Orthogonal Frequency Division Multiplexing (OFDM)

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OFDM Advantages

- OFDM is a spectrally efficient modulation technique
- It is conveniently implemented using IFFT and FFT operations
- It handles frequency selective channels well when combined with error correction coding

OFDM Disadvantages

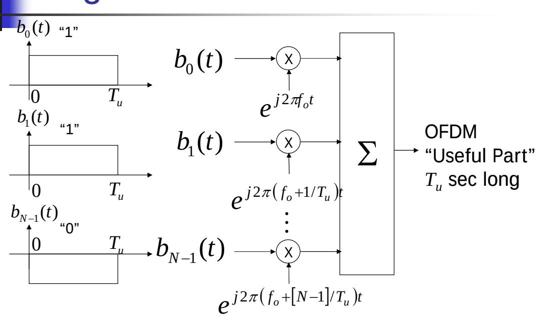
- More complex than single-carrier modulation
- Requires a more linear power amplifier

OFDM Concept

- Suppose the symbol length is T_u
- Sinusoidal signals differing in frequency by $1/T_u$ will be orthogonal over the period T_u

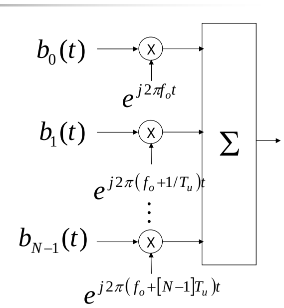
$$\int_{t_s}^{t_s+T_u} \left[e^{j2\pi f_o t}\right]\left[e^{-j2\pi\left(f_o+\frac{1}{T_u}\right)t}\right]dt = 0$$

Conceptual Transmitter Block Diagram



Subcarriers

- Each branch corresponds to a *subcarrier*
- Subcarriers are separated by $1/T_u$ Hz
- Each subcarrier modulates a different symbol
  - b_k can be QAM

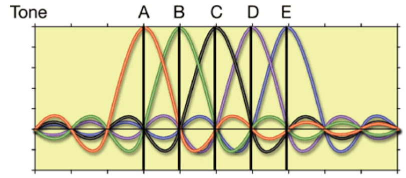


One OFDM Symbol

$$s(t) = \begin{cases} \sum_{k=0}^{N-1} b_k(t) e^{-j2\pi\left(f_o + \frac{k}{T_u}\right)t} & 0 < t < T_u \\ 0 & otherwise \end{cases}$$

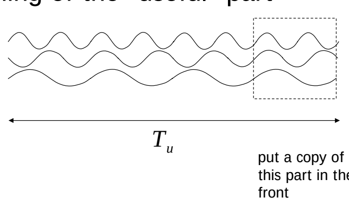
Subcarrier Spectra

- Each modulated subcarrier has a spectrum in the shape of a sinc squared function



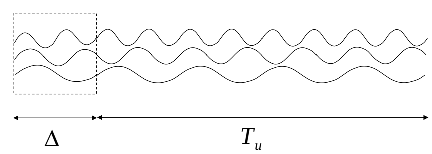
Cyclic Prefix Generation

- To avoid losing the power from echoes, a copy of the end is appended to the beginning of the "useful" part



Cyclic Prefix Appended

- The length of the cyclic prefix, also known as the Guard Interval, D, is supposed to be longer than the excess delay of the longest significant echo



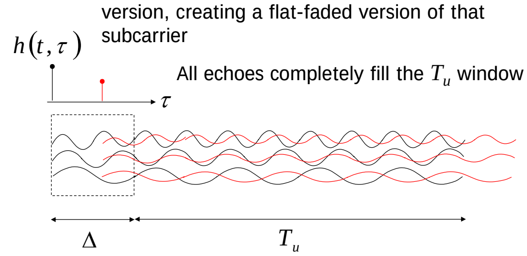
DSRC/WAVE Timing-Related Parameters

TABLE 4 Timing-related Parameters[A]

Parameter	Value
N_{SD}: number of data subcarriers	48
N_{SP}: number of pilot subcarriers	4
N_{ST}: number of subcarriers, total	52 (N_{SD}+ N_{SP})
Δ_F: subcarrier frequency spacing	156.25 kHz (=10 MHz/64)
T_{FFT}: IFFT/FFT period	6.4 μs (1/Δ_F)
$T_{PREAMBLE}$: PLCP preamble duration	32 μs (T_{SHORT}+ T_{LONG})
T_{SIGNAL}: duration of the SIGNAL BPSK-OFDM symbol	8 μs (T_{GI}+ T_{FFT})
T_{GI}: GI duration	1.6 μs (T_{FFT}/4)
T_{GI2}: training symbol GI duration	3.2 μs (T_{FFT}/2)
T_{SYM}: symbol interval	8 μs (T_{GI}+ T_{FFT})
T_{SHORT}: short training sequence duration	16 μs (10 × T_{FFT}/4)
T_{LONG}: long training sequence duration	16 μs (T_{GI2}+ 2 × T_{FFT})

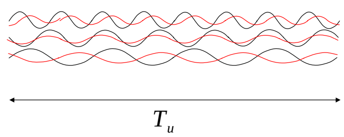
Effects of Multipath Delays

- A delayed echo of each subcarrier adds either constructively or destructively to its un-delayed version, creating a flat-faded version of that subcarrier



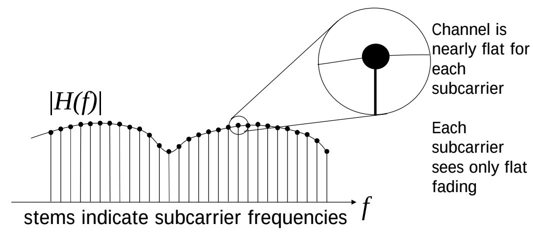
Cyclic Prefix Removal

- After the symbol has been received and stored in a buffer, the cyclic prefix is removed, leaving only the modulated and faded subcarriers



Fading

- The subcarrier spacing is typically much less than the coherence bandwidth

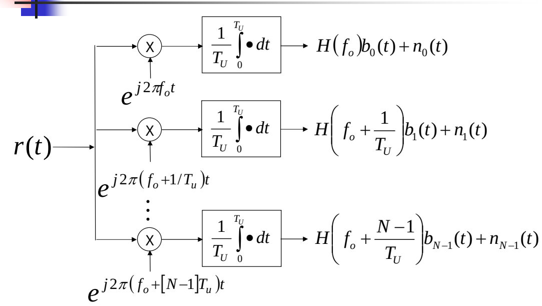


Received OFDM Symbol, After Cyclic Prefix Has Been Removed

- For a static, frequency selective channel,

$$r(t)=\begin{cases}\sum_{k=0}^{N-1} b_k(t)H\left(f_o+\frac{k}{T_u}\right)e^{-j2\pi\left(f_o+\frac{k}{T_u}\right)t}+n(t) & 0<t<T_u\\ 0 & otherwise\end{cases}$$

Correlator Demodulator Block Diagram (Baseband)



FFT

- These correlations are conveniently performed by the Fast Fourier Transform (FFT)
- The modulation is performed by the inverse FFT (IFFT)
- There are very fast and efficient implementations of the FFT and IFFT, which is a big reason for the popularity of OFDM

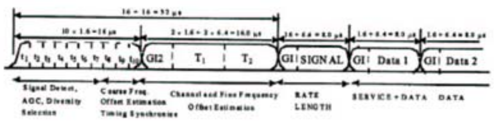
Channel Estimation

- In order to detect the bits, the effects of channel gains must be compensated
- The subcarrier channel gains are normally estimated using a preamble and pilot tones
- Simplest approach is to just divide the kth demodulated output by an estimate of

$$H\left(f_o+\frac{k}{T_U}\right)$$

Preamble Structure

- The Preamble comprises 12 training symbols, 10 short ones and 2 longer ones



Forward Error-Correction Coding (FEC)

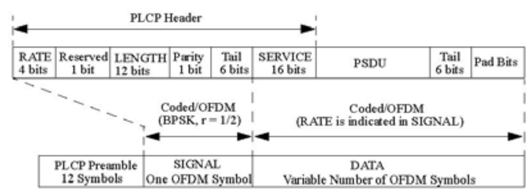
- The information is typically FEC encoded and interleaved prior to modulation
- The bits carried by faded subcarriers might be detected in error without the FEC
- With FEC and interleaving, erroneous bits may be correctable, thereby providing frequency diversity

Modes of DSRC/WAVE

- Modulation and Coding Rate depend on channel quality

Data Rate Mbits/s	Modulation	Coding Rate (R)	Coded Bits per Subcarrier (N_{BPSC})	Coded Bits per OFDM Symbol (N_{CBPS})	Data Bits per OFDM Symbols (N_{DBPS})
3	BPSK	1/2	1	48	24
4.5	BPSK	3/4	1	48	36
6	QPSK	1/2	2	96	48
9	QPSK	3/4	2	96	72
12	16-QAM	1/2	4	192	96
18	16-QAM	3/4	4	192	144
24	64-QAM	2/3	6	288	192
27	64-QAM	3/4	6	288	216

DSRC PPDU Structure



Summary

- OFDM is a multi-carrier modulation technique
- Each subcarrier carries BPSK, QPSK or QAM
- The subcarriers are so close, that each subcarrier sees a flat-faded channel
- The Guard Interval ensures that successive OFDM symbols do not interfere with each other
- FEC and interleaving provide frequency diversity
- OFDM modulation and demodulation is conveniently performed by fast DSP operations (FFT and IFFT)