OFDM Basics at 5 GHz

Magis Technical Forum

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Overview

- OFDM History
- OFDM for the Indoor Wireless Channel
- Basic OFDM Principles
- Some specifics for IEEE 802.11a OFDM
- Challenges posed by using OFDM
- Wrap-up and Q & A

(Factors that make Magis technology stand out compared to our competitors will be discussed in an upcoming Tech Forum session.)

OFDM History

- OFDM is an acronym for “orthogonal frequency division multiplex”
- OFDM or variants of it have found their way into a wide range of wireless and wired systems
  - DAB- Direct Audio Broadcast (Europe)
  - DVB-T- Digital TV (Europe)
  - HDTV Terrestrial
  - ADSL \ DSL \ VSDL
- Technique can be viewed as a frequency multiplexing method or a parallel data transmission method

OFDM History

- Some early developments date back to the 1950's
  - Mosier, R.R., R.G. Clabaugh, "Kineplex, a Bandwidth Efficient Binary Transmission System," AIEE Trans., Vol. 76, Jan. 1958
- Parallel data transmission and frequency division multiplexing began receiving attention primarily at Bell Labs in circa-1965
  - R.W. Chang, "Synthesis of Band Limited Orthogonal Signals for Multichannel Data Transmission," Bell Syst. Tech. J., Vol. 45, Dec. 1996
  - B.R. Salzberg, "Performance of an Efficient Parallel Data Transmission System," IEEE Trans. Comm., Vol. COM-15, Dec. 1967

OFDM History

- One of the earliest patents pertaining to OFDM was filed in 1970
  - "Orthogonal Frequency Division Multiplexing," U.S. Patent No. 3,488,455 filed Nov. 14, 1966, issued Jan. 6, 1970
- Early OFDM systems were extremely complicated and bulky.
- Major simplification resulted using the Fast Fourier Transform in transmitters and receivers
  - Weinstein, S.B., P.M. Ebert, "Data Transmission by Frequency Division Multiplexing Using the Discrete Fourier Transform," IEEE Trans. Comm., Vol. COM-19, Oct. 1971
  - Hirosaki, B., "An Orthogonally Multiplexed QAM System Using the Discrete Fourier Transform," IEEE Trans. Comm., Vol. COM-15, April 1967

OFDM for Indoor Wireless Channel

- Communication over the indoor wireless channel is made difficult due to the extreme multipath nature of the channel.
- The multipath factor is exasperated as range and data throughput rate are increased.
- Traditional single-carrier communication methods and even spread-spectrum (DSSS) techniques to a degree are greatly hampered by the indoor multipath channel.

OFDM for Indoor Wireless Channel

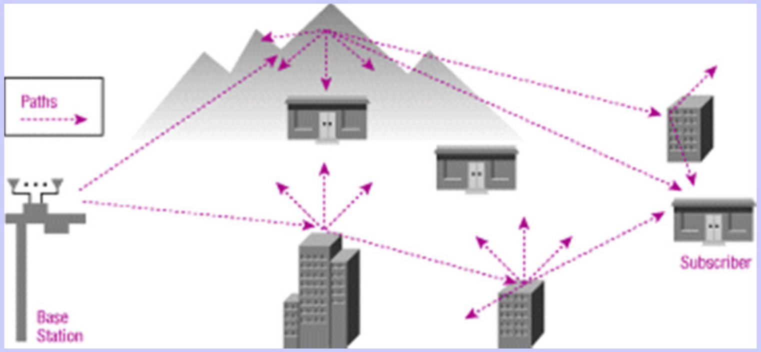
- OFDM Virtues for Indoor WLAN
  - Provides a theoretically optimal means to deal with frequency-selective fading that arises from multipath
  - Combats frequency-selective fading with a complexity level that is several orders of magnitude less than a conventional single-carrier with channel equalizer system
  - Capable of "optimal" bandwidth utilization in terms of bits-per-Hz throughput
  - Fundamentals still permit coherent signaling techniques to be used and the benefits associated with them (e.g., counter-example would be DPSK)
  - Proper design permits the data throughput rate to be varied over a wide range to support different range/throughput rate objectives.

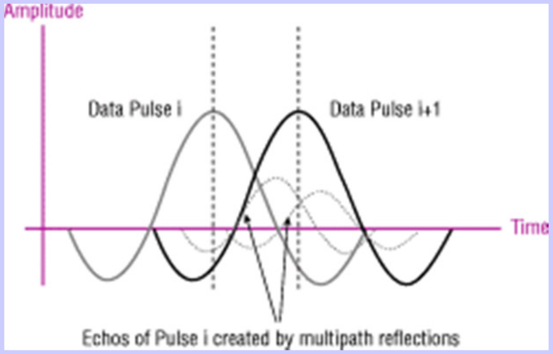
OFDM for Indoor Wireless Channel

- OFDM Challenges for WLAN
  - Transmitter peak-to-average-power-ratio PAPR is higher than other traditional single-carrier waveforms
  - Receiver complexity is high, as are requirements for (transmitter and receiver)linearity
  - Difficulty is amplified by our strategic objective to move unprecedented data throughput rates reliably over the indoor channel to support HDTV, etc.
  - Magis is patenting a wide range of algorithms and techniques to achieve our objectives thereby making it very difficult for competitors to follow

OFDM for Indoor Wireless Channel

- Multipath and the underlying (time) delay spread involved can cripple high-speed single-carrier communication systems





Multipath over a terrestrial channel is not unlike what we deal with indoors

Delay spread simply means that different frequency portions of the signal will reach the receiver at different times

OFDM for Indoor Wireless Channel

- The performance degradation due to channel-related delay spread becomes worse as the delay spread compared to each modulation symbol period becomes appreciable.

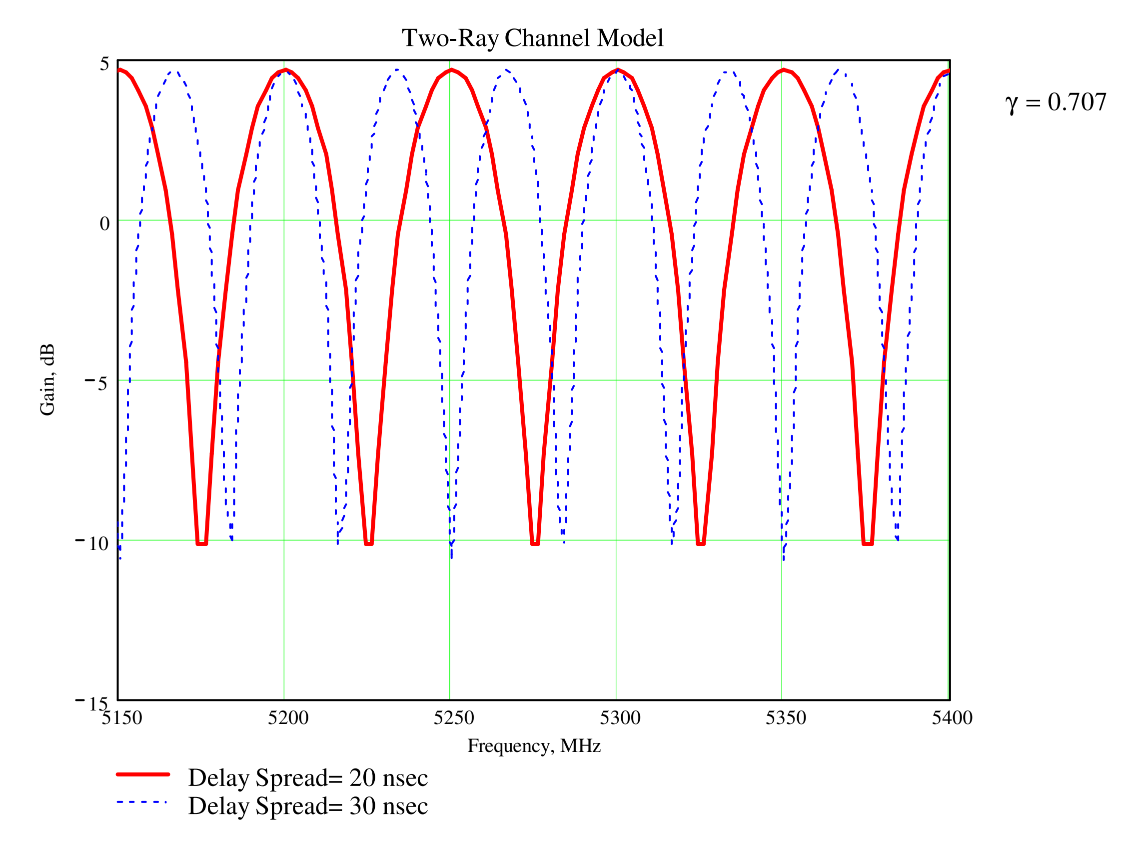
$$\frac{\tau_{Delay}}{T_{sym}} = \tau_{Delay} F_{sym} = DS$$ Normalized delay spread

- In a simple 2-ray multipath channel model, delay spread can be easily estimated based upon the spacing of attenuation peaks across the modulation bandwidth

$$G_{channel}(f) = 10 Log_{10}\left[\left|1+\gamma e^{j\left(2\pi f \tau_{dly}+\phi\right)}\right|^2\right]$$

OFDM for Indoor Wireless Channel

- Simple 2-ray multipath model reveals clear attenuation peaks and nulls across the RF frequency range
- In the indoor channel, many many multiple propagation paths co-exist.



OFDM for Indoor Wireless Channel

- Delay spread for a given office or home region is given approximately as

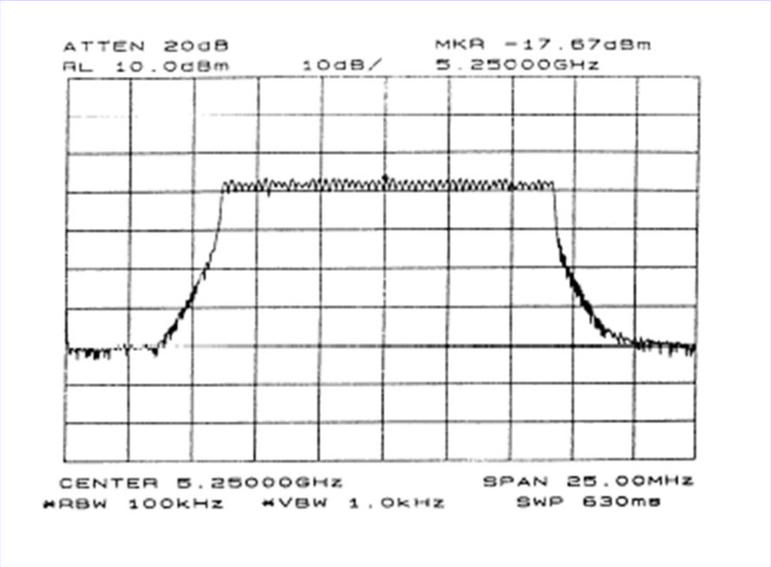
$$DelaySpread_{ns} \approx k\sqrt{FloorArea_{meters}} \quad rms\, n\sec$$

where k is given as typically 3 nsec/m to 4 nsec/m for office spaces; more on the order of 2 nsec/m in residential spaces

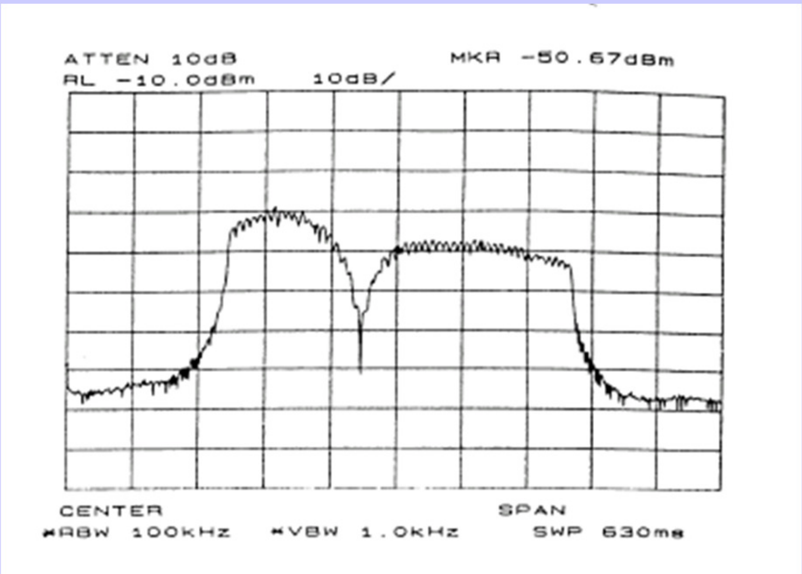
- Using this approximation, the delay spread for the third-floor at Magis is roughly 85 nsec rms.
- For IEEE 802.11a utilizing a symbol rate of 250 kHz, the normalized delay spread is small at 0.0212 rms whereas for a typical single-carrier system with a symbol rate of 5 MHz, the normalized delay spread would be 0.425 rms !

OFDM for Indoor Wireless Channel

- Multipath gives rise to frequency-selective channel attenuation and fading which translates to reduced theoretical system throughput capacity



Ideal flat transmitted RF spectrum at 5 GHz



Received signal spectrum due to frequency-selective nature of propagation channel

OFDM for Indoor Wireless Channel

- The theoretical throughput capacity (in the Shannon sense) for the channel can be computed as

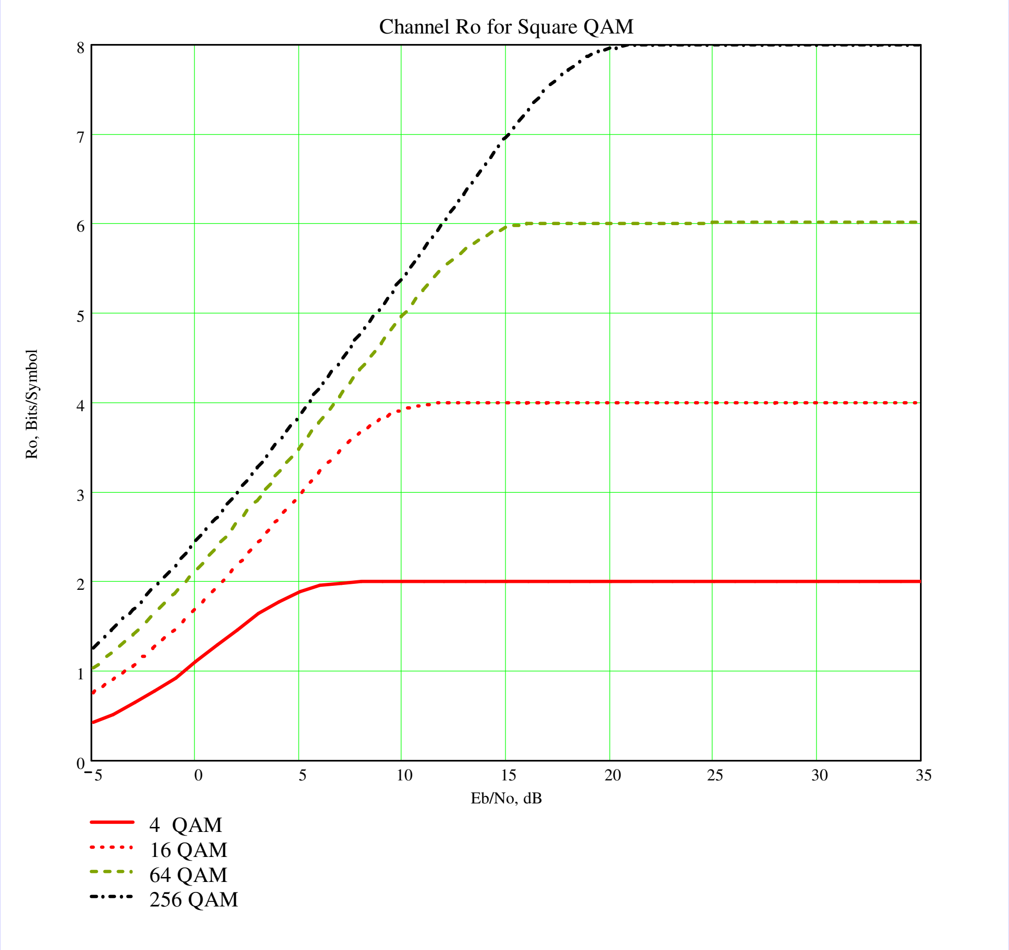
$$C = \int_{F_L}^{F_H} \log_2\left[1+\rho\left(f\right)\right]df$$

where $\rho(f)$ is the numerical signal-to-noise ratio of the received signal across the modulation bandwidth on a per-Hz basis.

- A more useful measure for our purposes is the composite channel cutoff rate which is customarily denoted by Ro because it takes into account the signal constellation type being used.

OFDM for Indoor Wireless Channel

- In the case of square quadrature-amplitude modulations (QAM) as in IEEE 802.11a, the cutoff rate is given by



$$R_o(N_o) = -Log_2\left[\frac{1}{M^2}\sum_{ki}\sum_{kj}\exp\left(\frac{\left\|S_{ki}-S_{kj}\right\|^2}{4N_o}\right)\right]$$

where N_o is the noise spectral density at the receiver and the S_{ki} are the ideal constellation points.

- This relationship can be summed versus SNR across the entire OFDM modulation bandwidth and an effective Ro computed.

Basic OFDM Principles: Orthogonality

- Orthogonality is a mathematical measure that can be defined in both the frequency and time domains.
- Orthogonality for real time-functions requires

$$\int_{-\infty}^{+\infty} x(t)\, y(t)\, dt = 0 \qquad \int_{-\infty}^{+\infty} X(t)\, Y^{*}(f)\, df = 0$$

Time Domain   Frequency Domain

- Fundamental estimation theory principles are based upon a similar orthogonality principle in the case where x and y are stochastic processes.

Basic OFDM Principles: Orthogonality

- Many possible choices for orthogonal set of signaling waveforms:
  - Sine and Cosine waves
  - Wavelets
  - Perfect-Reconstruction (PR) filter basis sets (e.g., cosine-modulated filter functions)
  - Raised-cosines
  - Eigen-functions of suitably defined linear systems
- The choice for the “best” orthogonal function set must be based upon (a) the channel involved and (b) complexity.
- It is desirable to have an orthogonal set of waveforms with the greatest cardinality possible because orthogonality is synonymous with dimensions. More dimensions translate into more communication throughput possible.

Basic OFDM Principles: Orthogonality

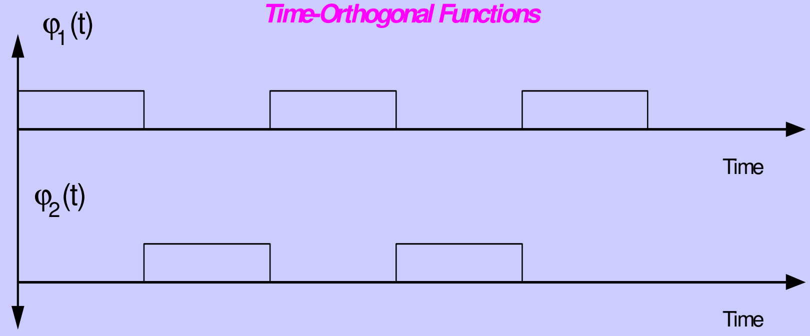
Dimensionality Theorem

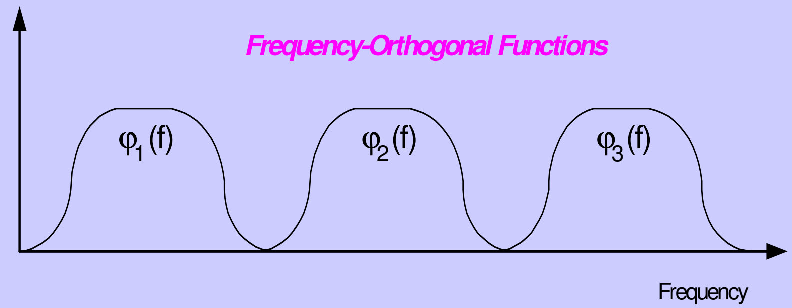
- Let $\{\varphi_j(t)\}$ denote any set of orthogonal waveforms of time duration T and "bandwidth" W. Require that each $\varphi_j(t)$ (1) be identically zero outside the time interval T, and (2) have no more than 1/12 of its energy outside the frequency interval of –W to +W.
- Then the number of different waveforms in the set $\{\varphi_j(t)\}$ is overbounded by 2.4WT when TW is large.

- Bottom line is that the theoretical number of available dimensions per unit time is limited

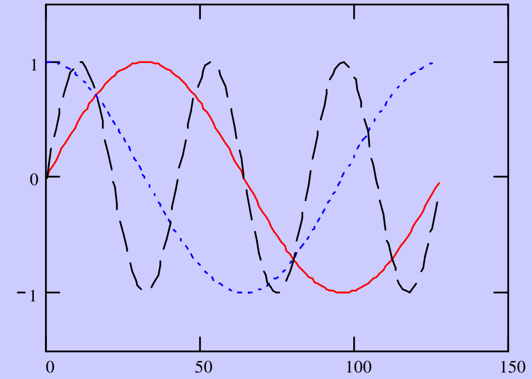
Basic OFDM Principles: Orthogonality

Simple examples of some orthogonal function pairs:

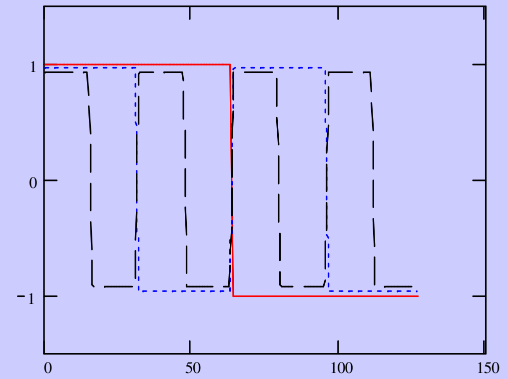




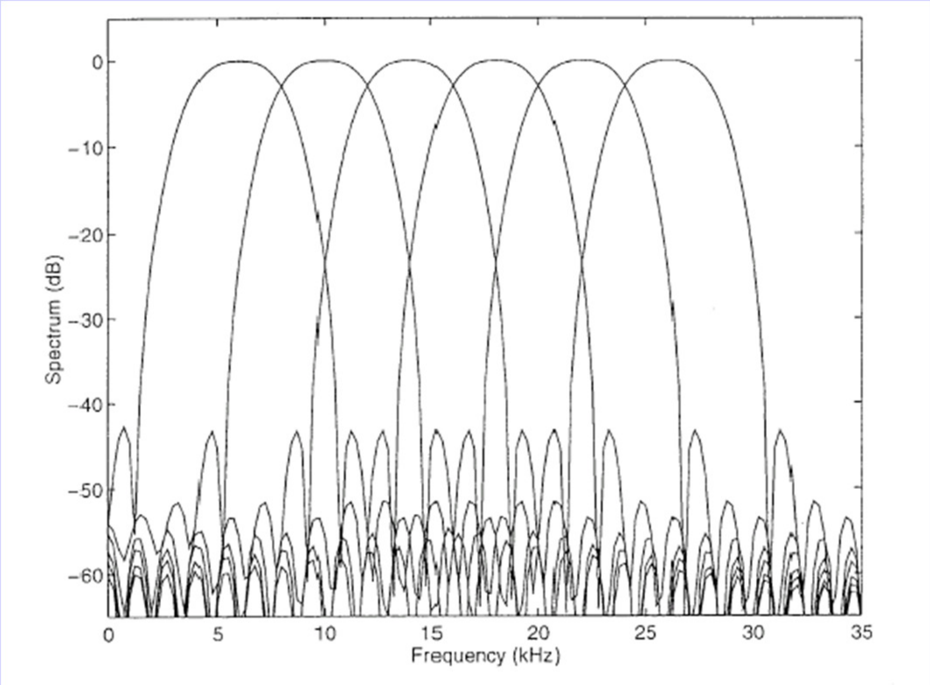
- Orthogonal sines and cosines



- Haar Wavelets



Basic OFDM Principles: Orthogonality



- Waveform spectra can still overlap and be orthogonal
- Example shown here is from Aware Technologies who advocated wavelet-based DSL signaling in the early 1990's

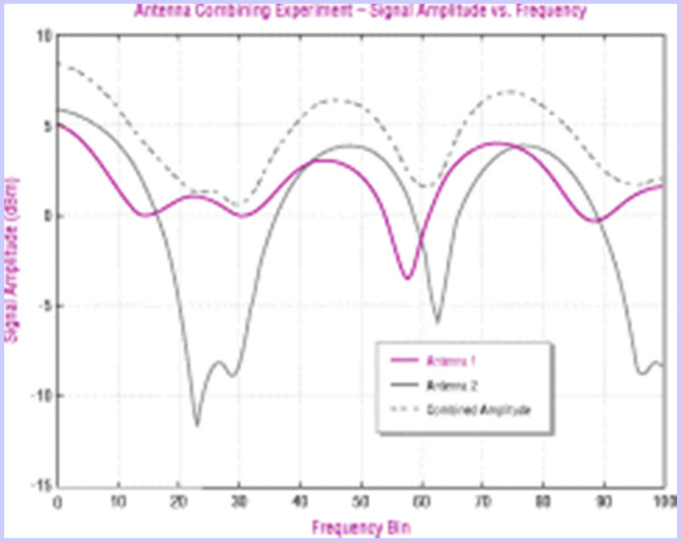
- The frequency bins in IEEE 802.11a also appear to overlap unless Nyquist filtering (i.e., using appropriate FFT) is used.

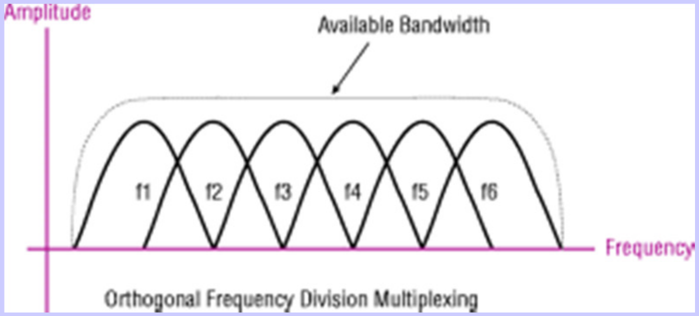
Basic OFDM Principles: Orthogonality

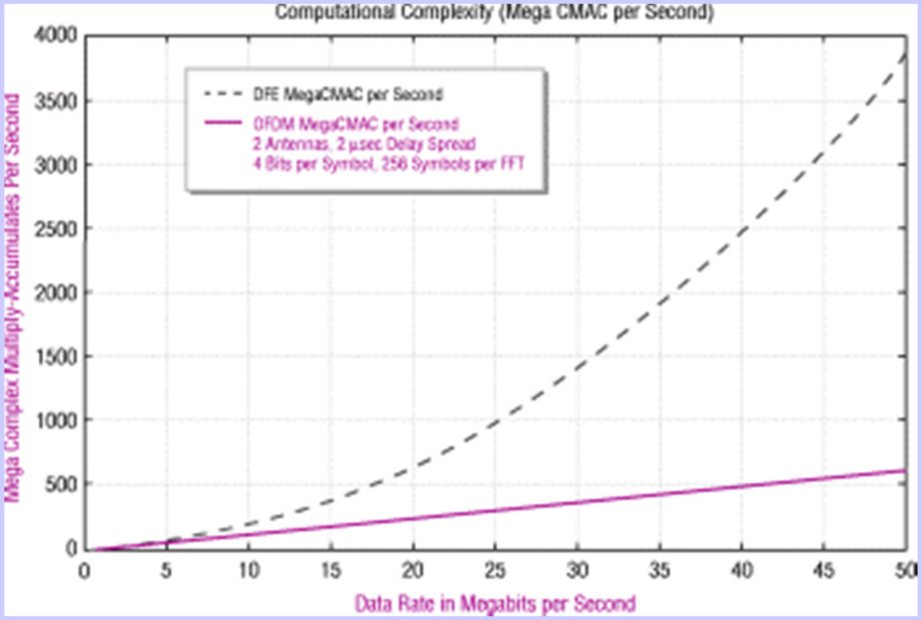
IEEE 802.11a OFDM utilizes sine and cosine signals spaced in frequency by precisely 312.5 kHz as its orthogonal basis function set

- Basis set is easily constructed on transmit and dimensionally separated on receive using the highly efficient FFT
- Use of a guard interval in front of every OFDM symbol largely defeats the delay spread problems by making the multipath appear to be cyclic
- Each basis function is tightly contained in frequency extent making it possible to equalize the amplitude of each OFDM frequency "bin" using simple scalar equalization
- Throughput rates are easily scaled versus range requirements.

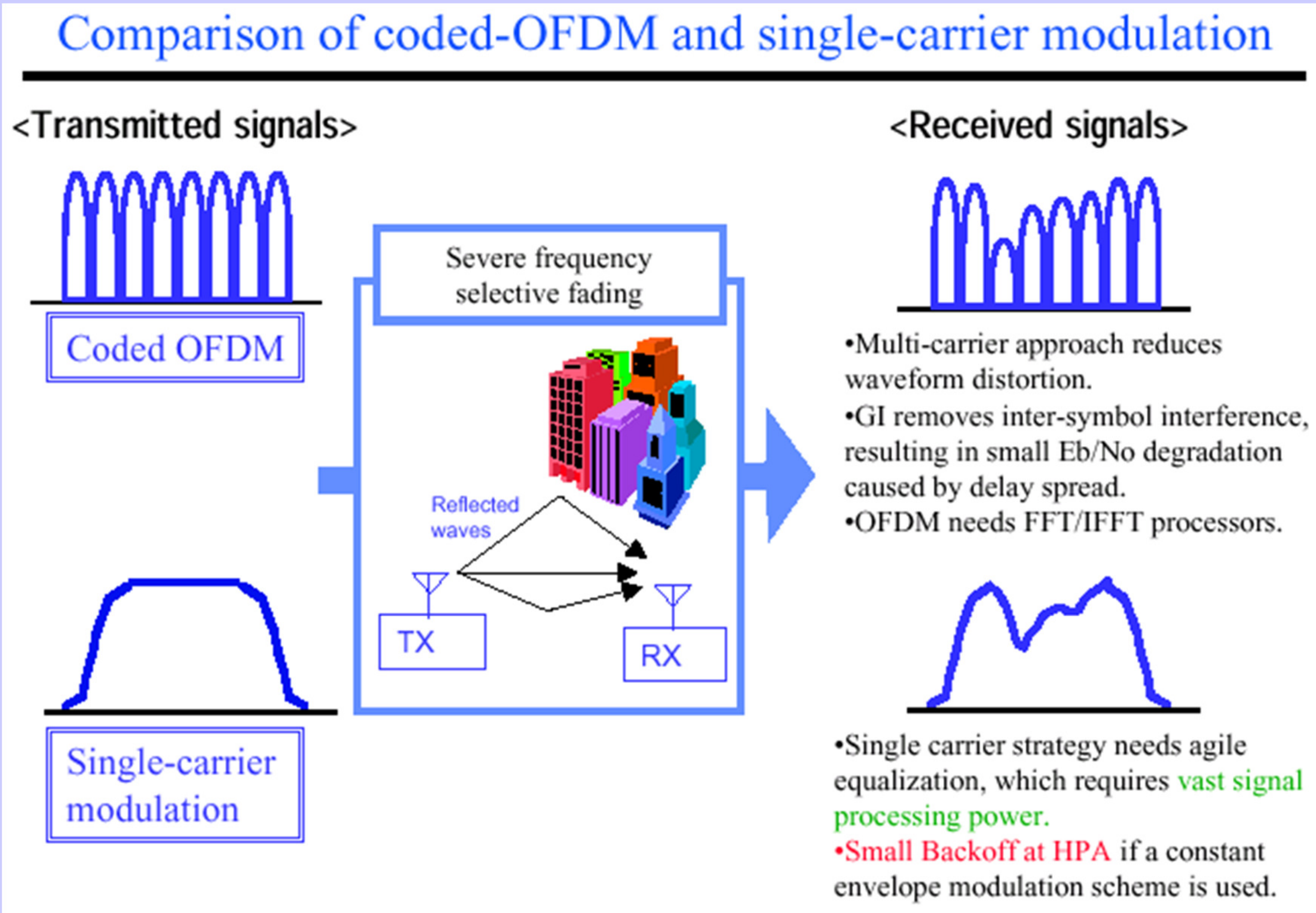
Basic OFDM: Dealing with Frequency-Selective Multipath





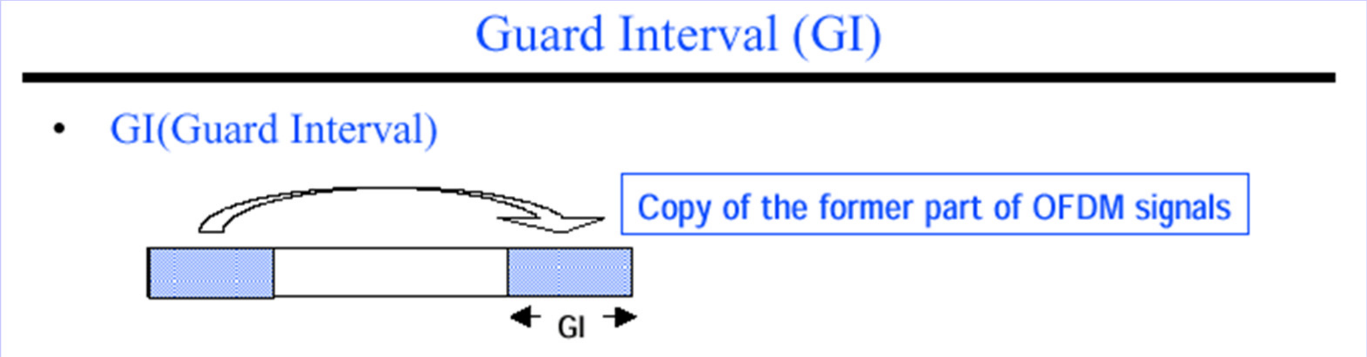


Basic OFDM: Dealing with Frequency-Selective Multipath

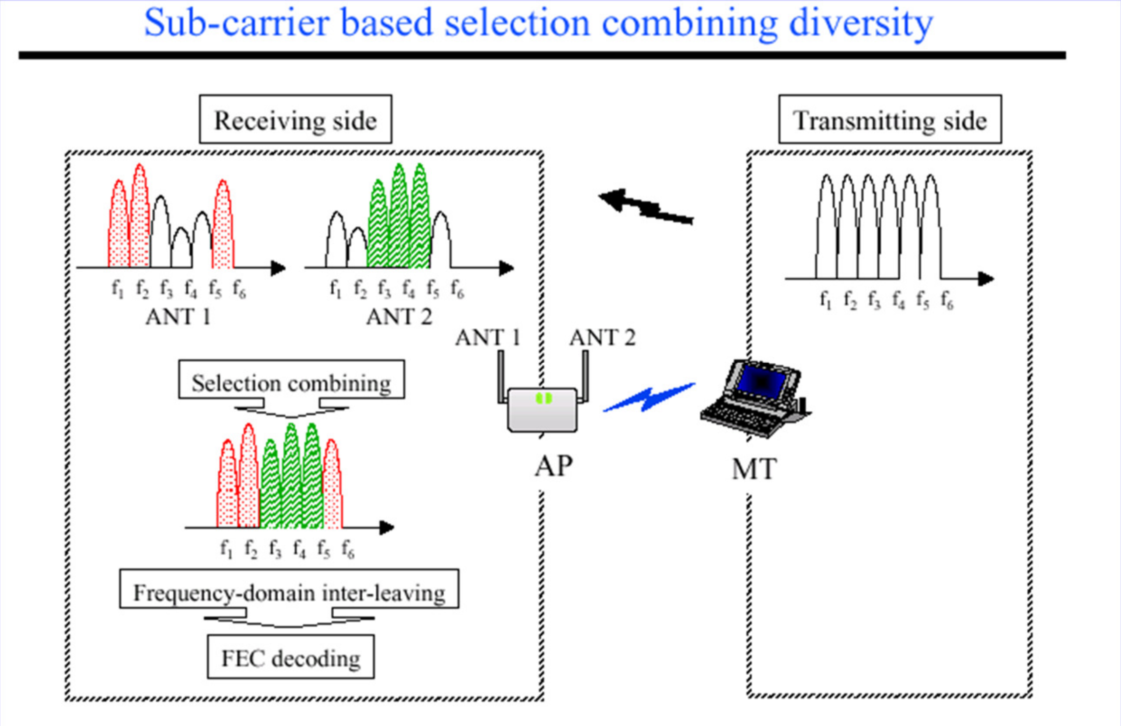


Basic OFDM: Dealing with Frequency-Selective Multipath

- OFDM very effectively combats inter-symbol interference from adjacent OFDM symbols by using a time guard interval
- For suitably bounded signal delays, the guard interval guarantees that the perfect sinusoidal nature of each symbol is preserved (i.e., no loss of orthogonality between OFDM subcarrier tones.



Basic OFDM: Dealing with Frequency-Selective Multipath



- Many different techniques have been proposed to diminish the degradations due to frequency-selective channels
- OFDM lends itself to many possibilities in this regard.
- One concept proposed by MMAC (Wireless 1394 in Japan) makes use of selection combining in the frequency space to achieve diversity
- Gains from diversity dwarf the additional gains that could be achieved with only more sophisticated FEC

Basic OFDM: Range & Throughput

- Predicting range for the indoor channel is very difficult due to multipath and absorption losses in non-line-of-sight (NLOS) communications
- First-order model makes use of the long-standing Friis formula for range:

$$R = \left[SNR \frac{F \; Bw \, N_o \left(\frac{4\pi}{\lambda} \right)^2}{P_T G_T G_R} \right]^{-\frac{1}{n}}$$

n=2 for free-space

n= 2.5 to 3.0 typical indoors due to multipath

SNR= Numerical signal-to-noise ratio

F= Noise Factor

Bw= Modulation Bandwidth, Hz

N_o= Noise Power Spectral Density

P_T= Transmit Power

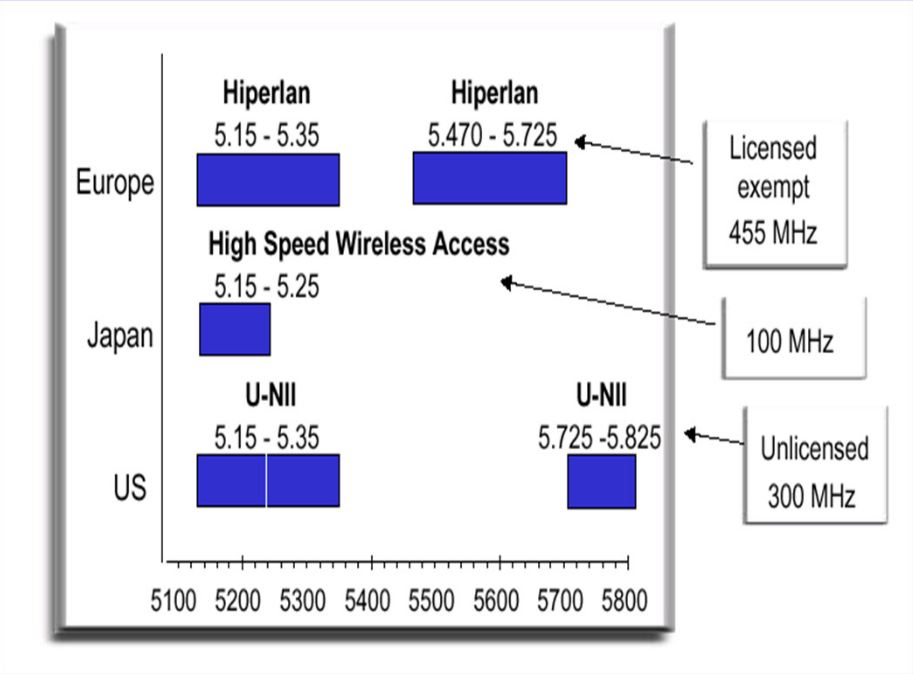
G_T= Transmit Antenna Gain

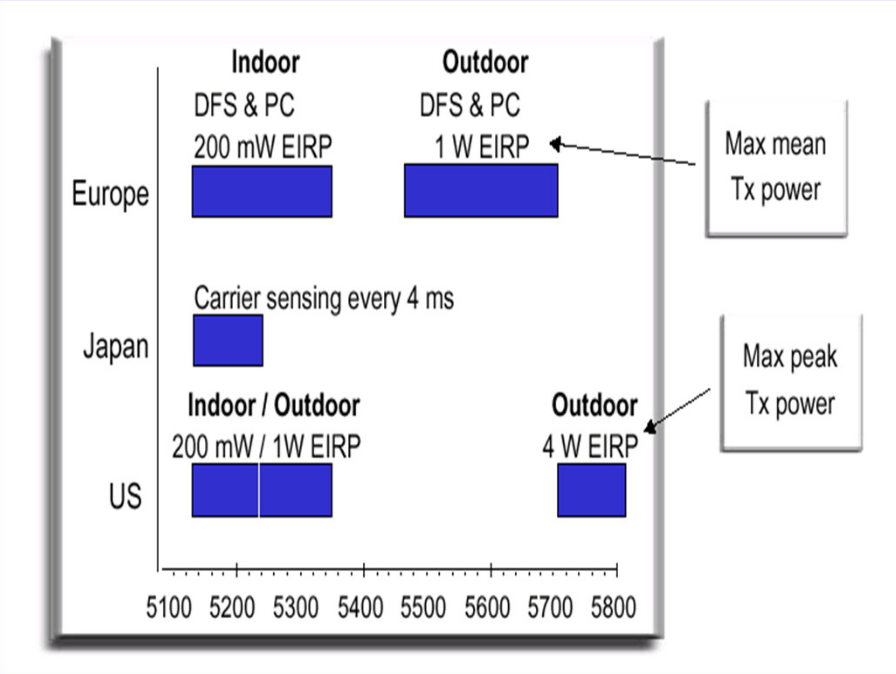
G_R= Receive Antenna Gain

n= Range loss exponent

IEEE 802.11a OFDM Specifics

IEEE 802.11a is attractive because (a) its available bandwidth makes all forms of communication (notably video) possible, and (b) overlapping frequency allocations exist world-wide making for a huge business opportunity.





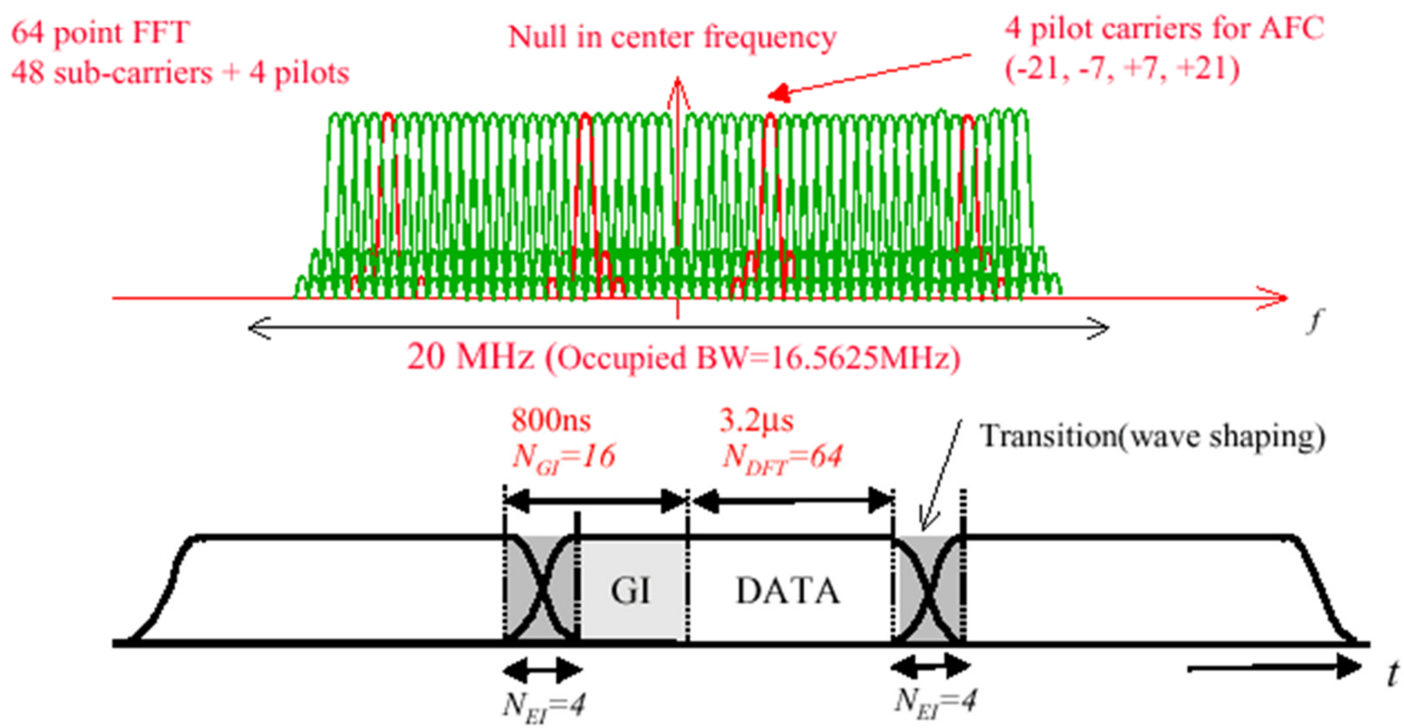
IEEE 802.11a OFDM Specifics

- IEEE 802.11a is a physical-layer (PHY) specification only

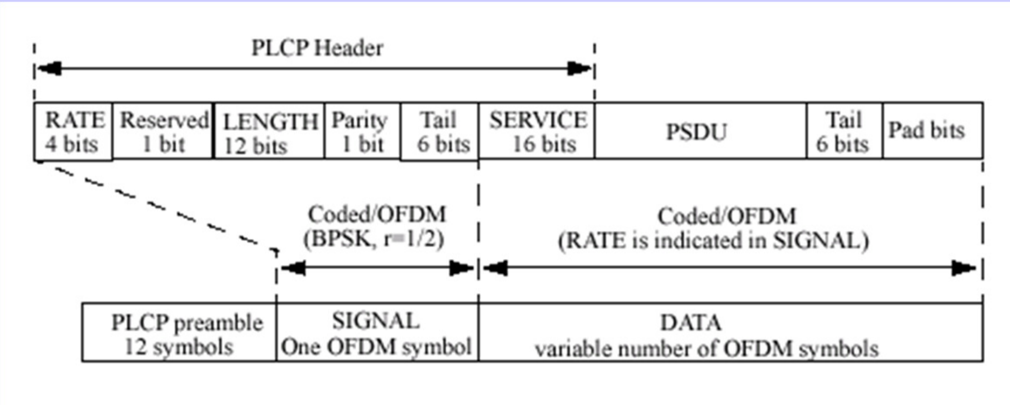
Major parameters of coded OFDM

Common 5GHz PHY for MMAC-HiSWAN, ETSI-BRAN, and IEEE802.11a

- Coded OFDM with R=1/2, K=7 convolutional coding and its punctured coding
- Channel spacing: 20MHz



IEEE 802.11a OFDM Specifics



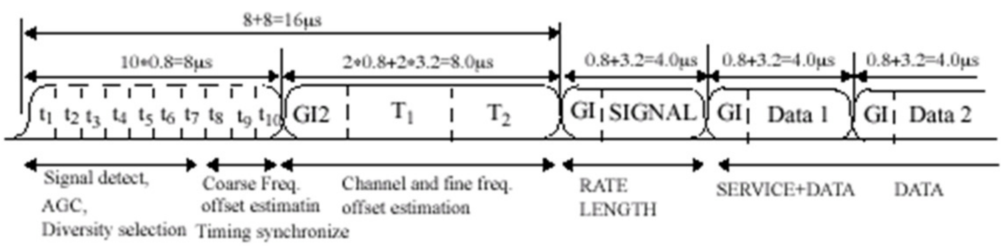
"Straight" IEEE 802.11a MAC frame structure. Magis has made some important enhancements in this area.

Data Rate	Modulation	Coding rate R	coded bits per subcarrier N_{BPSC}	coded bits per OFDM symbol N_{CBPS}	data bits per OFDM symbol N_{DBPS}
6 Mbit/s	BPSK	1/2	1	48	24
9 Mbit/s	BPSK	3/4	1	48	36
12 Mbit/s	QPSK	1/2	2	96	48
18 Mbit/s	QPSK	3/4	2	96	72
24 Mbit/s	16QAM	1/2	4	192	96
36 Mbit/s	16QAM	3/4	4	192	144
48 Mbit/s	64QAM	2/3	6	288	192
54 Mbit/s	64QAM	3/4	6	288	216

"Straight" IEEE 802.11a PHY-mode chart. Magis has made additional enhancements possible in this area as well.

IEEE 802.11a OFDM Specifics

The OFDM physical layer waveform is considerably more complex than cellular phone type waveforms.

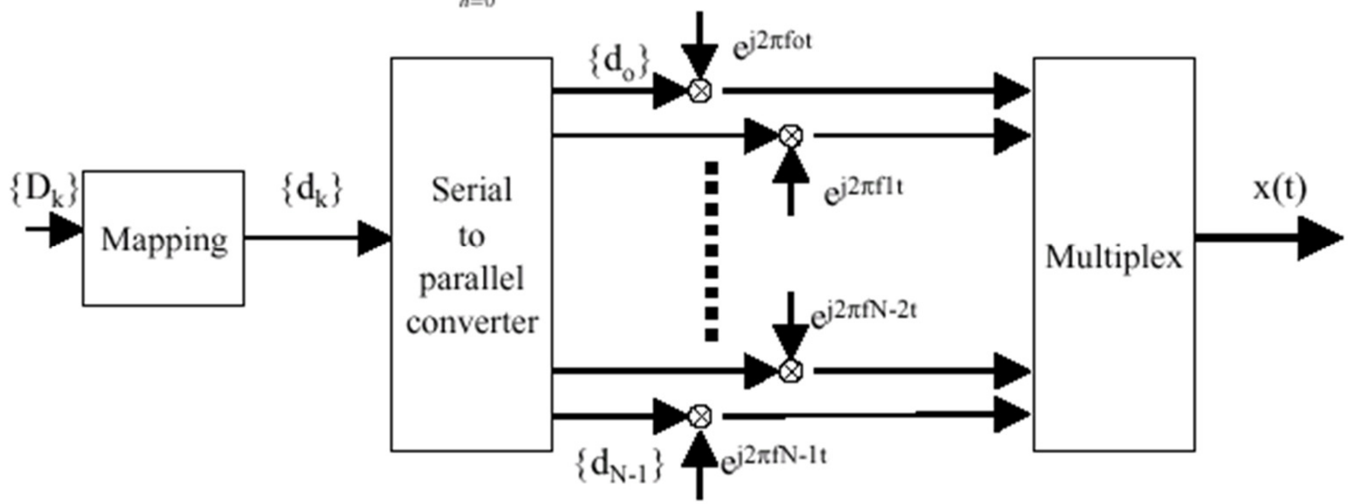


Parameter	Value
N_{SD} : Number of data subcarriers	48
N_{SP} : Number of pilot subcarriers	4
N_{ST} : Number of subcarriers, total	52 ($N_{SD} + N_{SP}$)
Δ_F : Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
T_{FFT} : IFFT/FFT period	3.2 μs ($1/\Delta_F$)
$T_{PREAMBLE}$:PLCP preamble duration	16 μs ($T_{SHORT}+ T_{LONG}$)
T_{SIGNAL} :duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{GI} + T_{FFT}$)
T_{GI} : Guard Interval duration	0.8 μs ($T_{FFT}/4$)
T_{GI2} : Training symbol Guard Interval duration	1.6 μs ($T_{FFT}/2$)
T_{SYM} : Symbol interval	4 μs ($T_{GI} + T_{FFT}$)
T_{SHORT} : short training sequence duration	8 μs ($10*T_{FFT}/4$)
T_{LONG} :long training sequence duration	8 μs ($T_{GI2} + 2*T_{FFT}$)

IEEE 802.11a OFDM Specifics

Principle of OFDM

- OFDM (Orthogonal Frequency Division Multiplexing)
  - Multi-carrier system by using IFFT for frequency multiplexing and FFT for frequency de-multiplexing instead of a set of frequency up-converters and down-converters
- Multiplexing : $x(n\Delta T) = \sum_{k=0}^{N-1} \{ d_k \cdot e^{j2\pi \frac{nk}{N}} \}$
- Demultiplexing : $d_k = \sum_{n=0}^{N-1} \{ x(n\Delta T) . e^{-j2\pi \frac{nk}{N}} \}$



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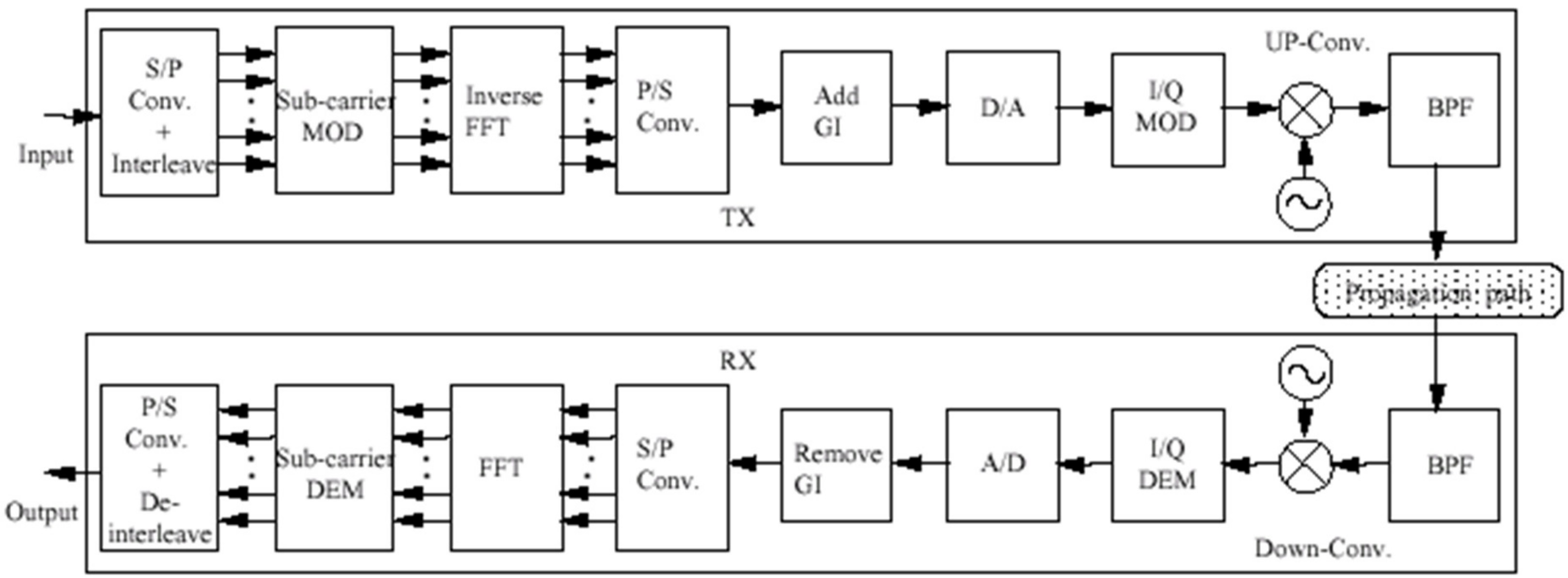
IEEE 802.11a OFDM Specifics

Schematic block diagram of OFDM modem

- TX: Sub-carrier modulation + Complex Inverse FFT (Multiplexer)
- RX: Complex FFT (Demultiplexer) + Sub-carrier demodulation



IEEE 802.11a OFDM Specifics

Minimal PHY functionality required in an IEEE 802.11a receiver:

- Preamble signal detection & AGC estimation
- Coarse and fine frequency estimation
- Fine time estimation
- Channel estimation (From T1 & T2)
- Selective channel filtering
- Frequency and phase tracking
- Guard-time removal
- Demodulation (i.e., FFT)
- Channel equalization
- Signal constellation de-mapping
- Viterbi convolutional decoding
- De-interleaving

Challenges Posed by OFDM

- Most of the challenges we presently face are due to higher throughput and Quality-of-Service (QoS) performance we seek to deliver compared to data-only providers.
- If we were doing what "everyone else" is doing, we would probably already be done.
- Chief challenges include:
  - Transmit
    - OFDM's inherently higher PAPR
    - RF linearity, primarily power amplifier
  - Receive
    - Frequency and time tracking
    - Extreme multipath scenarios
    - Sophisticated diversity techniques that go far beyond anything contemplated in IEEE 802.11a (needed for QoS and link robustness)
    - General complexity
  - MAC
    - Delivering graded QoS for many different services
    - Anticipating future growth needs & opportunities
    - Range and power control (for dense deployments)
    - General complexity