barker code word = 1 μs

Code word rate = 1 Mwords/s

Each code word carries the information of 1 bit (DBPSK) or 2 bits (DQPSK)

=> Bit rate = 1 Mbit/s (DBPSK) or 2 Mbit/s (DQPSK)

802.11b transmission at 5.5 Mbit/s



Code word repetition rate = 1.375 Mwords/s

Why 5.5 Mbit/s ?

Chip rate = 11 Mchips/s (same as in IEEE 802.11)

Duration of one chip = 1/11 μs

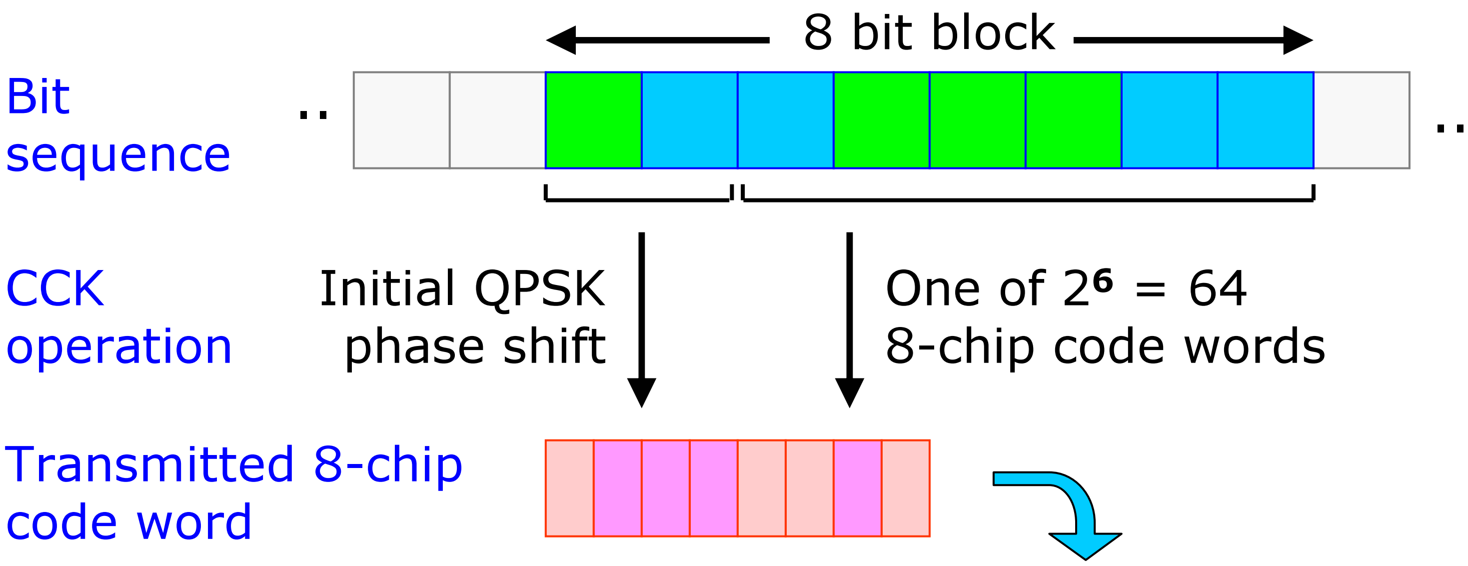
Duration of 8 chip code word = 8/11 μs

Code word rate = 11/8 Mwords/s = 1.375 Mwords/s

Each code word carries the information of 4 bits

=> Bit rate = 4 x 1.375 Mbit/s = 5.5 Mbit/s

802.11b transmission at 11 Mbit/s



Code word repetition rate = 1.375 Mwords/s

Why 11 Mbit/s ?

Chip rate = 11 Mchips/s (same as in IEEE 802.11)

Duration of one chip = 1/11 μs

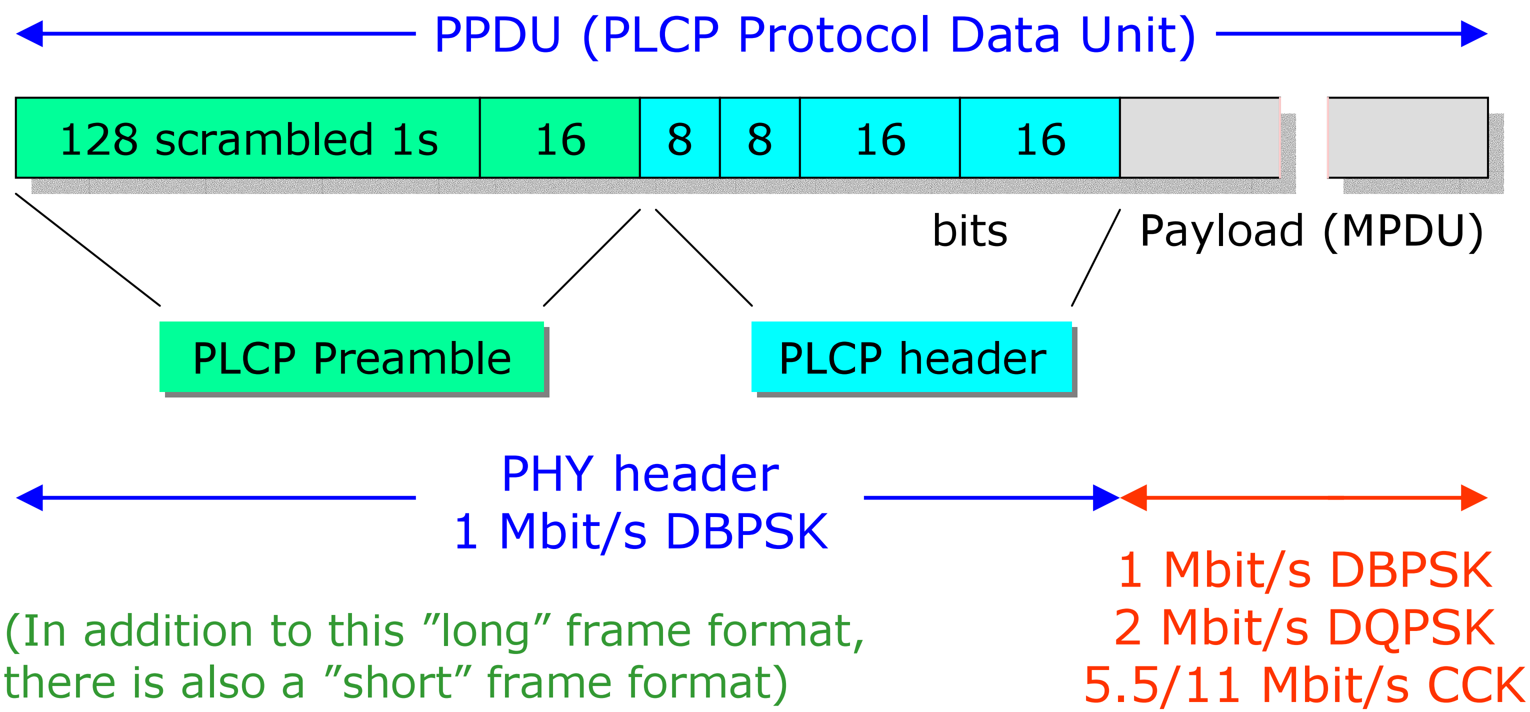
Duration of 8 chip code word = 8/11 μs

Code word rate = 11/8 Mwords/s = 1.375 Mwords/s

Each code word carries the information of 8 bits

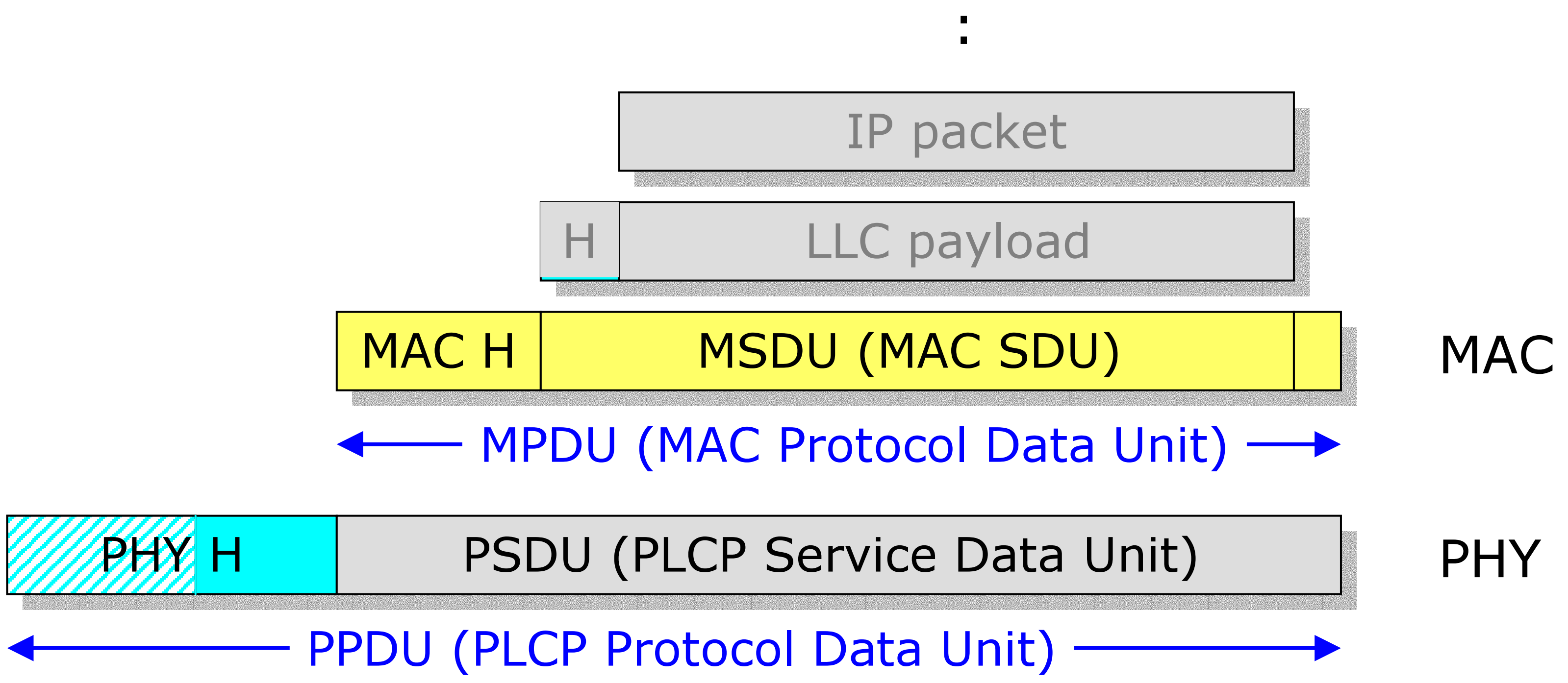
=> Bit rate = 8 x 1.375 Mbit/s = 11 Mbit/s

IEEE 802.11b frame structure (PHY layer)



(In addition to this ”long” frame format, there is also a ”short” frame format)

IEEE 802.11b frame structure



IEEE 802.11a/g

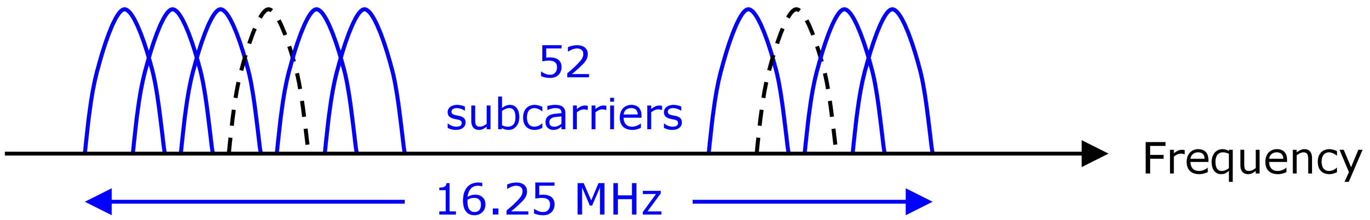
This physical layer implementation is based on OFDM (Orthogonal Frequency Division Multiplexing).

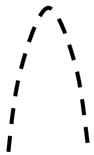
The information is carried over the radio medium using orthogonal subcarriers. A channel (16.25 MHz wide) is divided into 52 subcarriers (48 subcarriers for data and 4 subcarriers serving as pilot signals).

Subcarriers are modulated using BPSK, QPSK, 16-QAM, or 64-QAM, and coded using convolutional codes (R = 1/2, 2/3, and 3/4), depending on the data rate.

Frequency domain

Presentation of subcarriers in frequency domain:

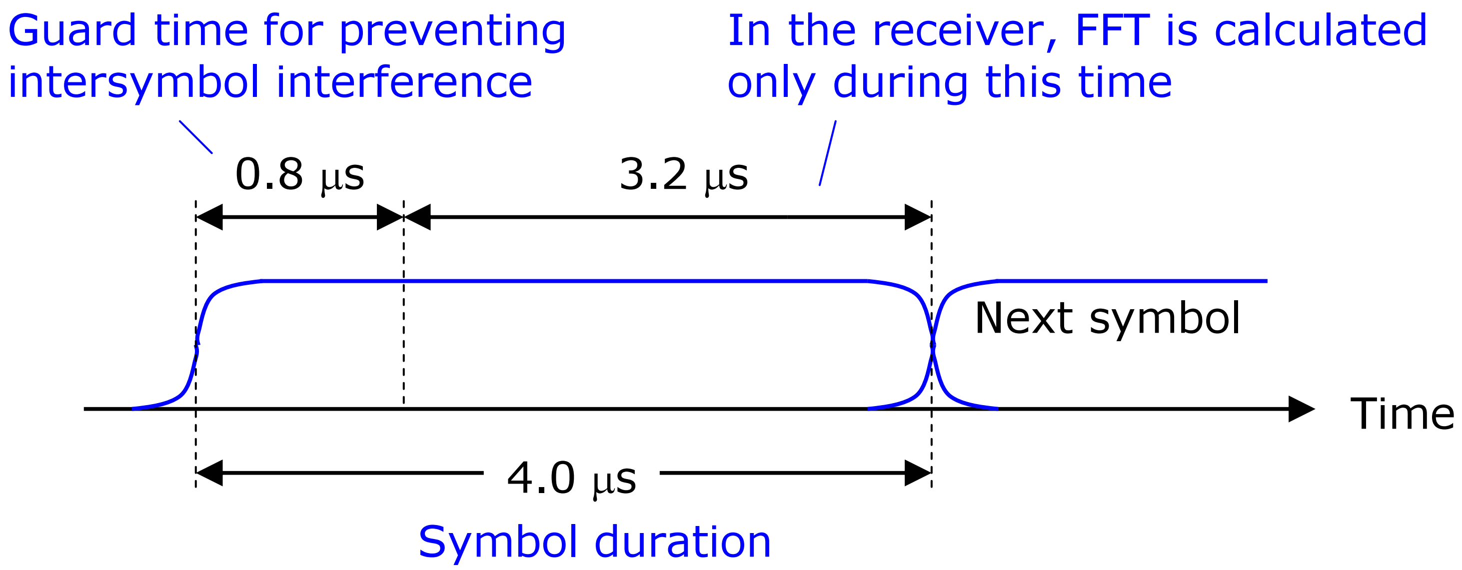




By using pilot subcarriers (-21, -7, 7 and 21) as a reference for phase and amplitude, the 802.11a/g receiver can demodulate the data in the other subcarriers.

Time domain

Presentation of OFDM signal in time domain:



Subcarrier modulation and coding

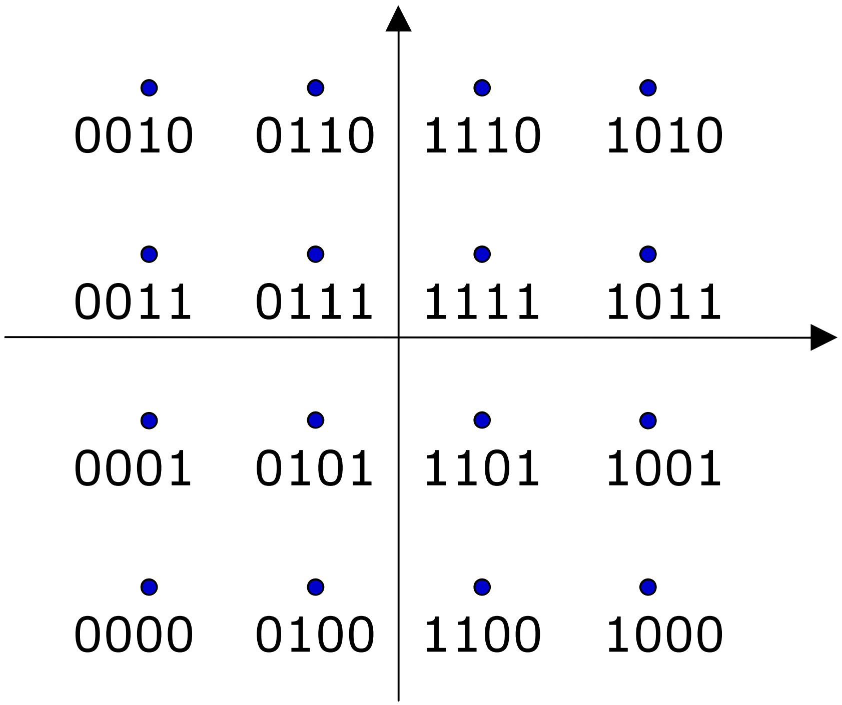
Modulation	Bit rate	Coding rate	Coded bits / symbol	Data bits / symbol
BPSK	6 Mbit/s	1/2	48	24
BPSK	9 Mbit/s	3/4	48	36
QPSK	12 Mbit/s	1/2	96	48
QPSK	18 Mbit/s	3/4	96	72
16-QAM	24 Mbit/s	1/2	192	96
16-QAM	36 Mbit/s	3/4	192	144
64-QAM	48 Mbit/s	2/3	288	192
64-QAM	54 Mbit/s	3/4	288	216

Bit-to-symbol mapping in 16-QAM

Gray bit-to-symbol mapping is usually used in QAM systems.

The reason: it is optimal in the sense that a symbol error (involving adjacent points in the QAM signal constellation) results in a single bit error.

Example for 16-QAM



Why (for instance) 54 Mbit/s ?

Symbol duration = 4 μs

Data-carrying subcarriers = 48

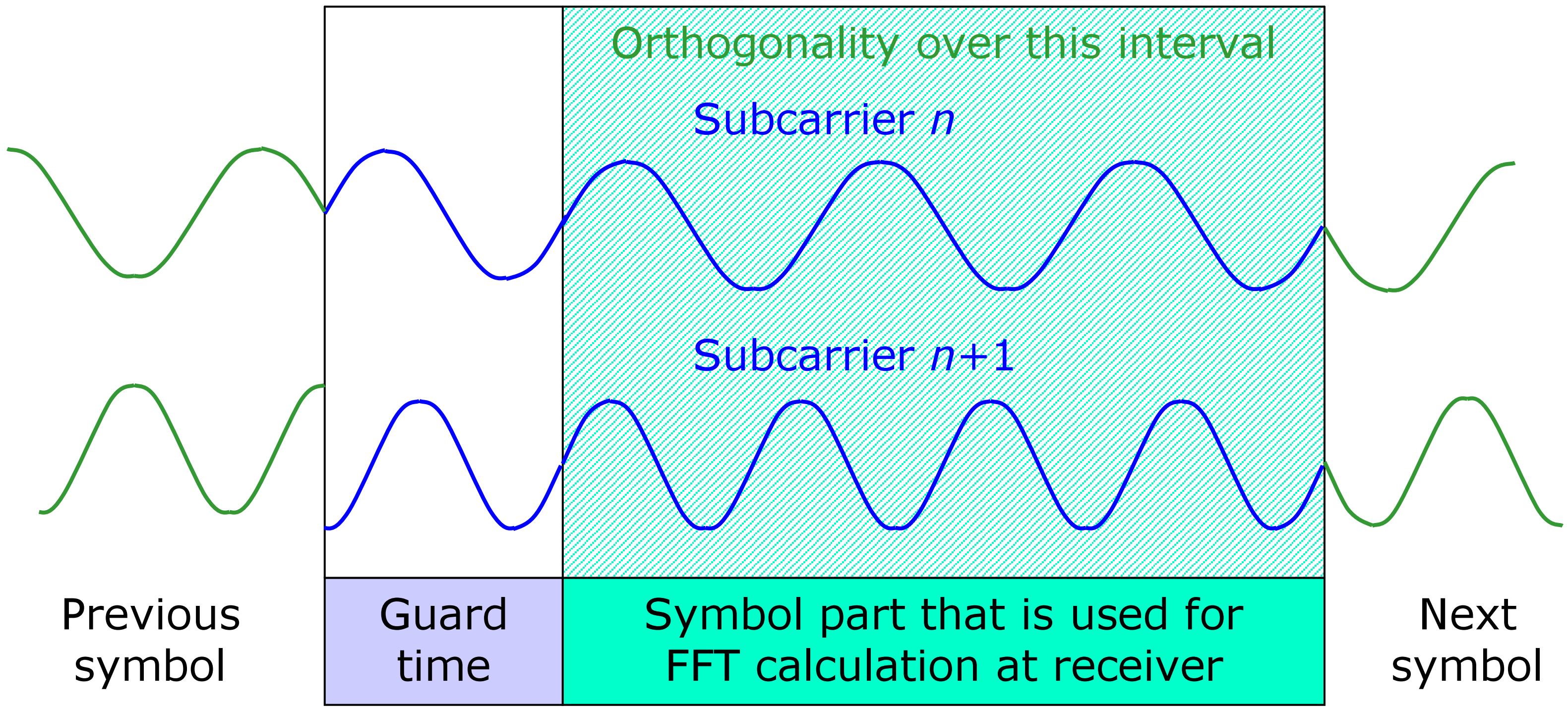
Coded bits / subcarrier = 6 (64 QAM)

Coded bits / symbol = 6 x 48 = 288

Data bits / symbol: 3/4 x 288 = 216 bits/symbol

=> Bit rate = 216 bits / 4 μs = 54 Mbit/s

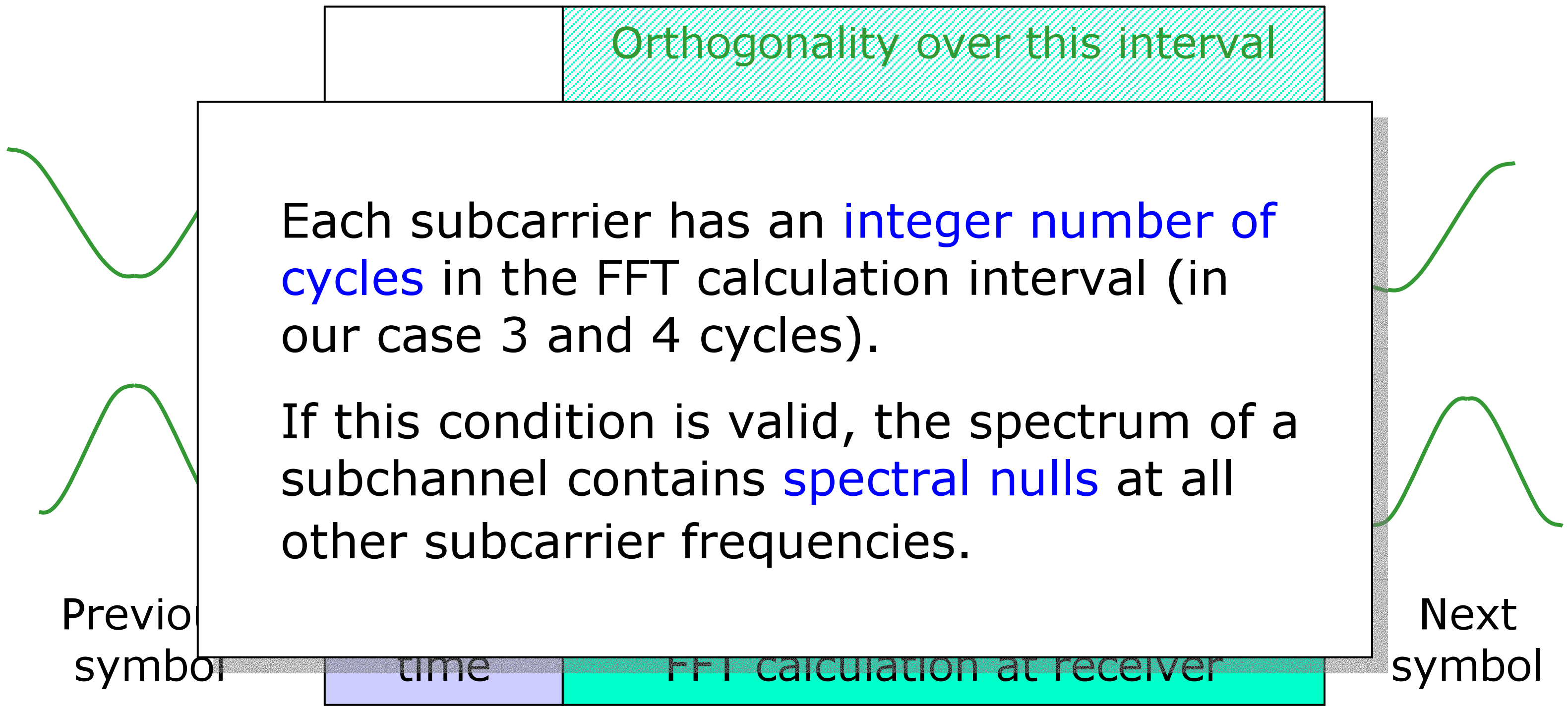
Orthogonality between subcarriers (1)



Orthogonality between subcarriers (2)

Each subcarrier has an integer number of cycles in the FFT calculation interval (in our case 3 and 4 cycles).

If this condition is valid, the spectrum of a subchannel contains spectral nulls at all other subcarrier frequencies.



Orthogonality between subcarriers (3)

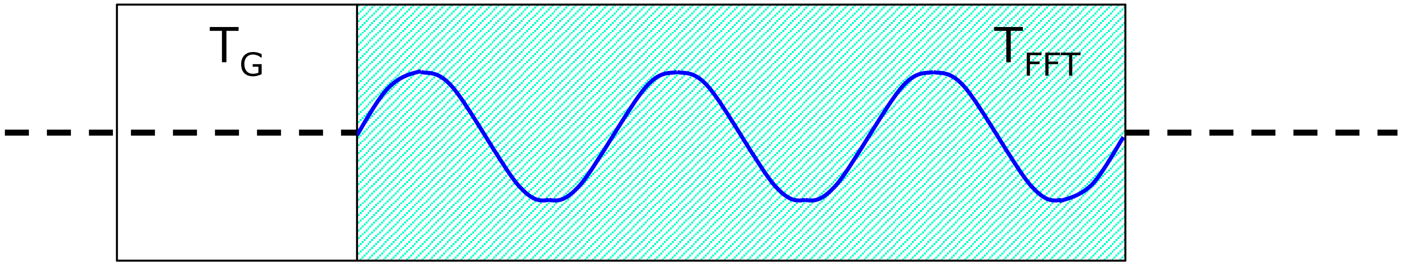
Orthogonality over the FFT interval (T_{FFT}):

$$\int_0^{T_{FFT}} \cos\left(2\pi mt/T_{FFT}\right)\cos\left(2\pi nt/T_{FFT}\right)dt = \begin{cases} T_{FFT}/2 & m = n \\ 0 & m \neq n \end{cases}$$

Phase shift in either subcarrier - orthogonality over the FFT interval is still retained:

$$\int_0^{T_{FFT}} \cos\left(2\pi mt/T_{FFT} + \phi\right)\cos\left(2\pi nt/T_{FFT}\right)dt = 0 \qquad m \neq n$$

Time vs. frequency domain



Square-windowed sinusoid in time domain

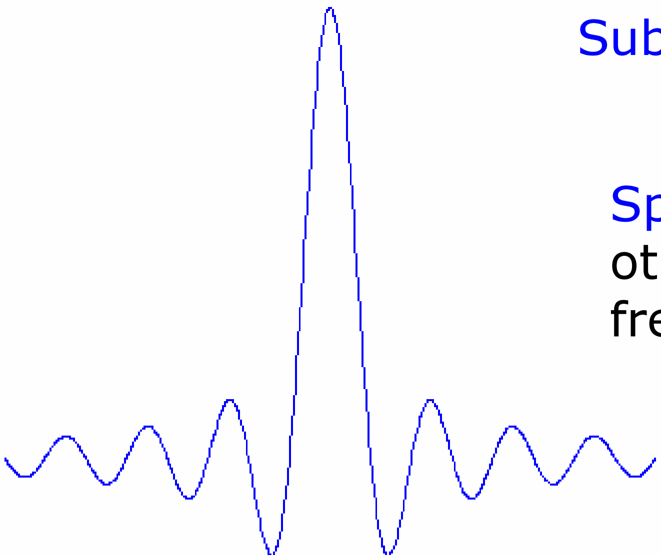
=>

"sinc" shaped subchannel spectrum in frequency domain

$$\text{sinc}\left(fT_{FFT}\right)=\left[\sin\left(\pi fT_{FFT}\right)\right]/\left(\pi fT_{FFT}\right)$$

Subchannels in frequency domain

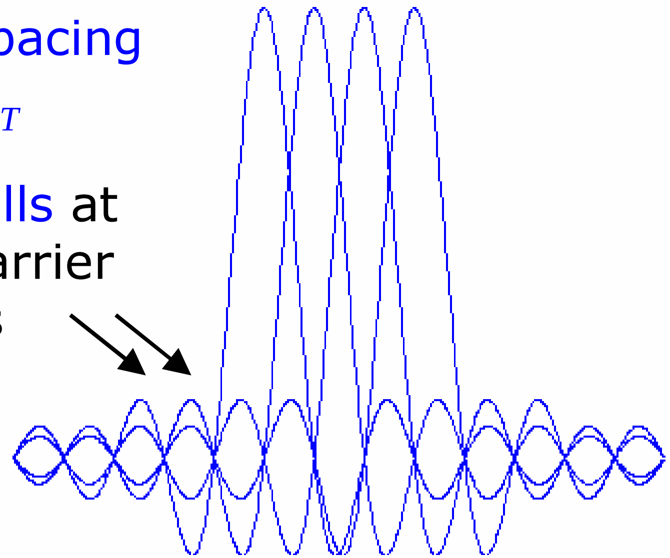
Single subchannel



OFDM spectrum

Subcarrier spacing $= 1/T_{FFT}$

Spectral nulls at other subcarrier frequencies



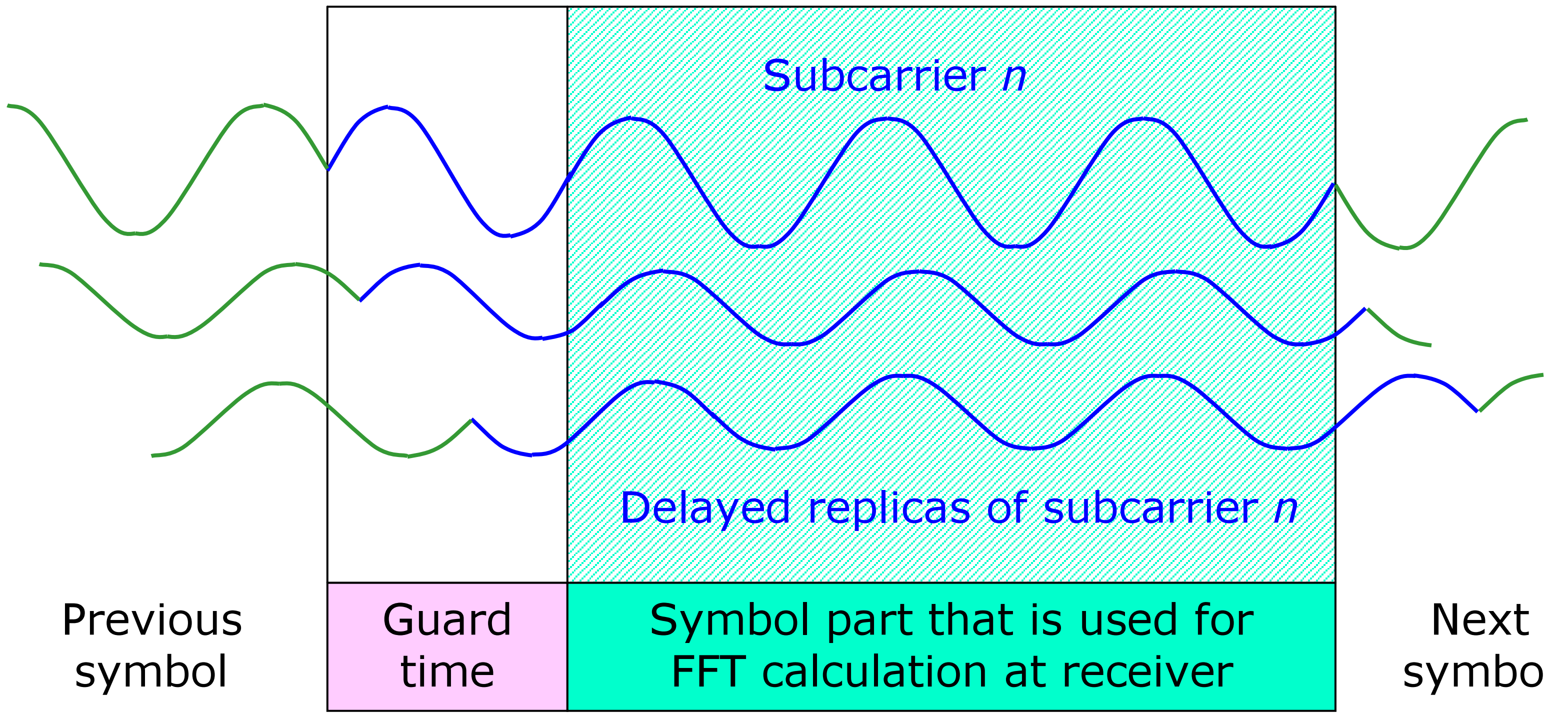
Presentation of OFDM symbol

In an OFDM symbol sequence, the *k*:th OFDM symbol (in complex low-pass equivalent form) is

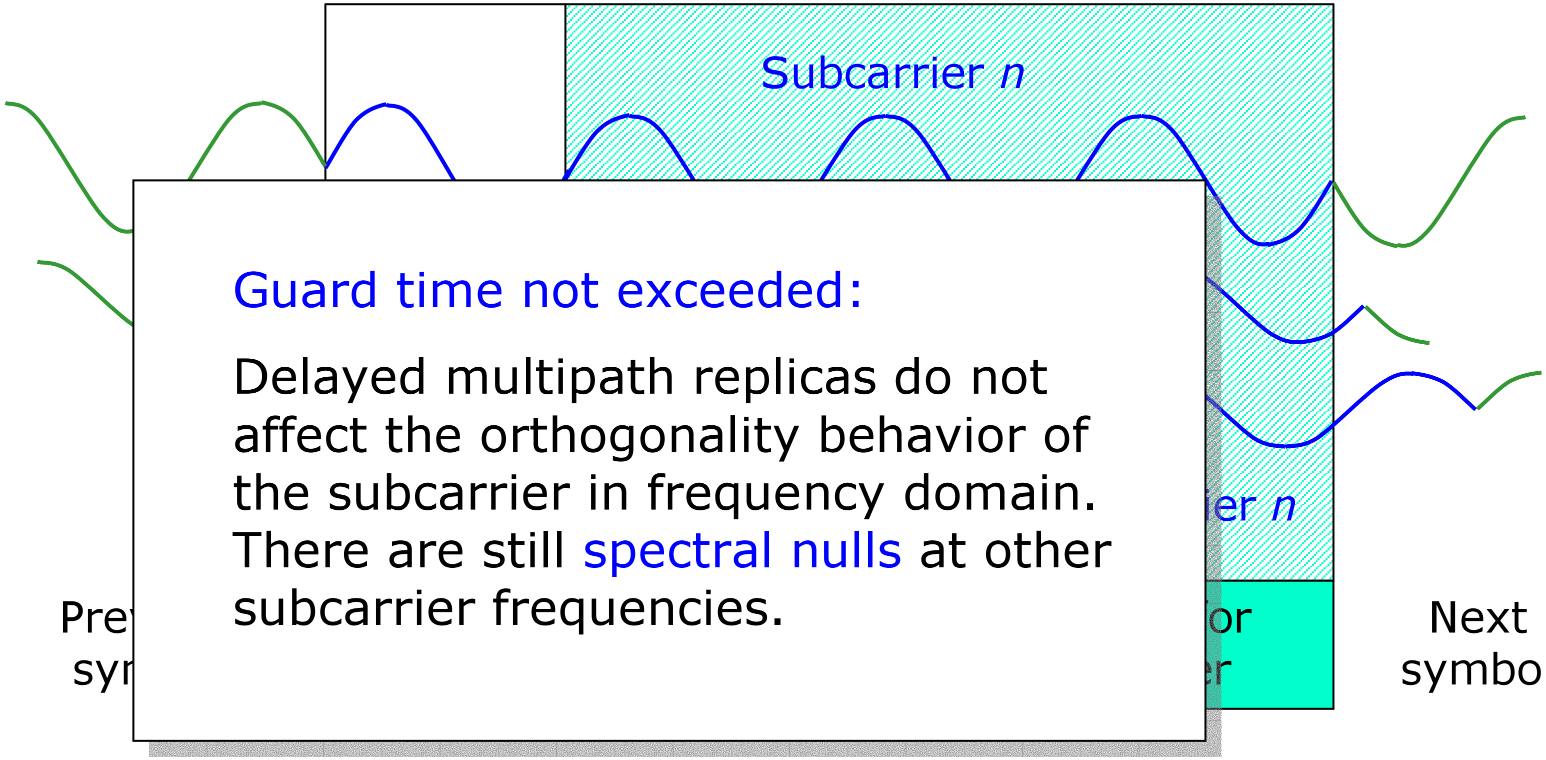
$$g_k(t) = \sum_{\substack{n=-N/2 \\ n\neq 0}}^{N/2} a_{n,k} \exp\left(j2\pi \frac{n}{T_{FFT}} t \right) \qquad (k-1)T < t < kT$$

where N = number of subcarriers, $T = T_G + T_{FFT}$ = symbol period, and $a_{n,k}$ is the complex data symbol modulating the *n*:th subcarrier during the *k*:th symbol period.

Multipath effect on subcarrier *n* (1)



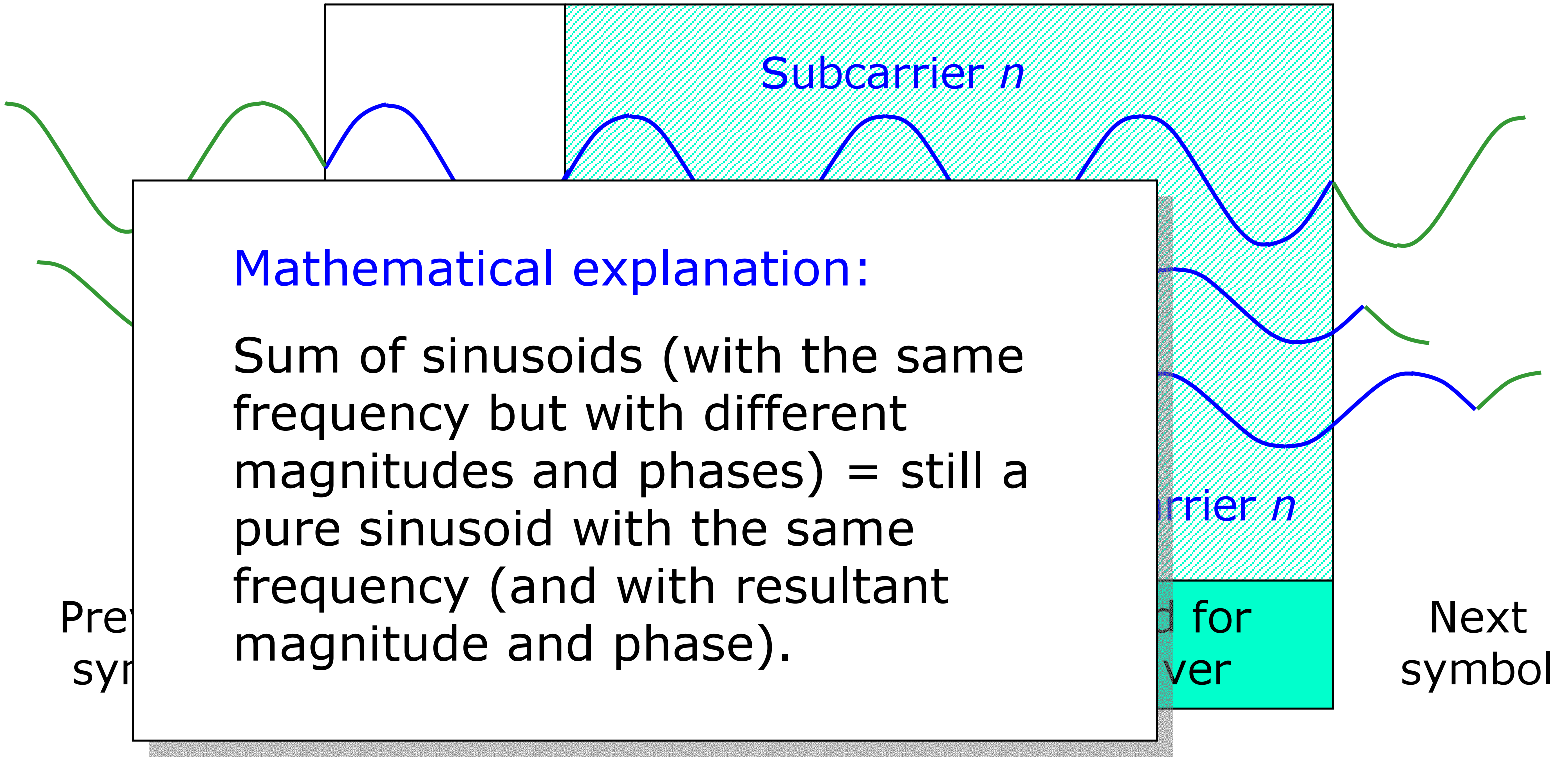
Multipath effect on subcarrier *n* (2)



Guard time not exceeded:

Delayed multipath replicas do not affect the orthogonality behavior of the subcarrier in frequency domain. There are still spectral nulls at other subcarrier frequencies.

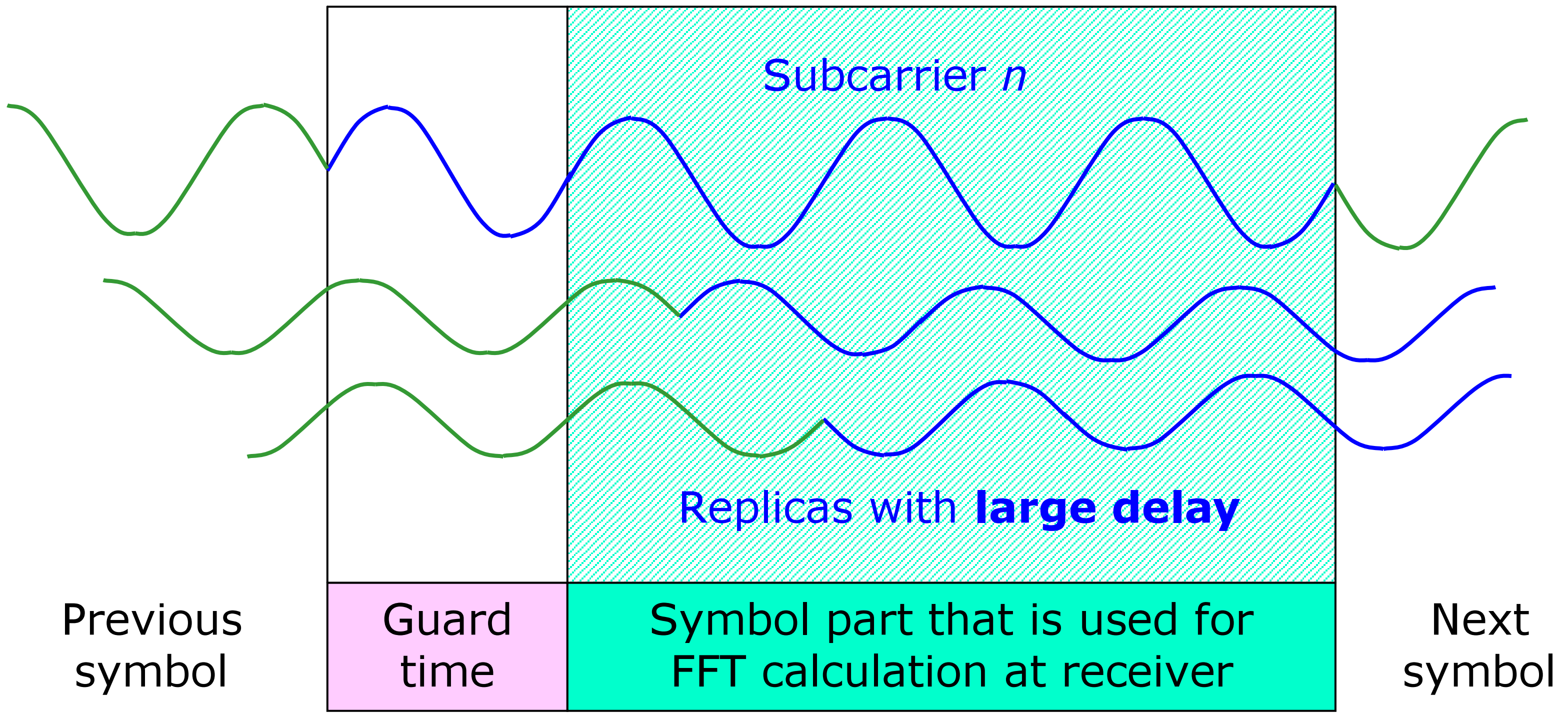
Multipath effect on subcarrier *n* (3)



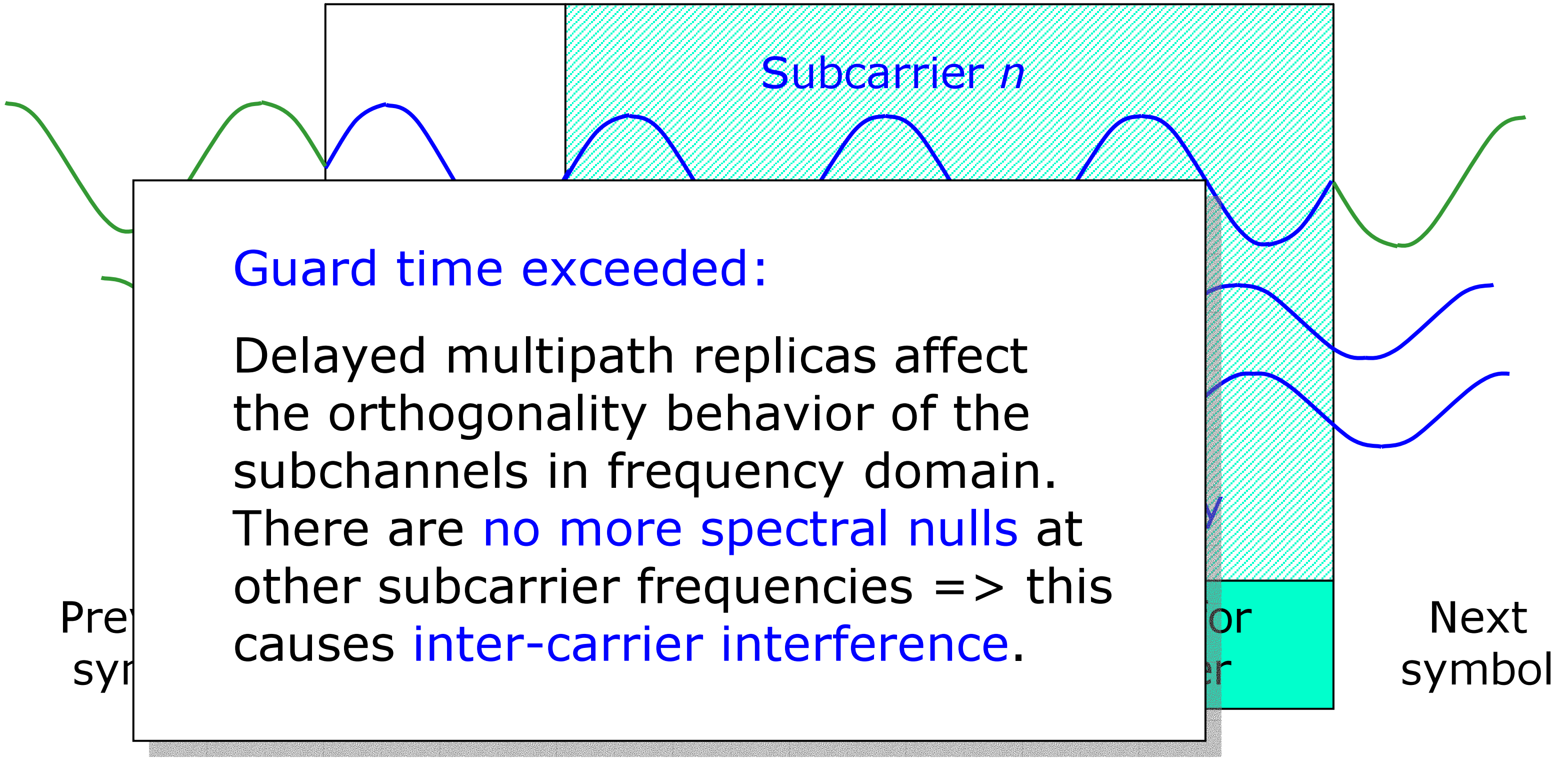
Mathematical explanation:

Sum of sinusoids (with the same frequency but with different magnitudes and phases) = still a pure sinusoid with the same frequency (and with resultant magnitude and phase).

Multipath effect on subcarrier *n* (4)



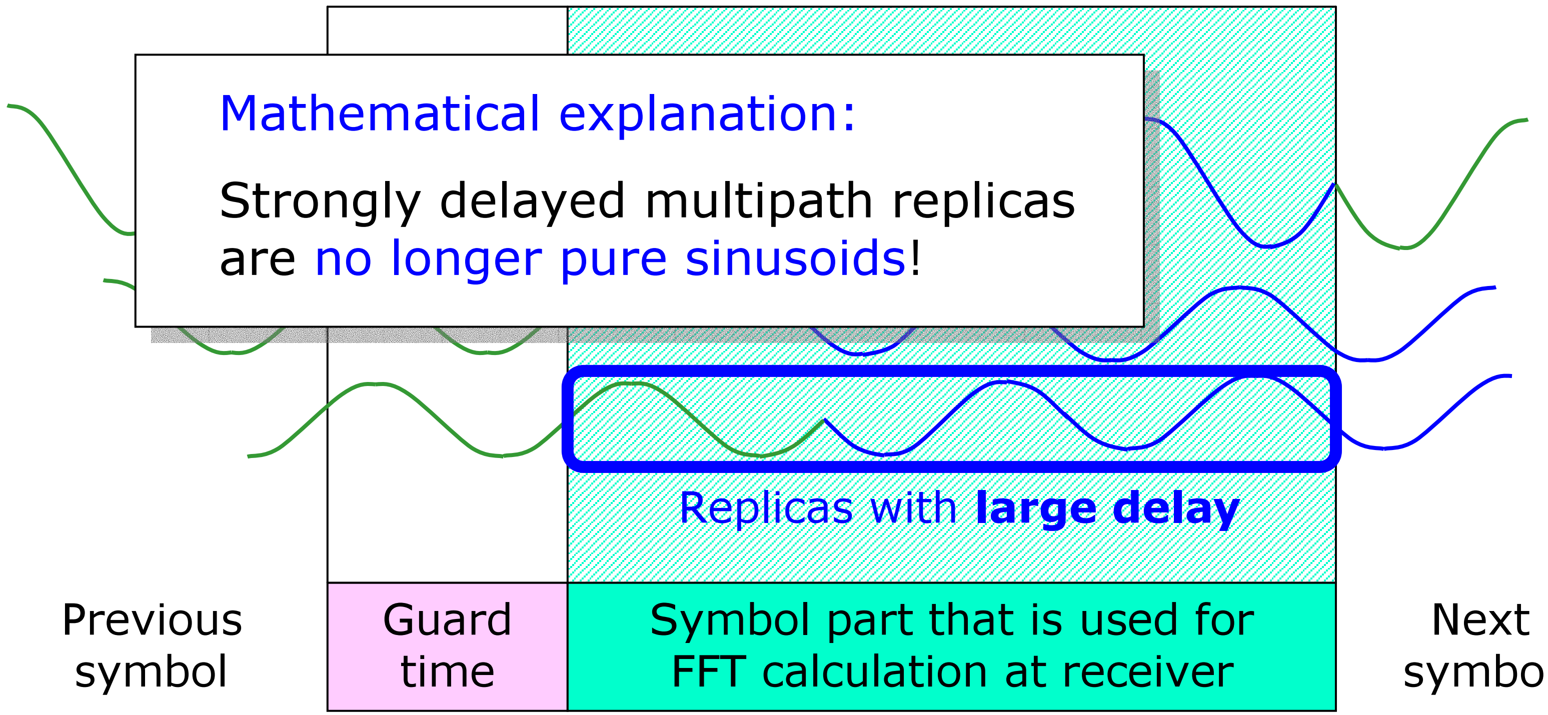
Multipath effect on subcarrier *n* (5)



Guard time exceeded:

Delayed multipath replicas affect the orthogonality behavior of the subchannels in frequency domain. There are no more spectral nulls at other subcarrier frequencies => this causes inter-carrier interference.

Multipath effect on subcarrier *n* (6)



IEEE 802.11a in Europe

802.11a was designed in the USA. In Europe, a similar WLAN system – HiperLAN2 – was designed by ETSI (European Telecommunications Standards Institute), intended to be used in the same frequency band (5 GHz).

Although HiperLAN2 has not (yet) took off, 802.11a devices, when being used in Europe, must include two HiperLAN2 features not required in the USA:

- DFS (Dynamic Frequency Selection)
- TPC (Transmit Power Control)

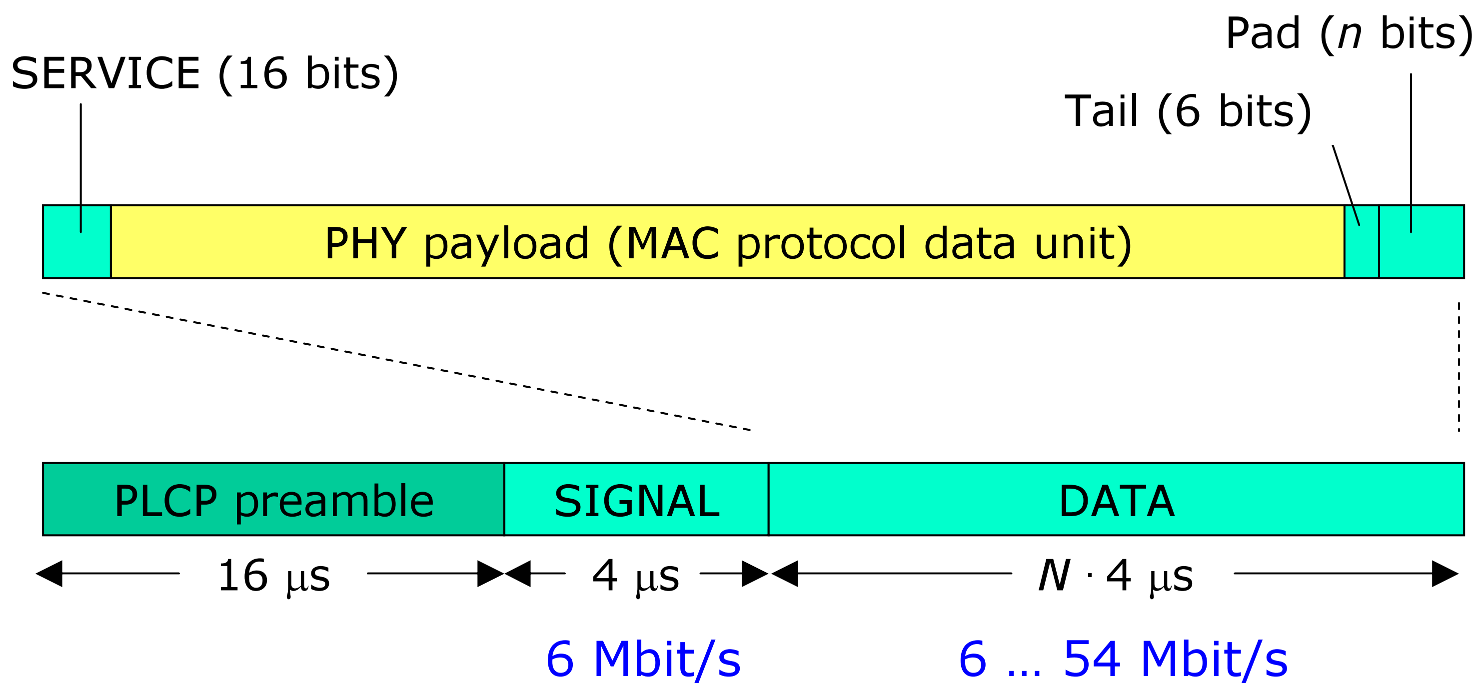
IEEE 802.11g PHY

802.11g is also based on OFDM (and same parameters as 802.11a). However, 802.11g uses the 2.4 GHz frequency band, like 802.11b (usually: dual mode devices).

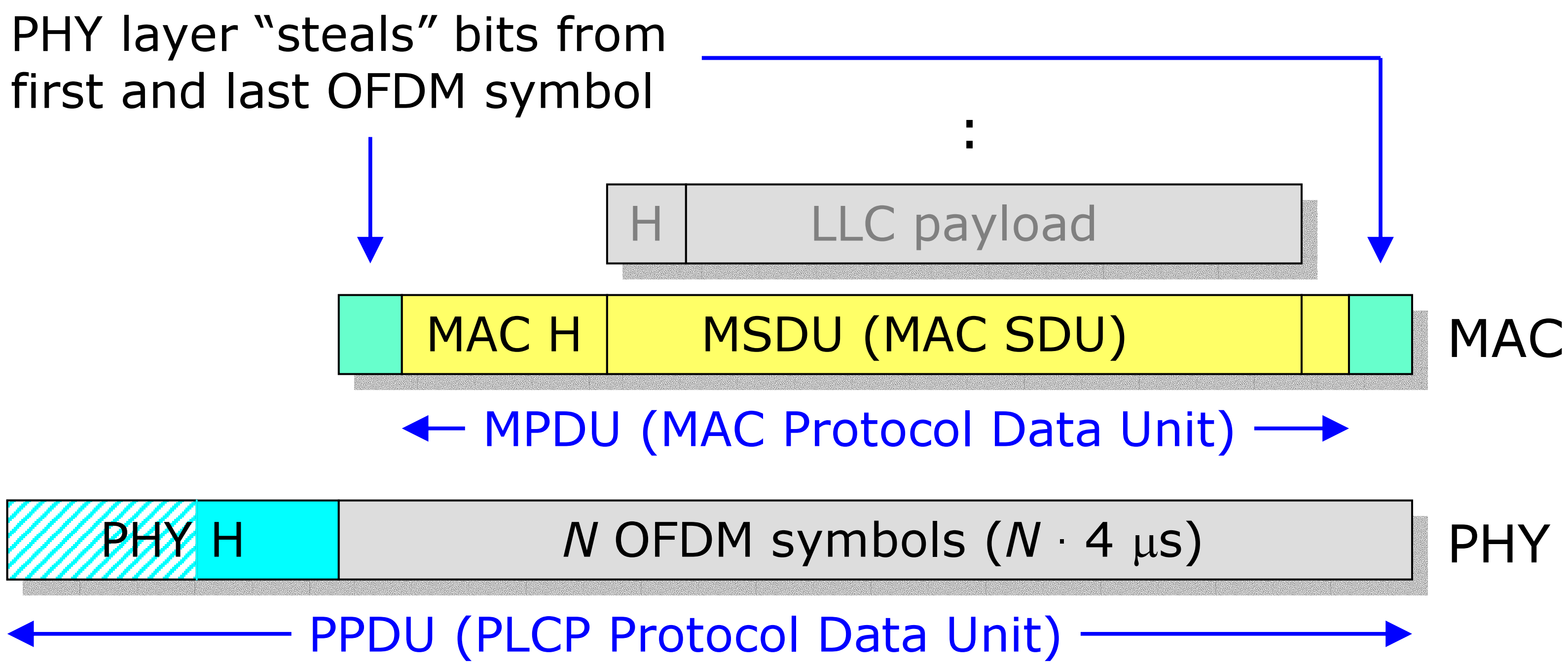
Since the bandwidth of a 802.11b signal is 22 MHz and that of a 802.11g signal is 16.25 MHz, 802.11g can easily use the same channel structure as 802.11b (i.e. at most three channels at the same time in the same area).

802.11g and 802.11b stations must be able to share the same channels in the 2.4 GHz frequency band
=> interworking required.

IEEE 802.11g frame structure (PHY layer)

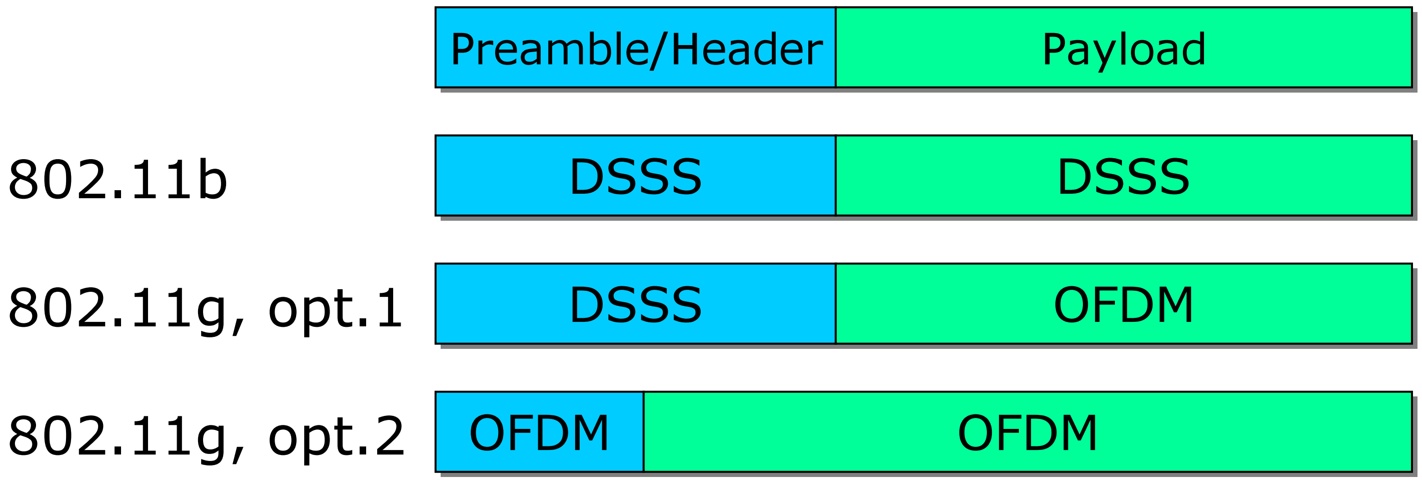


IEEE 802.11g frame structure



IEEE 802.11g and 802.11b interworking (1)

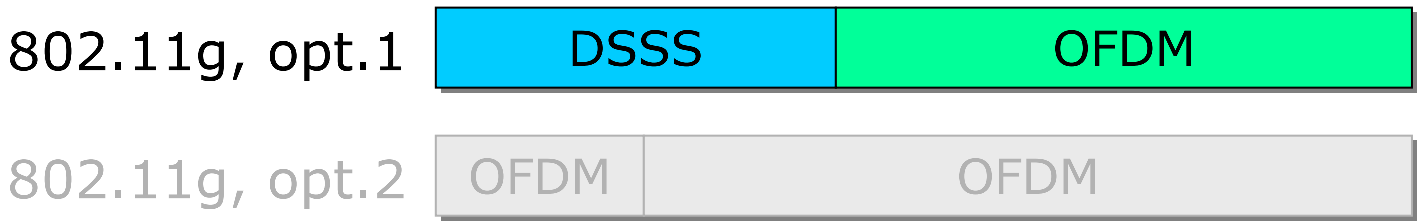
802.11g and 802.11b interworking is based on two alternatives regarding the 802.11g signal structure:



IEEE 802.11g and 802.11b interworking (2)

Option 1 (*): The preamble & PLCP header part of 802.11g packets is based on DSSS (using BPSK at 1 Mbit/s or QPSK at 2 Mbit/s), like 802.11b packets.

802.11g and 802.11b stations compete on equal terms for access to the channel (CSMA/CA). However, the 802.11g preamble & header is rather large (compared to option 2).

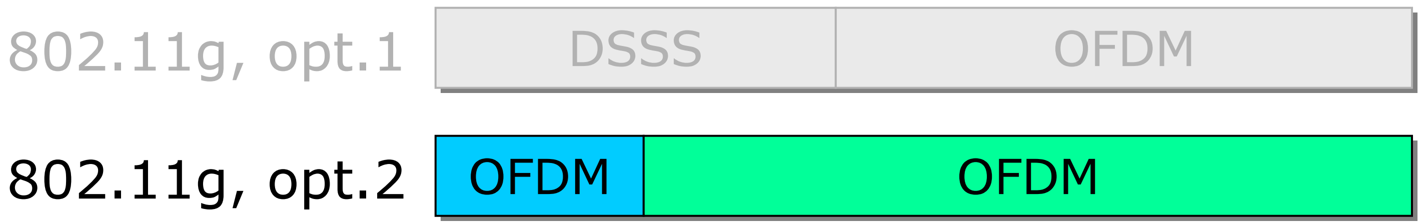


(*) called DSSS-OFDM in the 802.11g standard

IEEE 802.11g and 802.11b interworking (3)

Option 2 (*): The preamble & header of 802.11g packets is based on OFDM (using BPSK at 6 Mbit/s).

Now, 802.11b stations cannot decode the information in the 802.11g packet header and the CSMA/CA scheme will not work properly. Solution: Stations should use the RTS/CTS mechanism before transmitting a packet.



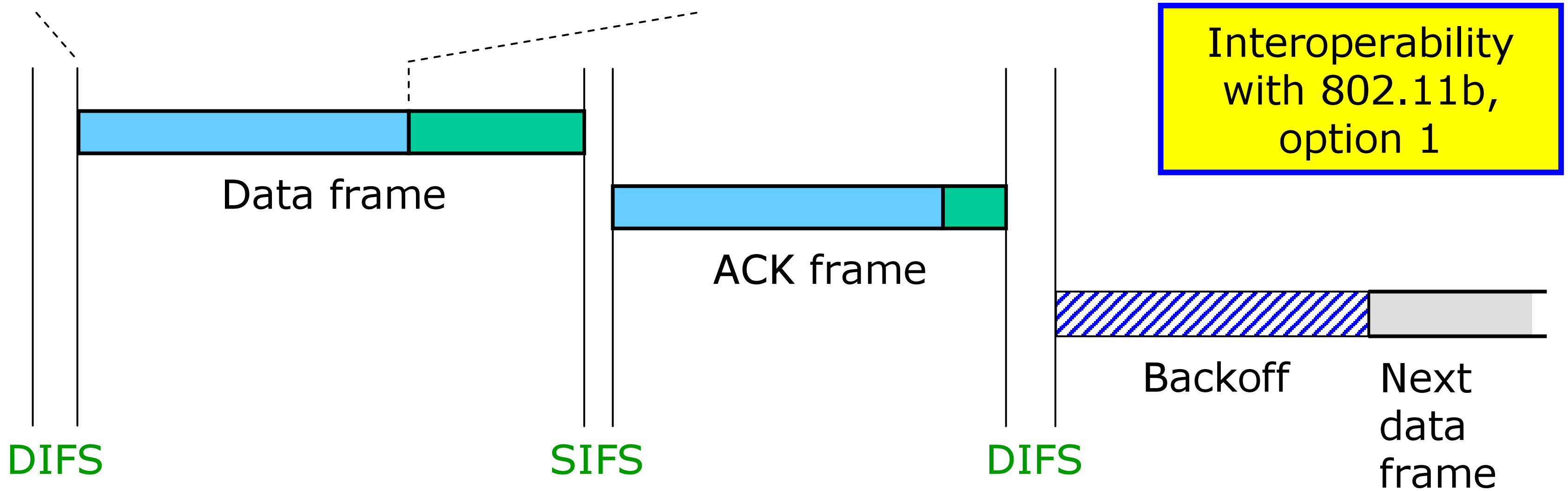
(*) called ERP-OFDM (ERP = Extended Rate PHY) in the 802.11g standard

IEEE 802.11a/g DSSS-OFDM option

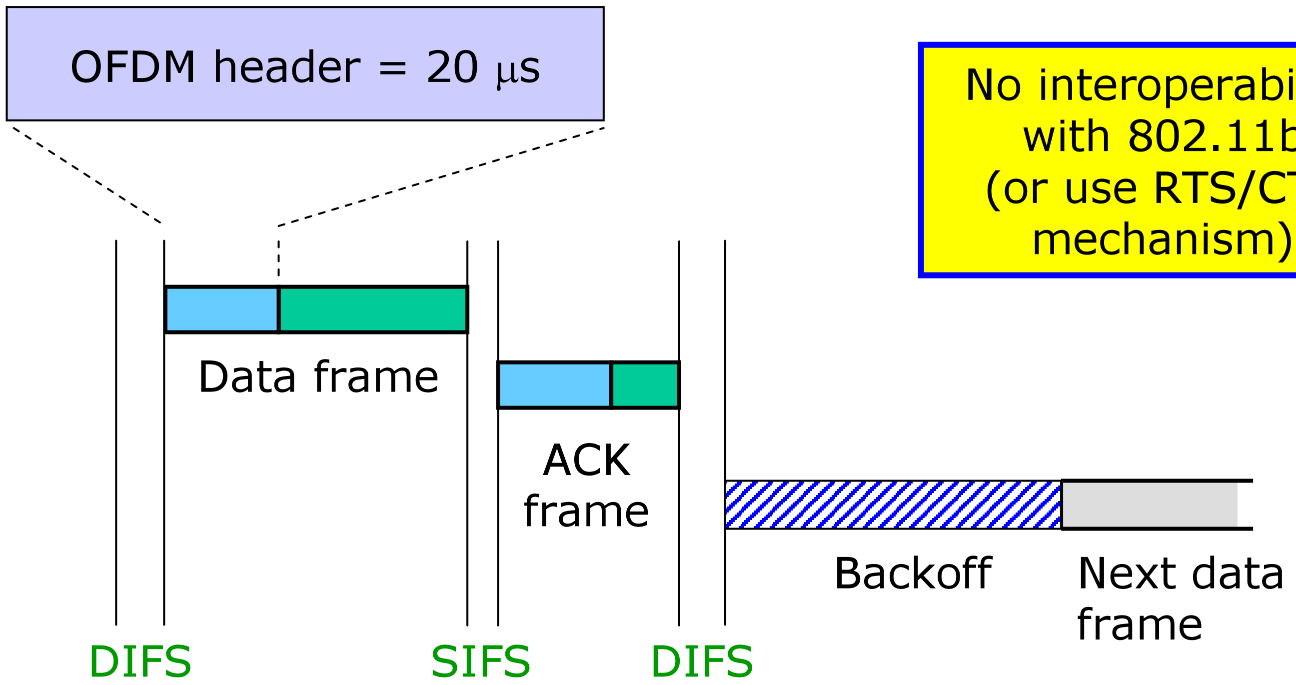
DSSS header = 144+48 bits = 192 μs (long preamble)

DSSS header = 96 μs (short preamble)

Interoperability with 802.11b, option 1



IEEE 802.11a/g ERP-OFDM option



No interoperability with 802.11b (or use RTS/CTS mechanism)