Channel Surfing

Managing Propagation in Broadband Wireless Systems

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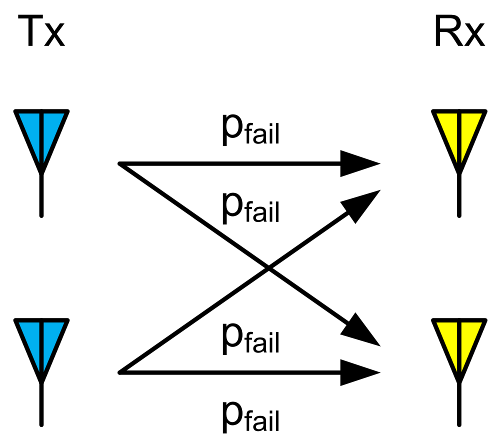
Outline

- Wireless Channels
- OFDM Modulation
- OFDMA Multiple Access in WiMAX Systems
- Implementation Challenges: What Limits Orthogonality
- Summary

The Mobile Broadband Wireless Channel

- Mobile broadband wireless channels have a number of unattractive attributes
  - Slow large-scale fades (shadow fading)
  - Fast small-scale fades (Rayleigh fading)
  - Frequency-selective due to multipath
  - Time-varying due to mobility
- The defining issue for mobile broadband is how to manage the channel while providing ever increasing data rates
- But, it’s not all bad news…
  - Frequency-selective channels have some benefits:
    - ➢Channel diversity
    - ➢Spatial multiplexing (e.g. spatial rate 2 MIMO)
- In broadband systems we take advantage of these characteristics to achieve higher throughputs and link diversity



$$p_{fail,tot} = p_{fail}^4 << p_{fail}$$

Path Loss Due to Fading

$$L_p(d) = 10\log_{10}\left(\frac{4\pi d_0}{\lambda}\right)^2 + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma + X_\rho$$

Path loss between isotropic antennas

Free-space loss to ref. distance, d_0

d^n loss from d_0 to d

Log-normal random variable (Shadow Fading)

Rayleigh distributed random variable (Rayleigh Fading)

- Shadow fading describes the attenuation of received power due to large-scale effects
  - Buildings, foliage, ground reflections, etc…
  - Path loss typically increases as d^n, where n~3-5.
  - Log-normal random component, with std-deviation of 8dB or greater!
- Rayleigh fading is a small-scale effect occurring due to carrier summation among multipath components
  - Fast fading in single-carrier systems occurs roughly every $\lambda/2$ distance
  - Multi-carrier systems take advantage of reduced correlation across frequency
  - 20-30dB needs to be budgeted for Rayleigh fades

Shadow Fading Example

- Measurements taken in and around eight suburban homes.
- CW @ 815MHz
- Dipole RX & TX antennas

- Measurement results show:
  - Distance exponent ~3.5-5.5
  - Log-normal σ ~ 10dB
  - Signal levels @ 1000ft ~ 27dB below what free-space propagation would predict

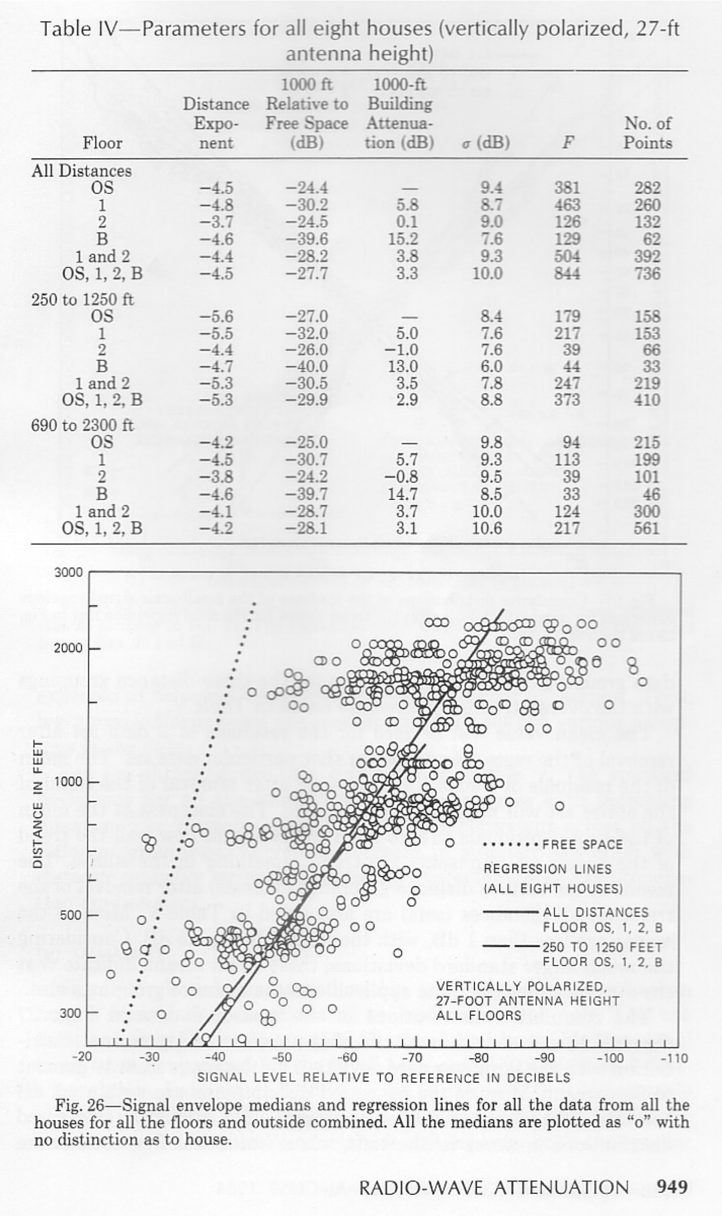


Table IV—Parameters for all eight houses (vertically polarized, 27-ft antenna height)

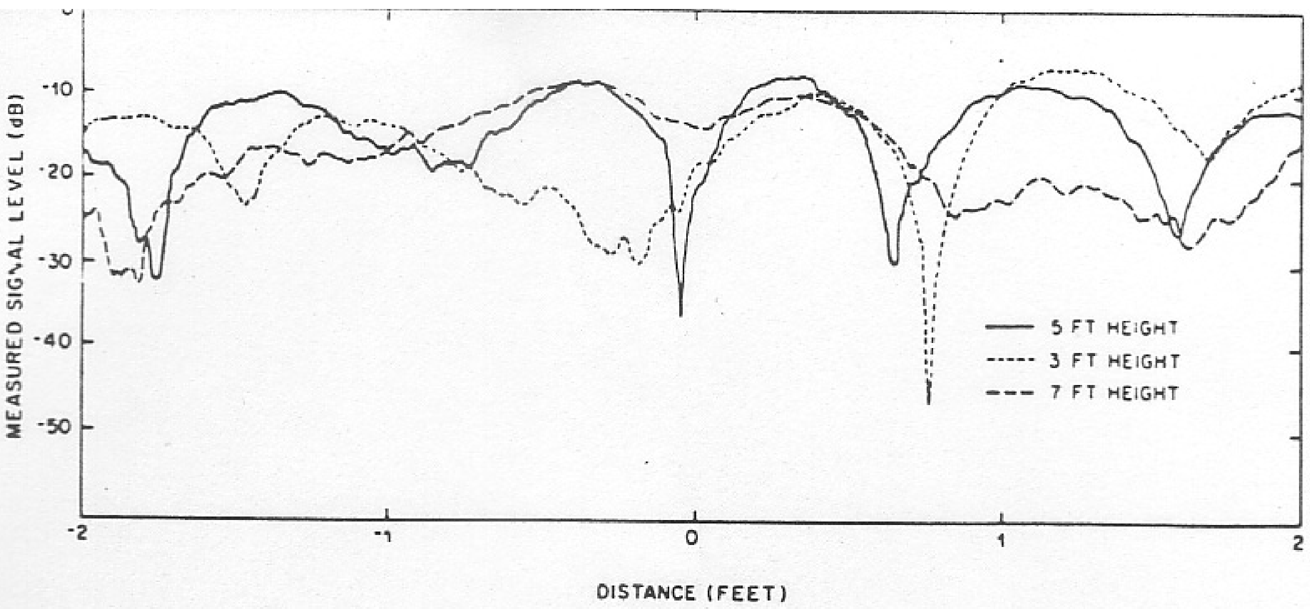
Floor	Distance Exponent	1000 ft Relative to Free Space (dB)	1000-ft Building Attenuation (dB)	σ (dB)	*F*	No. of Points
All Distances						
OS	−4.5	−24.4	—	9.4	381	282
1	−4.8	−30.2	5.8	8.7	463	260
2	−3.7	−24.5	0.1	9.0	126	132
B	−4.6	−39.6	15.2	7.6	129	62
1 and 2	−4.4	−28.2	3.8	9.3	504	392
OS, 1, 2, B	−4.5	−27.7	3.3	10.0	844	736
250 to 1250 ft						
OS	−5.6	−27.0	—	8.4	179	158
1	−5.5	−32.0	5.0	7.6	217	153
2	−4.4	−26.0	−1.0	7.6	39	66
B	−4.7	−40.0	13.0	6.0	44	33
1 and 2	−5.3	−30.5	3.5	7.8	247	219
OS, 1, 2, B	−5.3	−29.9	2.9	8.8	373	410
690 to 2300 ft						
OS	−4.2	−25.0	—	9.8	94	215
1	−4.5	−30.7	5.7	9.3	113	199
2	−3.8	−24.2	−0.8	9.5	39	101
B	−4.6	−39.7	14.7	8.5	33	46
1 and 2	−4.1	−28.7	3.7	10.0	124	300
OS, 1, 2, B	−4.2	−28.1	3.1	10.6	217	561

Fig. 26—Signal envelope medians and regression lines for all the data from all the houses for all the floors and outside combined. All the medians are plotted as "o" with no distinction as to house.

RADIO-WAVE ATTENUATION 949

Donald C. Cox, R.R. Murray and A.W. Norris, "800-MHz Attenuation Measured In and Around Suburban Houses," AT&T Bell Laboratories Technical Journal, vol. 63, no. 6, July-August 1984, pp.921-954.

Rayleigh Fading Example



3. Typical Signal Scan

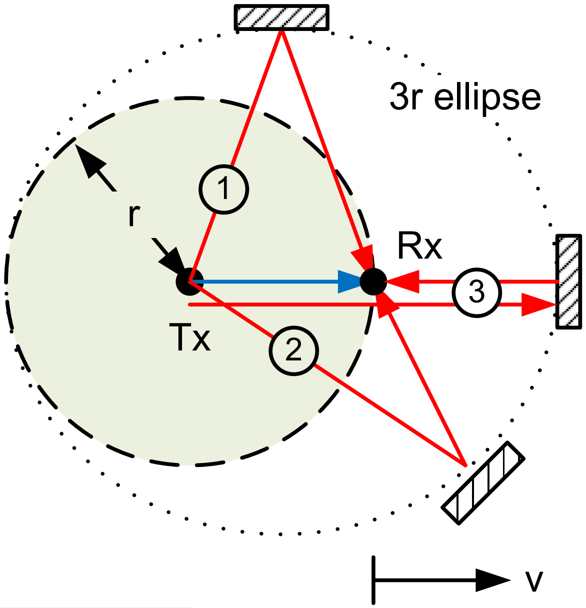
Fig. 7. Small-scale variations of a narrow-band signal at 900 MHz as an antenna is moved at different heights in the multipath environment within a building.

- Indoor measurements @ 900MHz
- Fades as deep as 30dB observed
- Note the small distance scale over which signal levels vary

Donald C. Cox, “Universal Digital Portable Radio Communications,” Proceedings of the IEEE, vol. 75, no. 4, April 1987, pp.436-477.

Effects of Multipath

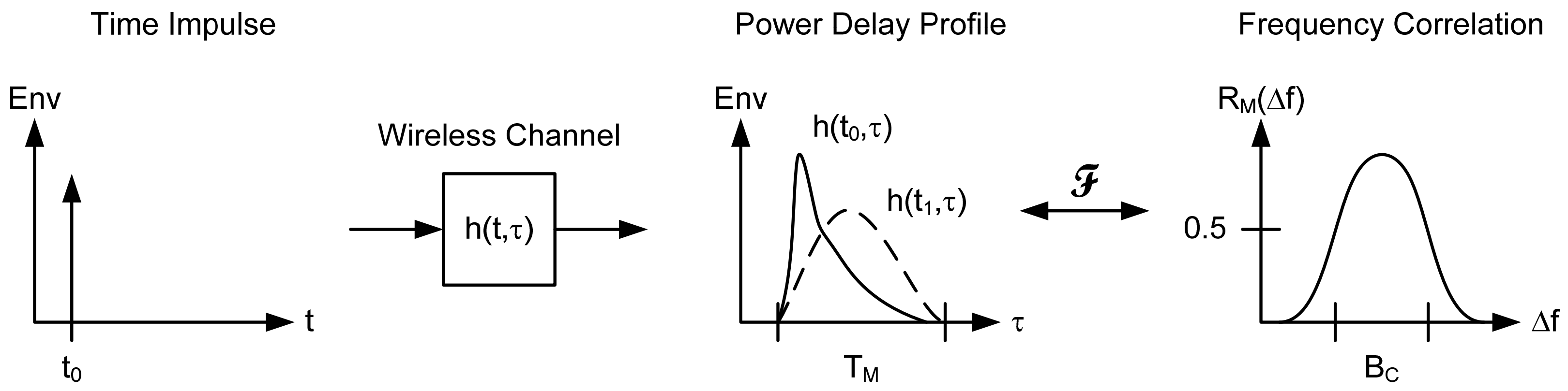
- Multiple paths from Tx converge on Rx
  - Each path has different delay (ISI)
  - Each path has different carrier phase (Rayleigh fading)
- Reflections occurring beyond the cell boundary can be significant
  - Assume d^4 roll-off
  - Path loss along 3x nominal length rays is about -20dB relative to the direct path.
  - Delay-spread due to 3x path lengths:
- Motion of the Rx antenna
  - All paths experience Doppler shift
  - Worst-case Doppler spread due to velocity v away from Tx antenna and toward a reflecting object:



$$\boxed{T_{M,3x} = \frac{2r}{c}}$$

$$\boxed{2f_D = \frac{2v}{\lambda}}$$

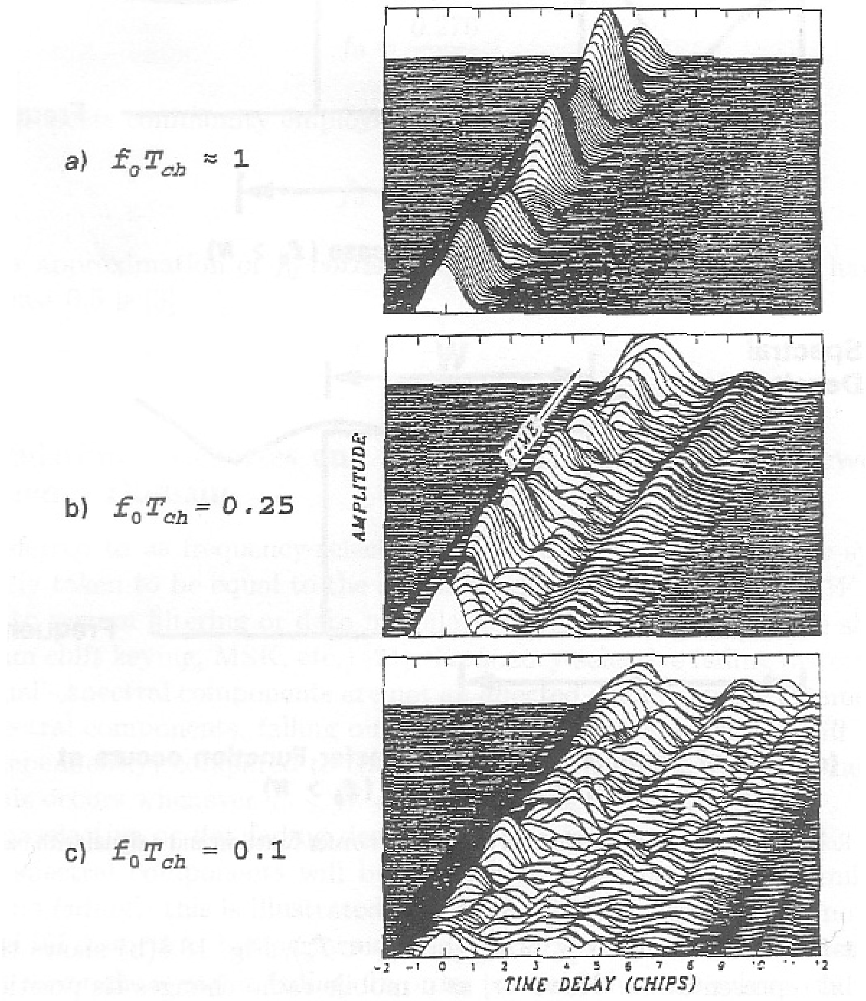
Multipath, Delay Spread and Coherence BW



Coherence BW: $\boxed{B_C \approx \frac{1}{4\sigma_T}}$

- Wireless channel has a time-varying impulse response.
  - Power delay profile gives the long-term response w/ expected power at each tap
- Received signals are spread in time.
  - Maximum delay spread, T_M, determined by the range of path lengths
  - RMS delay spread, σ_T, is a common metric
  - This causes ISI – inter-symbol interference
- Coherence BW is the width of the power spectrum of the impulse response
  - Gives a measure of the bandwidth of signals that can be sent over the channel without equalization.

Delay Spread Examples



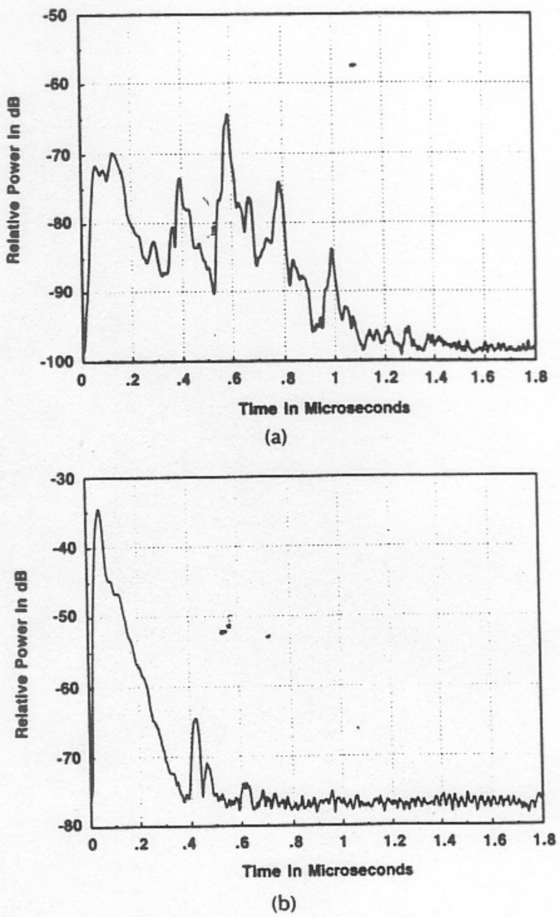
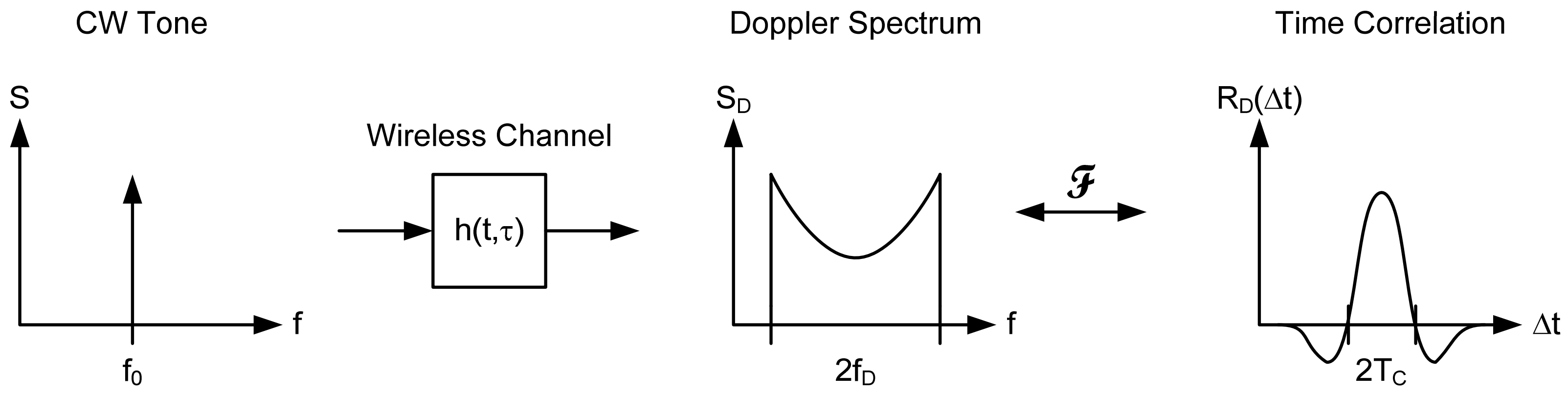


Fig. 6. (a) Average relative power received as a function of time delay for an 850-MHz probing transmitter and receiver located in different places in a large building. The transmitter and receiver locations were obscured from each other by walls. (b) Average relative power received as a function of time delay similar to Fig. 6(a). For Fig. 6(b), the transmitter and receiver were located in different places in the building than they were for Fig. 6(a).

[1] B. Sklar, “Rayleigh Fading Channels,” in The Mobile Communications Handbook, CRC Press, 1999, pp. 18-1 to 18-39.
[2] Donald C. Cox, “Universal Digital Portable Radio Communications,” Proceedings of the IEEE, vol. 75, no. 4, April 1987, pp.436-477.

Time-Variance, Doppler Spectrum and Coherence Time



Coherence Time: $\boxed{T_C \approx \frac{1}{2f_D}}$

- Dual of delay spread test: Apply a CW tone to the channel
  - "Frequency-domain impulse"
- Received signals are spread in frequency.
  - Maximum frequency spread, f_D, determined by the Doppler shift
  - This causes ICI – inter-carrier interference
- Coherence time is the spacing between zero-crossings of the time autocorrelation function
  - Gives a measure of the interval over which the channel appears to be time-invariant.

Dense-Scatterer Model Doppler Spectrum

Uniformly distributed angle of arrival

$$\langle P_R\rangle = 2\int_{-\pi/2}^{\pi/2}\frac{P_R}{2\pi}\,d\alpha$$

Doppler shift w/ Velocity V

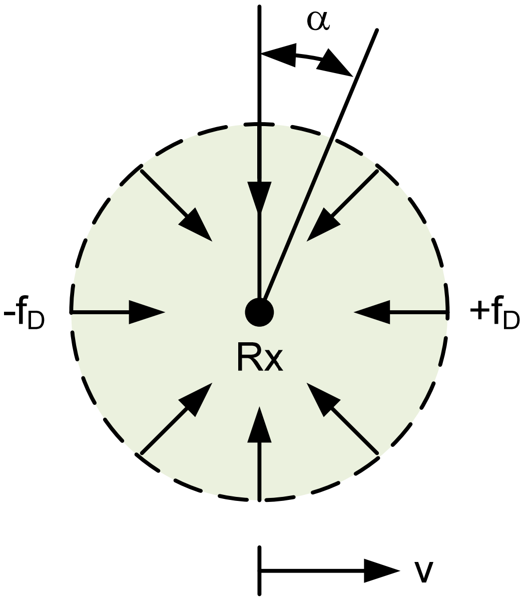
$$\Delta f = \frac{v}{\lambda}\sin\alpha = f_D\sin\alpha$$

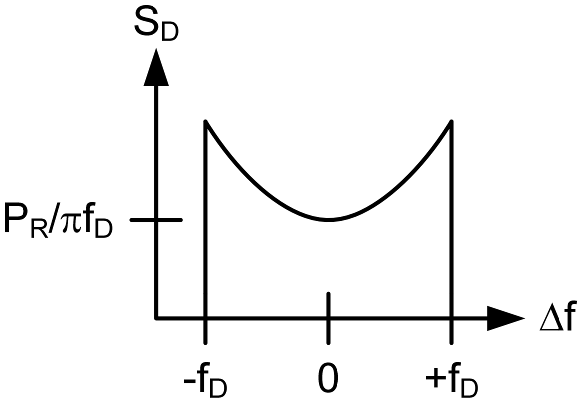
Change of variables yields integral over Δf

$$\langle P_R\rangle = \int_{-f_D}^{f_D}\frac{P_R}{\pi f_D\sqrt{1-\frac{\Delta f^2}{f_D^2}}}\,d\Delta f$$

Doppler spectrum:

$$\boxed{S_D(\Delta f) = \frac{P_R}{\pi f_D\sqrt{1-\frac{\Delta f^2}{f_D^2}}}}$$





Scattering Functions

- Wireless channels scatter energy in both *frequency* and *time*.

- Scattering Function:

$$S(\tau,\nu)$$

- Delay Power Spectrum:

$$S(\tau)=\int_{-\infty}^{\infty} S(\tau,\nu)d\nu$$

- Doppler Power Spectrum:

$$S(\nu)=\int_{0}^{\infty} S(\tau,\nu)d\tau$$

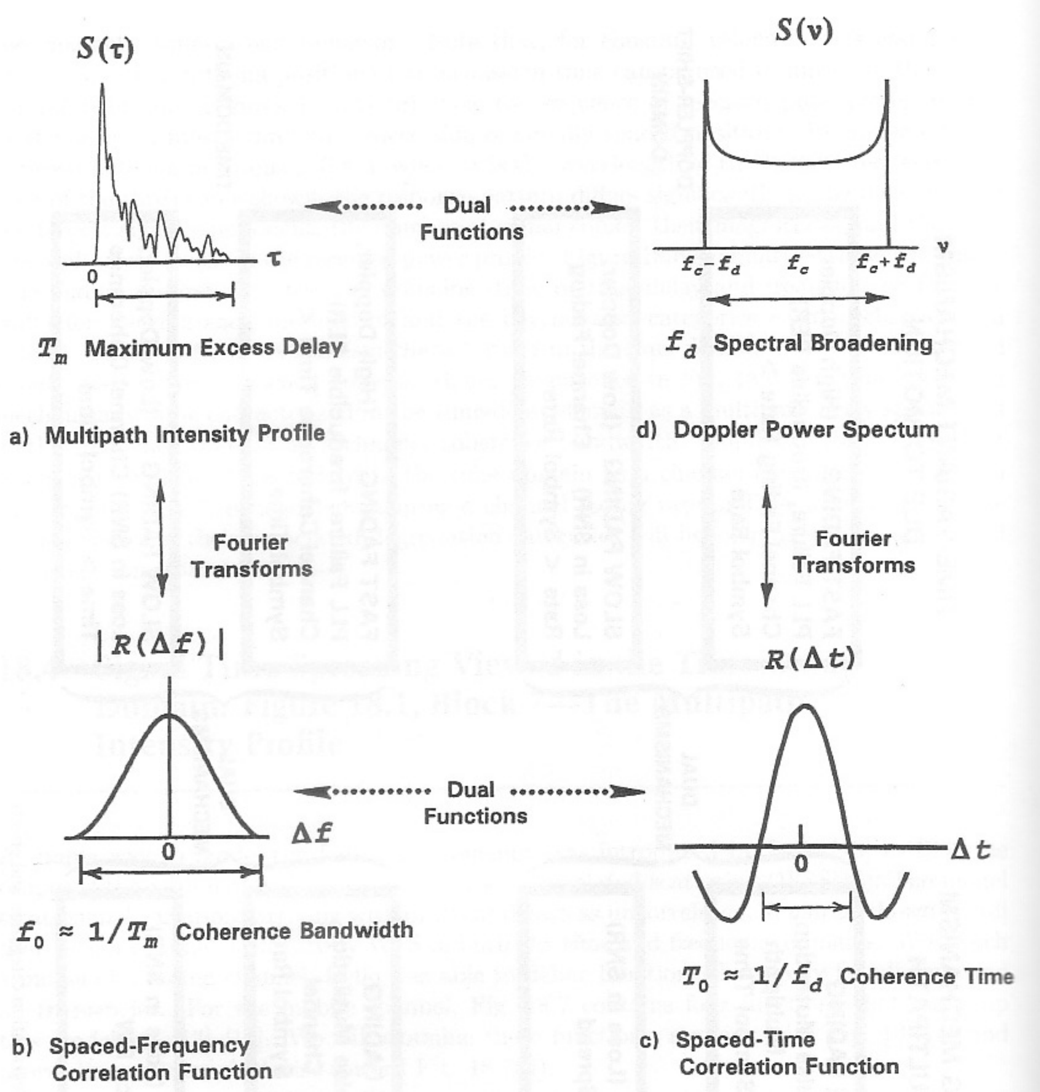


FIGURE 18.7 Relationships among the channel correlation functions and power density functions.

[1] E. Biglieri, J. Proakis and S. Shamai, “Fading Channels: information-Theoretic and Communications Aspects,” IEEE Transactions on Information Theory, vol. 44, no. 6, October 1998, pp.2619-2692.
[2] B. Sklar, “Rayleigh Fading Channels,” in The Mobile Communications Handbook, CRC Press, 1999, pp. 18-1 to 18-39.

Equivalent Model

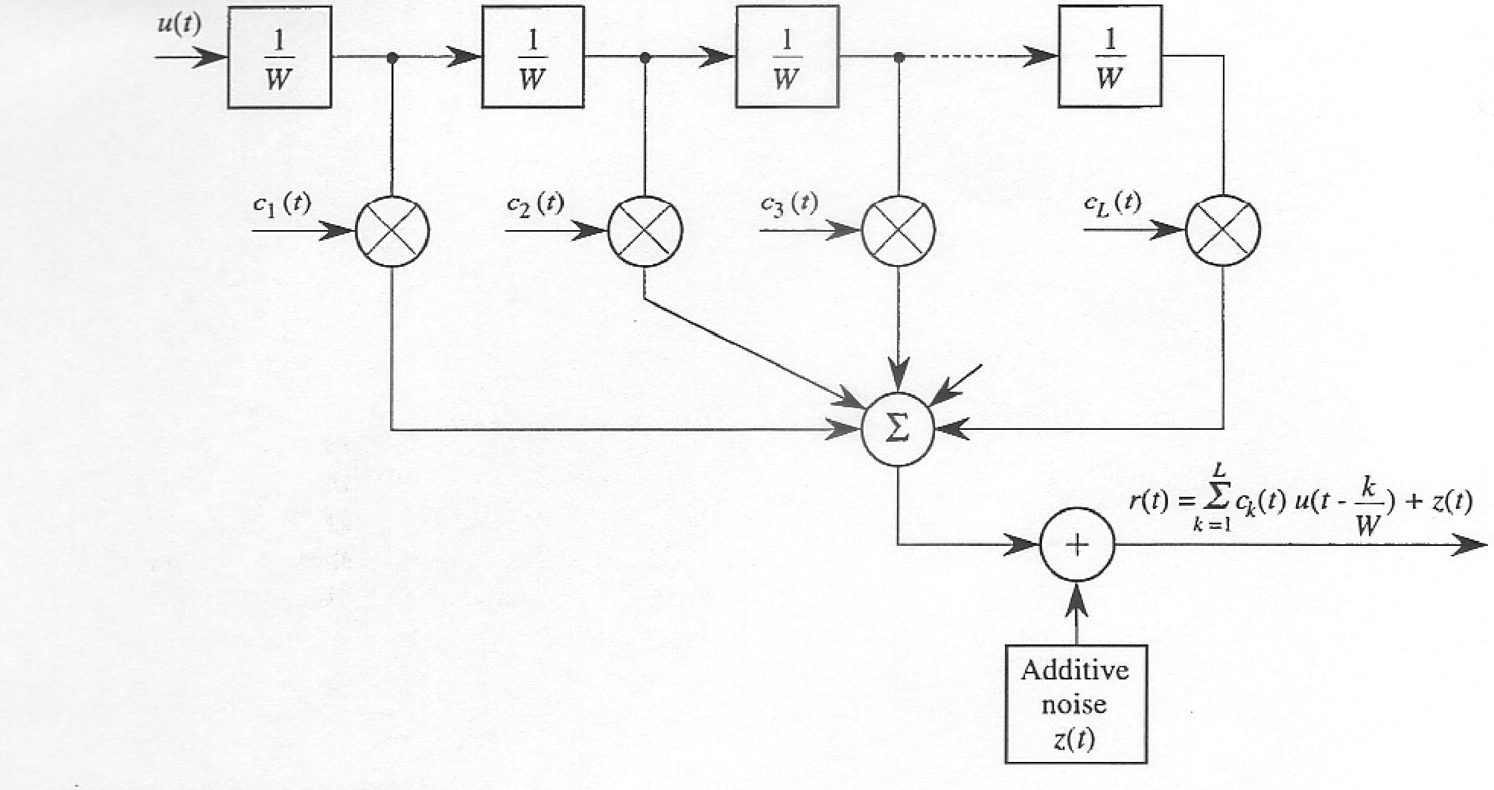
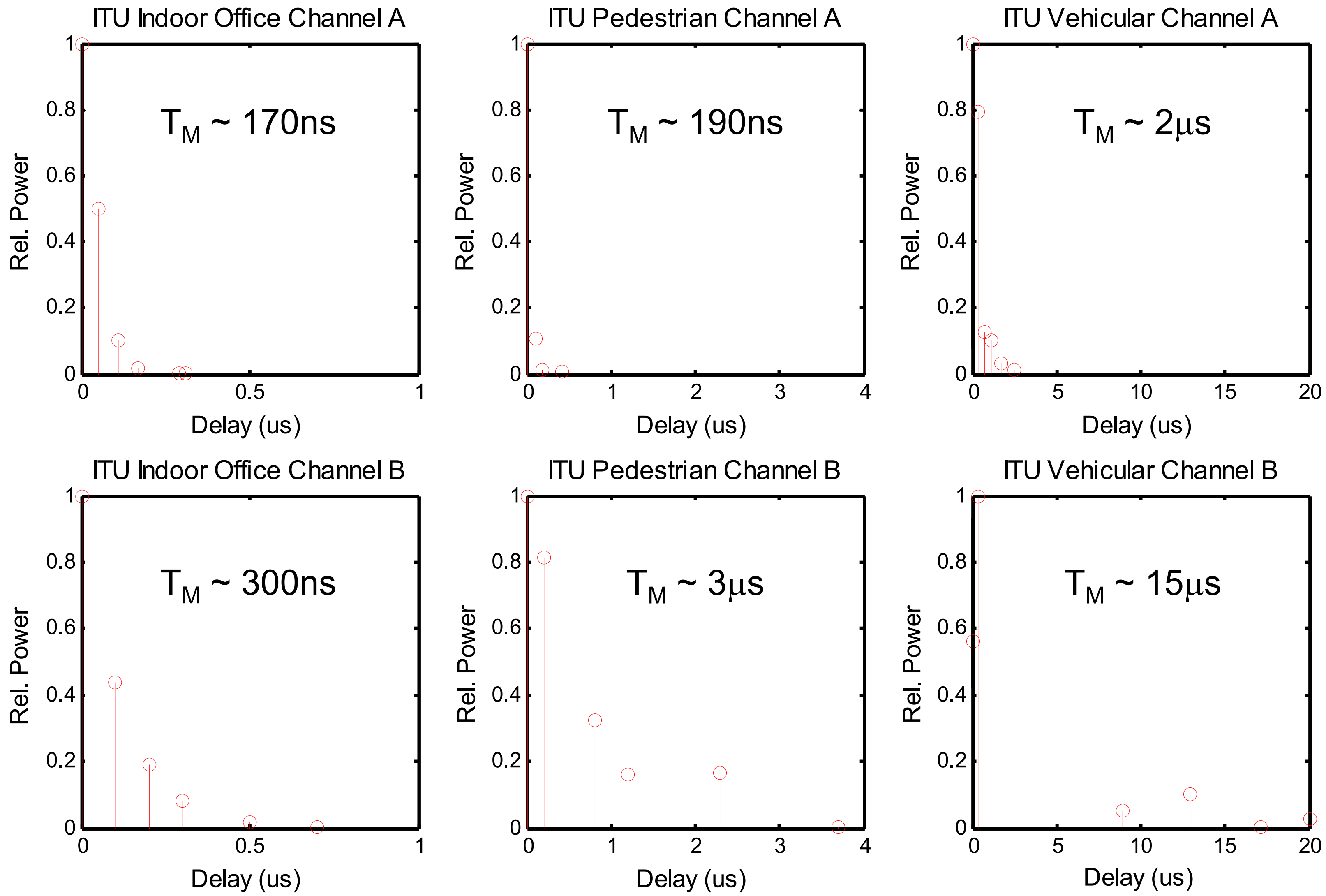


Fig. 2. Tapped-delay-line channel model.

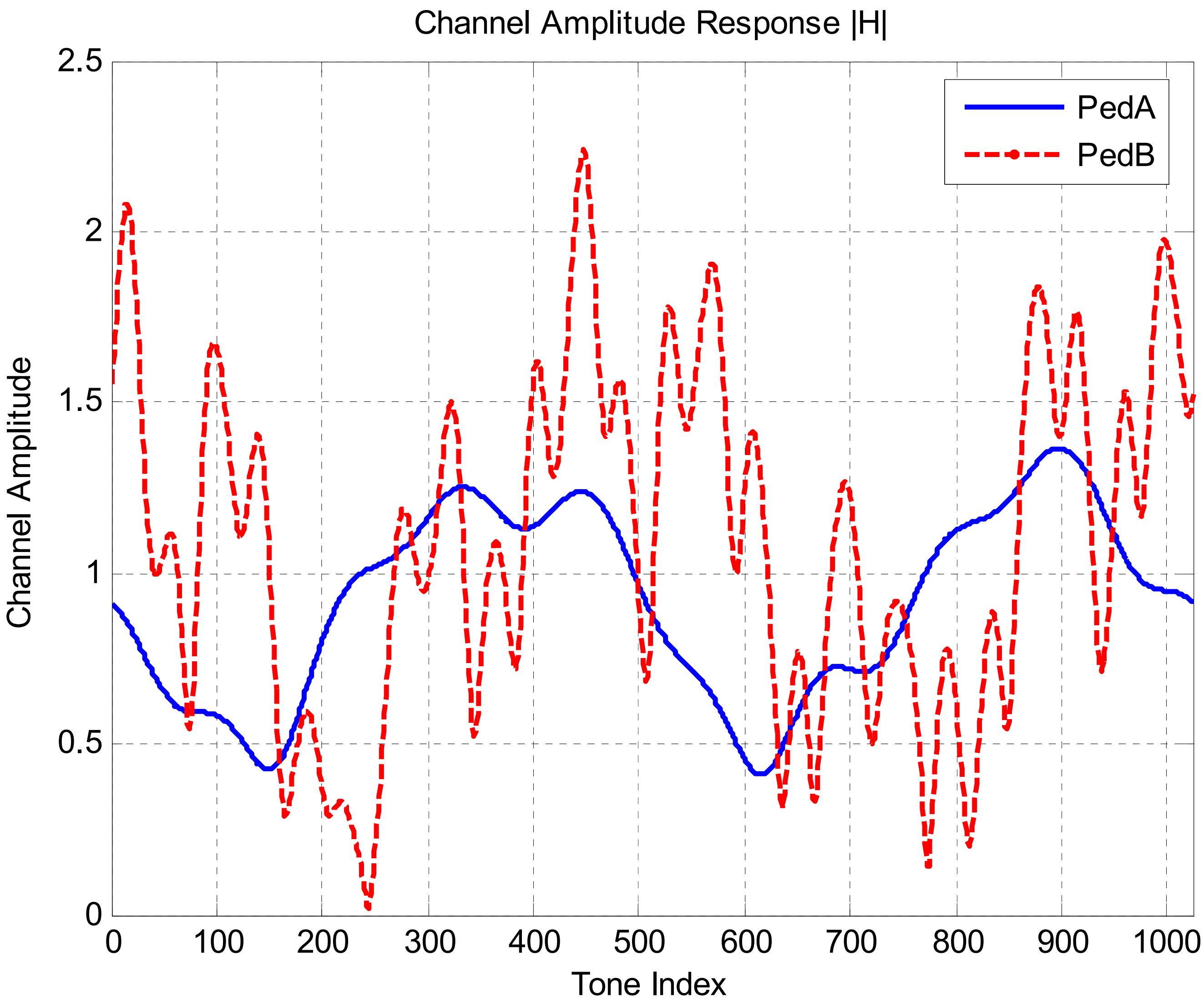
- Tapped delay line model.
- Time-varying taps modeled as stationary (wide-sense) uncorrelated random variables with specified Doppler power spectra.

[1] E. Biglieri, J. Proakis and S. Shamai, “Fading Channels: information-Theoretic and Communications Aspects,” IEEE Transactions on Information Theory, vol. 44, no. 6, October 1998, pp.2619-2692.

ITU Channel Models – Time Domain



ITU Channel Models – Frequency Domain



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- OFDMA Multiple Access in WiMAX Systems
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Optimal Symbol Period

- To transmit symbols while avoiding ISI and ICI, the symbol period should satisfy the following condition:

$$\frac{1}{2f_D} >> T_S >> T_M$$

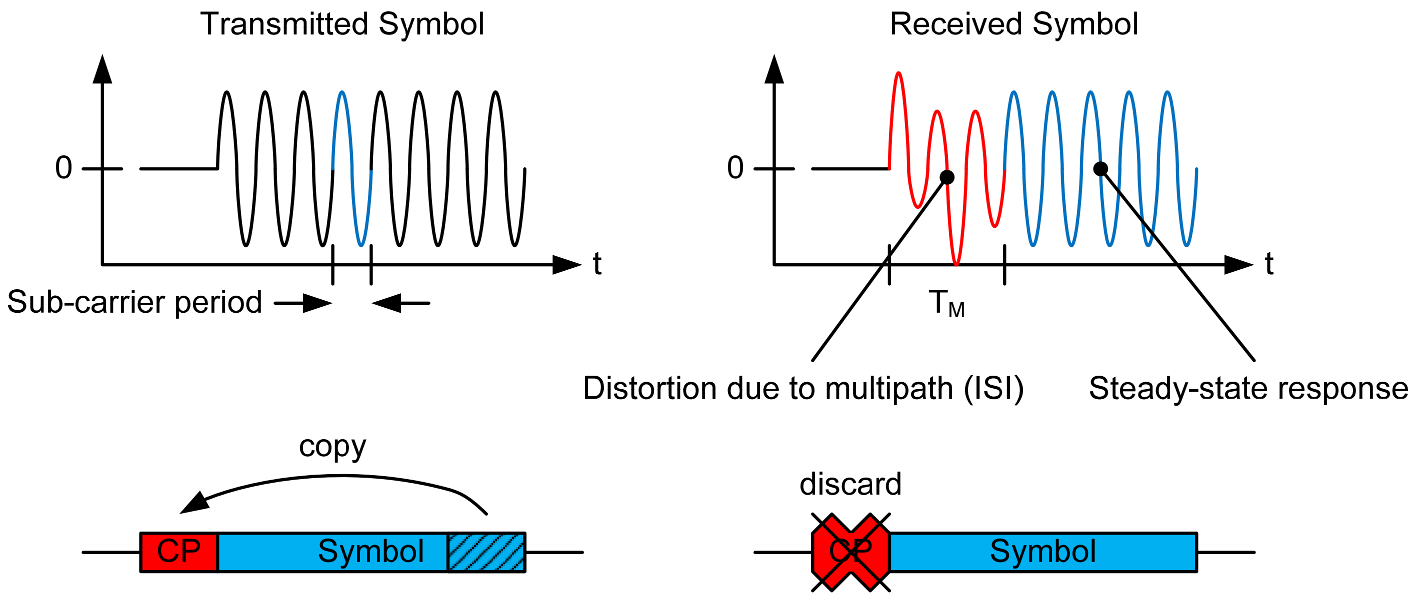
- That is:
  - Symbols should be short enough to avoid fast fades
  - Symbols should be long enough that ISI is insignificant

A reasonable choice: $\boxed{T_S \sim \sqrt{T_{M,3x}/2f_D} = \sqrt{r/vf_0}}$

- Example:
  - Assume 1-km cell radius, 100-km/h speed, 2.5-GHz carrier frequency

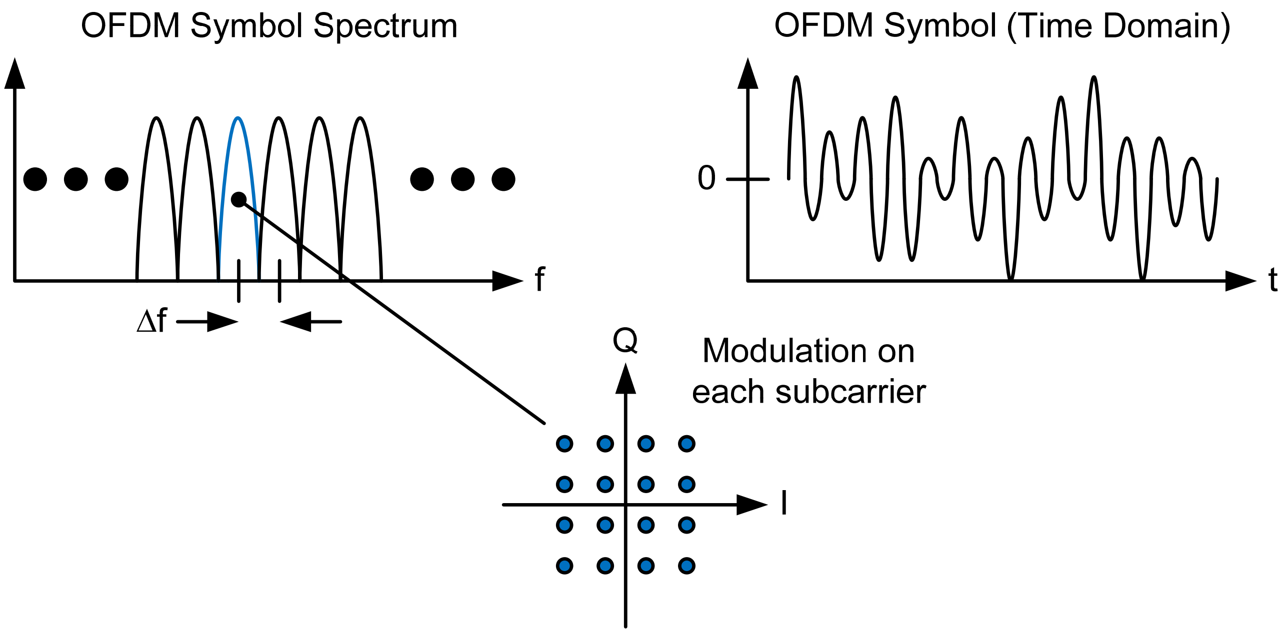
$$\frac{1}{2f_D} \sim 2.2ms >> T_S \sim 120\mu s >> T_M \sim 6.7\mu s$$

The Concept of a Cyclic Prefix – Avoid ISI



- A single-carrier transmitted symbol is a carrier burst whose amplitude and phase carry the desired information.
  - Note that a single symbol contains an integer number of sub-carrier cycles.
- The beginning of the received symbol is corrupted by multipath.
  - Distortion persists until the homogeneous response of the channel dies out.
- Add a 'cyclic prefix' to the symbol
  - Copy the end of the symbol to the beginning.
  - Discard the CP at the receiver end.

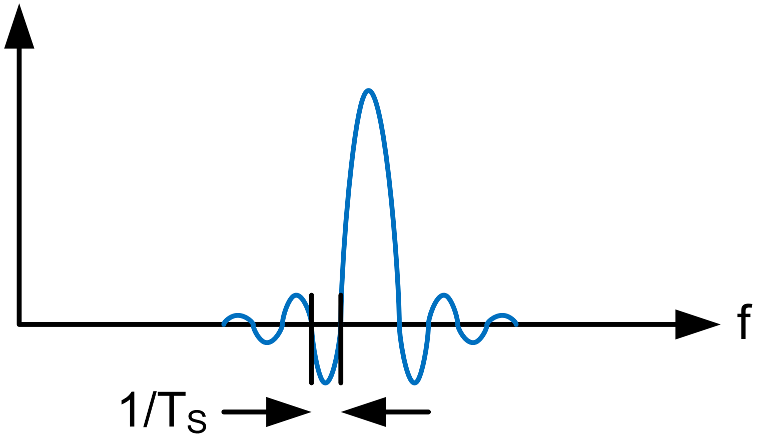
OFDM Signals



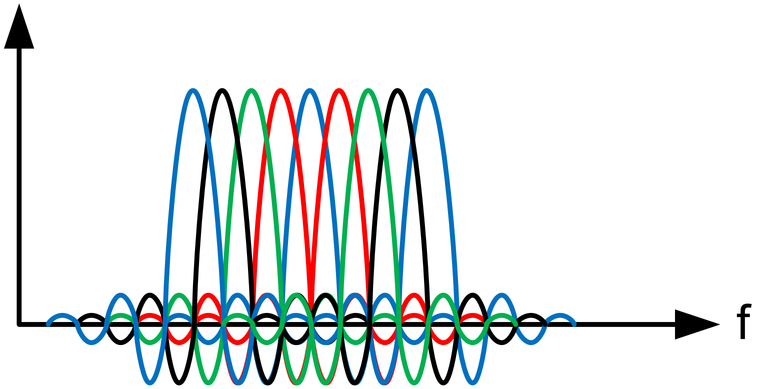
- Symbol period, T_S, is too long to support a high data rate with a single subcarrier.
- Combine multiple subcarriers to be transmitted simultaneously
  - This way, we can scale up the data rate while maintaining a long symbol period.
  - Use a cyclic prefix to avoid any distortion due to ISI from multipath.
  - Subcariers can carry multiple bits / symbol using high order modulation (e.g. 16-QAM) as SNR permits.
- ‘Orthogonal Frequency Division Multiplexing (OFDM)’

The Concept of Orthogonality – Avoid ICI

Subcarrier Spectrum



OFDM Spectrum



- With multiple subcarriers present, there is potential for ICI.
  - Spectral side-lobes of a given sub-carrier can interfere with adjacent sub-carriers.
- To avoid this, we construct the composite signal such that all sub-carriers are orthogonal.
- The condition for doing so is that the symbol should contain an integer number of cycles of each and every sub-carrier (neglecting the CP).
  - In the presence of multipath, the cyclic extension of the symbol with the CP maintains the orthogonality of all subcarriers.
- This ensures that the transmitted OFDM symbol will be free of ICI.

Mathematical Description of OFDM Signals

A Single OFDM Symbol:

$$s(t) = \mathrm{Re}\left[e^{j2\pi f_0 t} \sum_{\substack{k=-(N_{used}-1)/2, \\ k\neq 0}}^{k=+(N_{used}-1)/2} c_k e^{j2\pi k\Delta f_{SC}(t-T_{CP})} \right]$$

f_0 : RF carrier frequency

Δf_{SC} : OFDM subcarrier frequency spacing

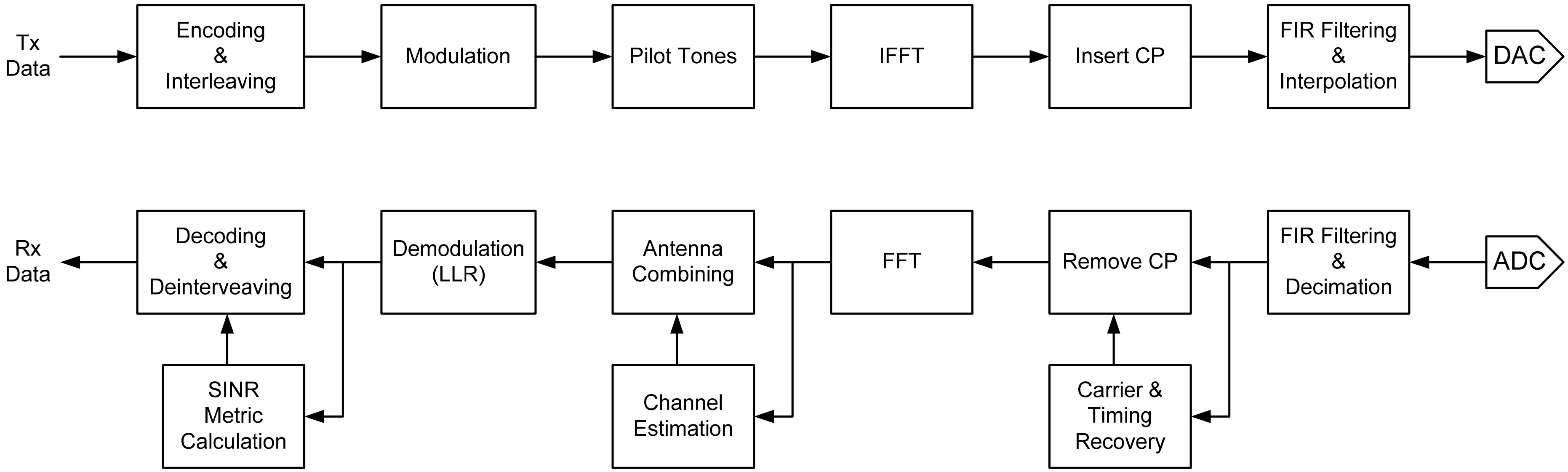
k : OFDM subcarrier index

c_k : Complex number representing the data on subcarrier k

T_{CP} : Cyclic prefix (guard) time

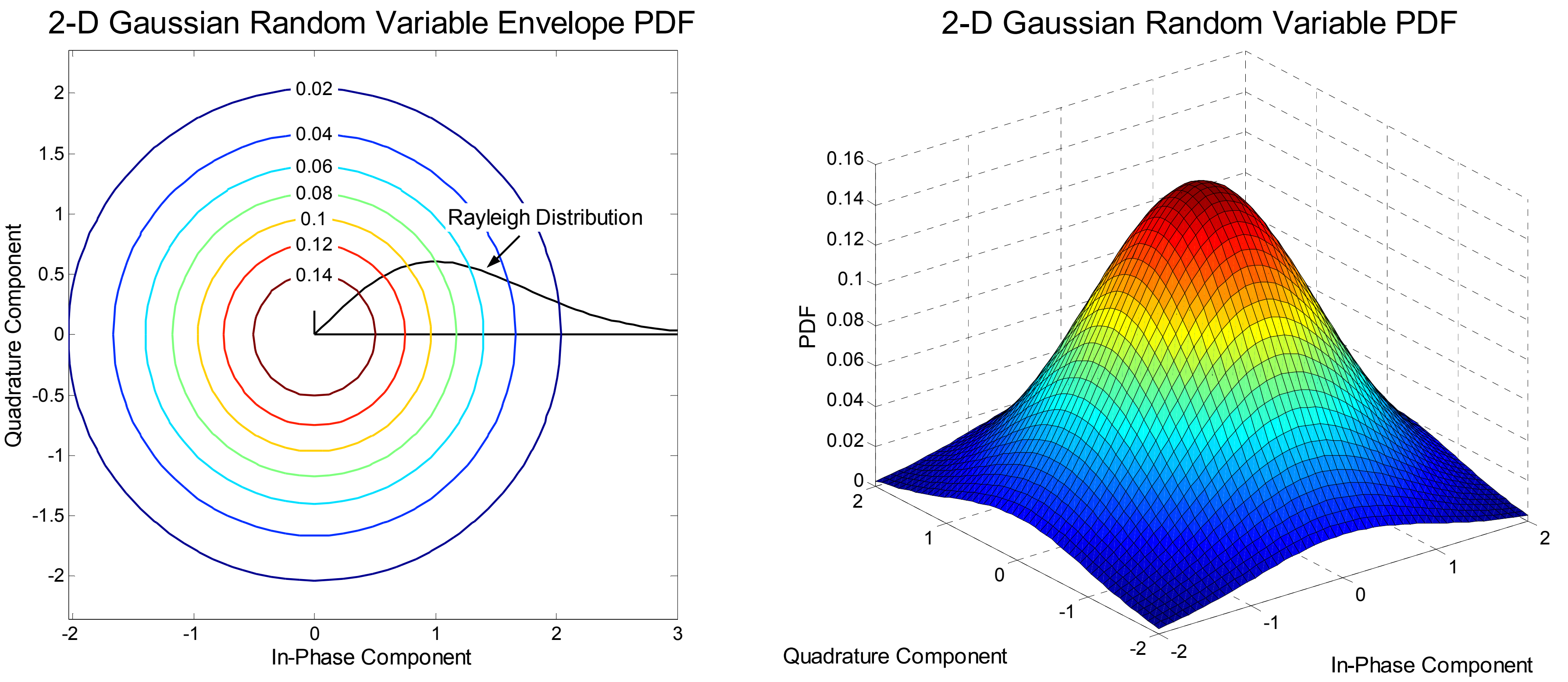
N_{used} : Number of subcarriers in use

OFDM Modulation and Demodulation (MS)



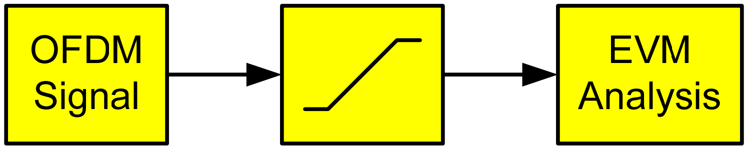
- Through the use of CP, the modulator becomes a simple IFFT.
  - Serial data are encoded and assigned to frequency bins.
  - IFFT generates the assembly of sub-carriers.
- On the Rx side, do the reverse.
  - Rx processing is generally much more complex: synchronization, interference mitigation, channel estimation, antenna combining, etc..

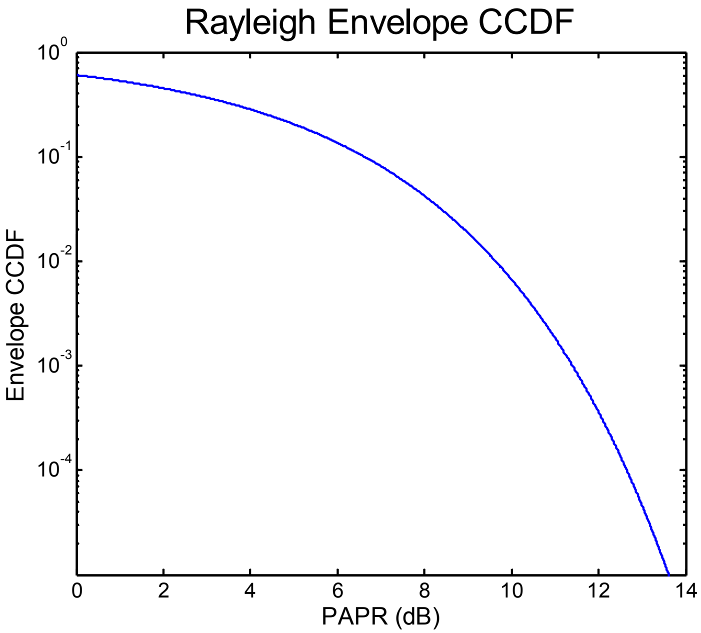
Envelope PDF / PAPR

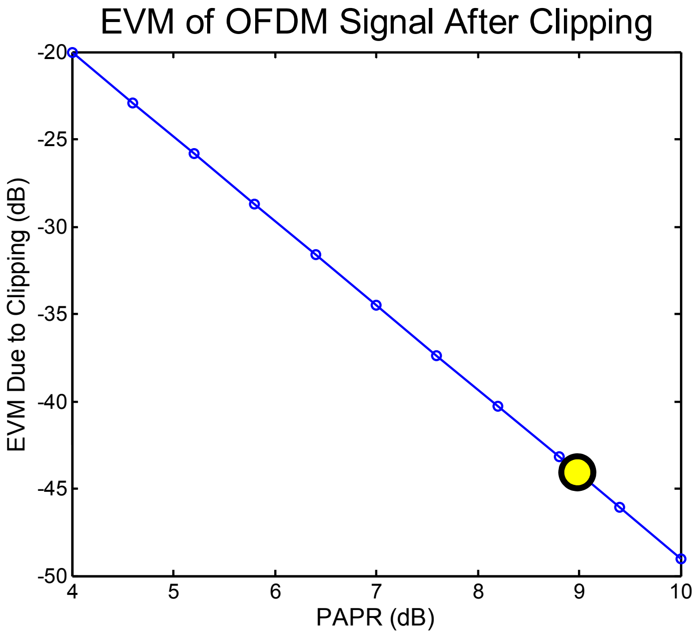


- With a large number of sub-carriers, the complex OFDM signal statistics approach that of a 2-D Gaussian random variable.
  - Central limit theorem
- Amplitude of the complex signal is Rayleigh distributed.

Implications of High-PAPR







- Rayleigh-distributed signals have high peak-to-average ratio.
- With finite headroom, compression will clip the signals, which degrades EVM.
  - Need to maintain about 9dB PAPR for clipped EVM < -45dB.
- PAR – “Peak-to-Average Ratio”: The PAR of the complete RF signal.
- PAPR – “Peak-to-Average Power Ratio”: The PAR of the RF <u>envelope</u>.

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WiMAX Modulation Schemes and Data Rates

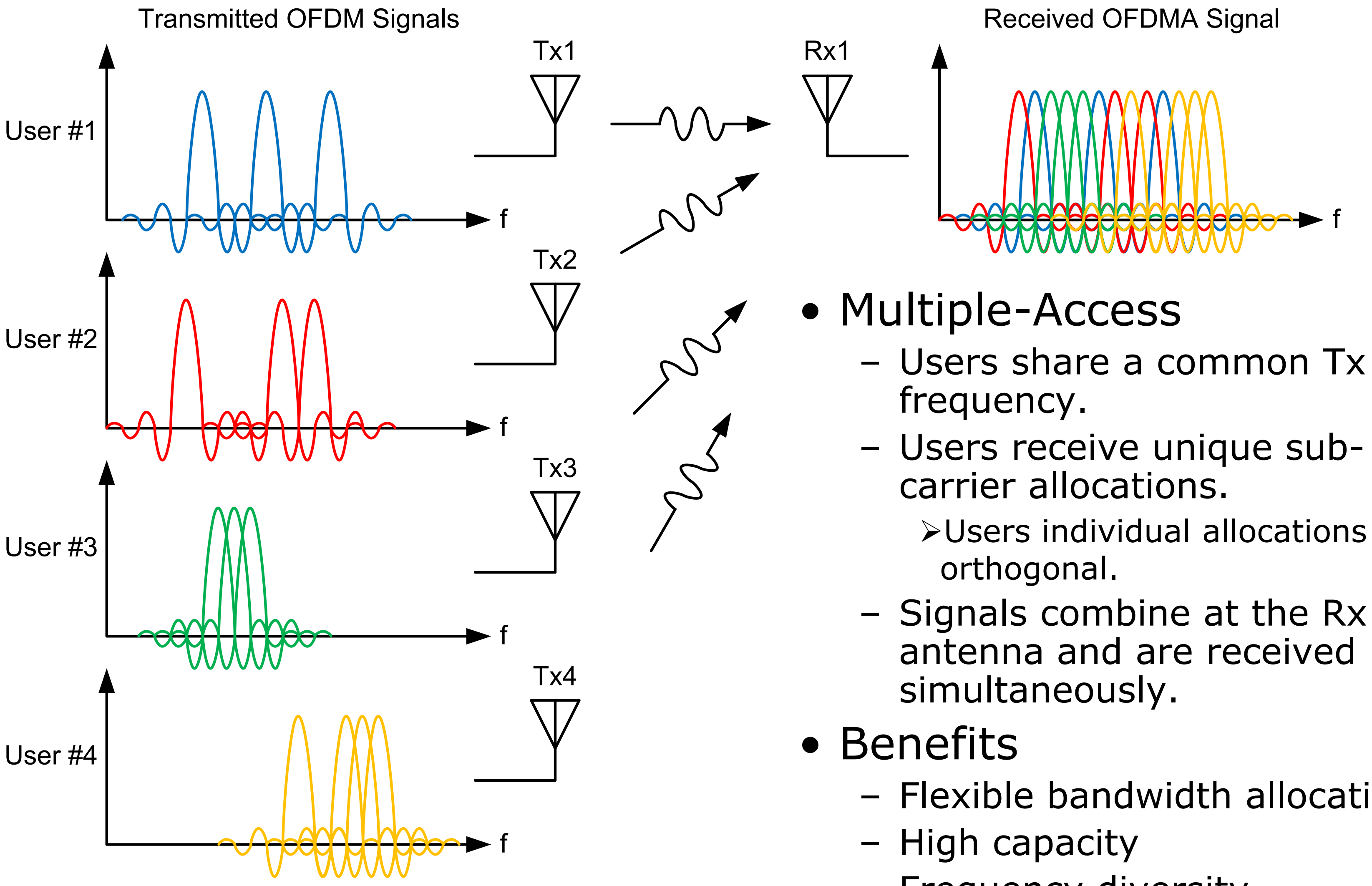
Bandwidth	RCE	5 MHz Ch Data Rates		10 MHz Ch Data Rates	
MCS	(dB)	Downlink	Uplink	Downlink	Uplink
QPSK ½ CC, 6x	-15.0	0.60	0.45	1.19	0.93
QPSK ½ CC, 4x		0.89	0.69	1.79	1.39
QPSK ½ CC, 2x		1.79	1.35	3.57	2.78
QPSK ½ CC, 1x		3.57	2.70	7.14	5.55
QPSK ¾ CC	-18.0	5.36	4.05	10.71	8.33
16QAM ½ CC	-20.5	7.14	5.40	14.28	11.11
16QAM ¾ CC	-24.0	10.71	8.10	21.42	16.66
64QAM ½ CC	-26.0	10.71	8.10	21.42	16.66
64QAM 2/3 CC	-28.0	14.29	10.79	28.56	22.21
64QAM ¾ CC	-30.0	16.07	12.14	32.14	25.00

MCS – “Modulation and Coding Scheme”

RCE – “Relative Constellation Error”

S. Lloyd and L. Jalloul, “802.16e WiMAX Key System and Circuit Design Issues,” Workshop WK151, RFIC 2006.

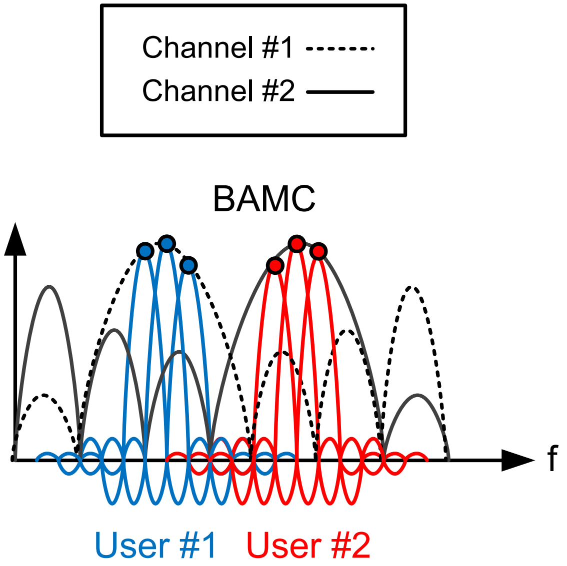
Multiple-Access w/ OFDMA



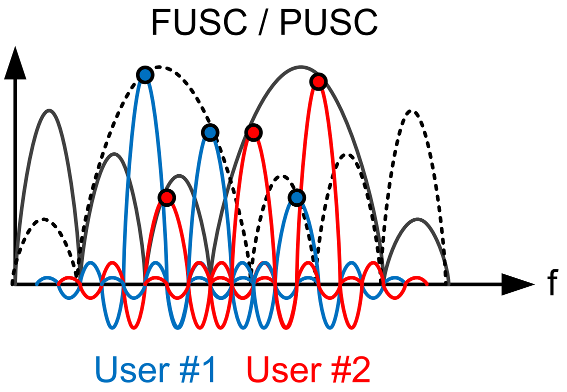
- Multiple-Access
  - Users share a common Tx frequency.
  - Users receive unique sub-carrier allocations.
    - Users individual allocations are orthogonal.
  - Signals combine at the Rx antenna and are received simultaneously.
- Benefits
  - Flexible bandwidth allocation
  - High capacity
  - Frequency diversity

Sub-Carrier Assignment Strategies (Simplified)

- BAMC
  - "Band Adaptive Modulation and Coding"
  - Contiguous allocations
  - Suitable for quasi-stationary channels
  - Enables multi-user diversity gains
  - MIMO (Rev. 2.0)


BAMC

- FUSC / PUSC
  - "Full (Partial) Usage of Sub-Carriers"
  - Allocations are dispersed over frequency (diversity)
  - Suitable for fading channels
  - Frequency diversity
  - MIMO


FUSC / PUSC

WiMAX MIMO Modes / Diversity Techniques

- Maximum Ratio / MMSE Combining
  - Multi-antenna Rx diversity technique
  - Improved SNR
- Opportunistic Scheduling (Multi-User Diversity)
  - Works well for slow-fading channels w/ good channel feedback
  - Reduced susceptibility to fading
- Beam Forming
  - Good for slow-fading channels w/ good channel feedback
    - However, can also be applied for closely-spaced antennas w/ faster fade rates
  - Improved SNR
- MIMO – Space Time Coding
  - Same data transmitted on multiple antennas and at multiple time instances
  - Each antenna is coded such that data components are transmitted at different times
  - Improved diversity
  - Easy decoding (Alamouti algorithm)
- MIMO – Spatial Multiplexing
  - Different data streams transmitted on each antenna
  - Increased channel capacity (~doubled for 2x2 system)

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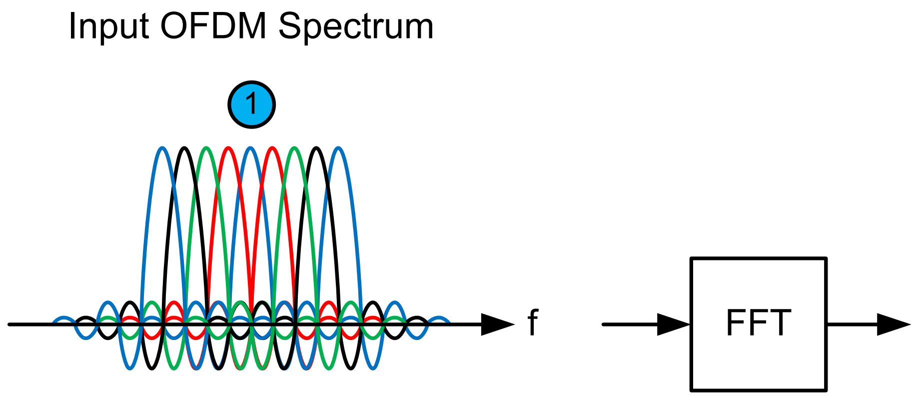
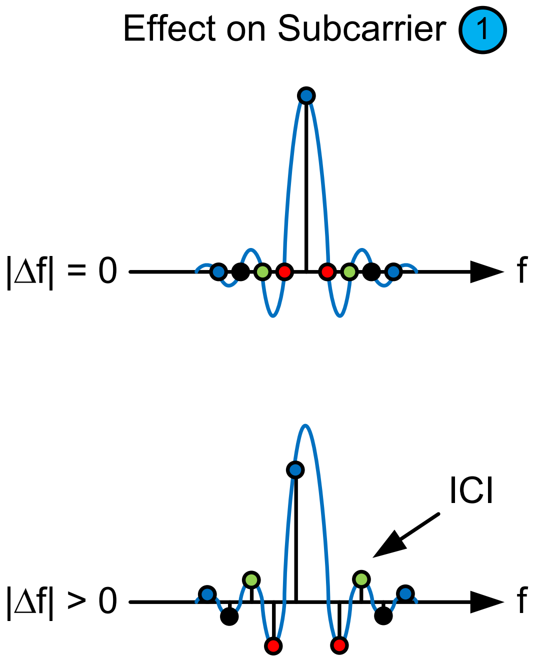
The Challenge of Maintaining Orthogonality

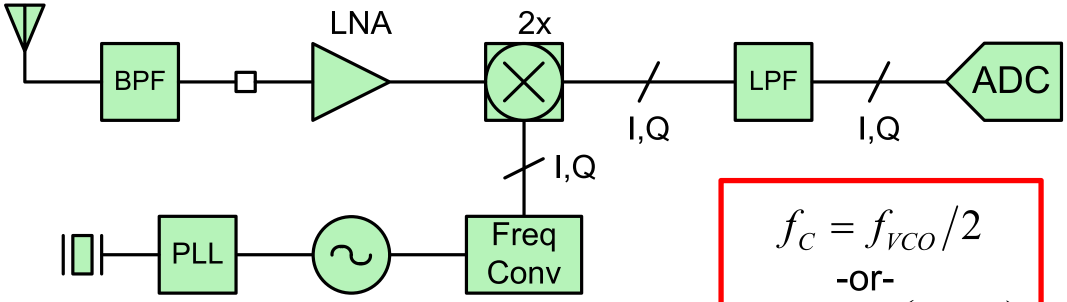




- Orthogonality is easily lost
  - Frequency offsets
    - ➢Preamble facilitates carrier frequency & symbol timing estimation
    - ➢UL frequency accuracy: < +/- 2% of SC spacing (RCT requirement)
    - ➢Frequency tracking error is typically much less than this
  - Doppler spreading (Rayleigh fading)
    - ➢Sub-carrier spacing selection is critical
    - ➢Symbol windowing can be used to reduce sub-carrier side-lobes
      - Not used in WiMAX.
    - ➢Distributed pilot tones used for timing and frequency error estimation.

Common Wideband Receiver Architectures

Direct Conversion

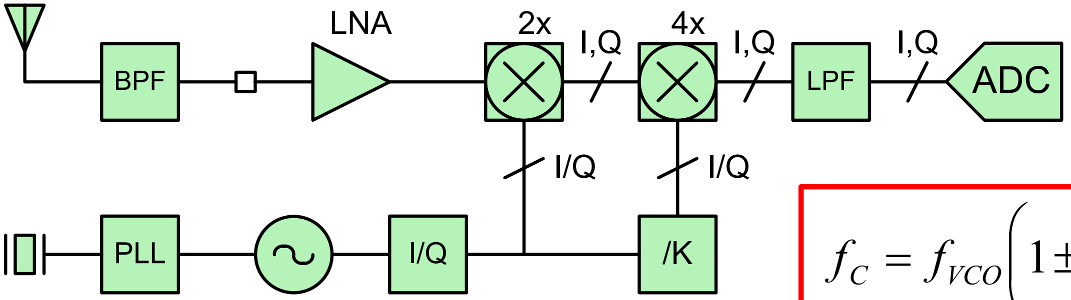


$$f_C = f_{VCO}/2$$

-or-

$$f_C = f_{VCO}\left(1 \pm \frac{1}{K}\right)$$

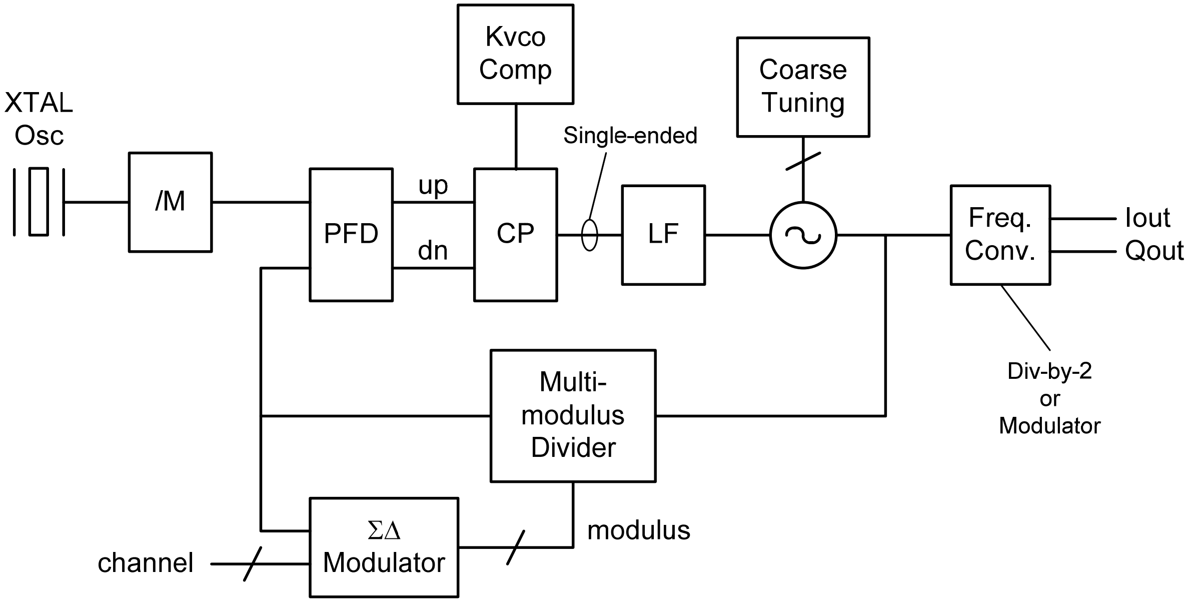
Sliding IF



$$f_C = f_{VCO}\left(1 \pm \frac{1}{K}\right)$$

- Direct Conversion
  - Frequency planning
    - ➢Run VCO at offset from carrier
    - ➢Div-by-2
    - ➢Offset-LO generation
  - D.C. offsets
  - IIP2
- Sliding IF
  - Frequency planning
    - ➢Run VCO at offset from carrier
    - ➢Dual-conversion
  - LO power consumption
  - D.C. offset issues are alleviated somewhat

A Typical Wireless PLL



- Fractional–N ΣΔ–Modulated Loop
  - Fine frequency resolution & support for multiple crystal frequencies
- Coarse Tuning
  - Minimize Kvco to keep spurious under control
- Kvco Compensation
  - Maintain loop dynamics over VCO fine-tuning range
- Freq. Conversion
  - For direct-conversion systems, VCO is off-frequency

Orthogonality and PLL Phase Noise

- Signal falling in the nth frequency bin:

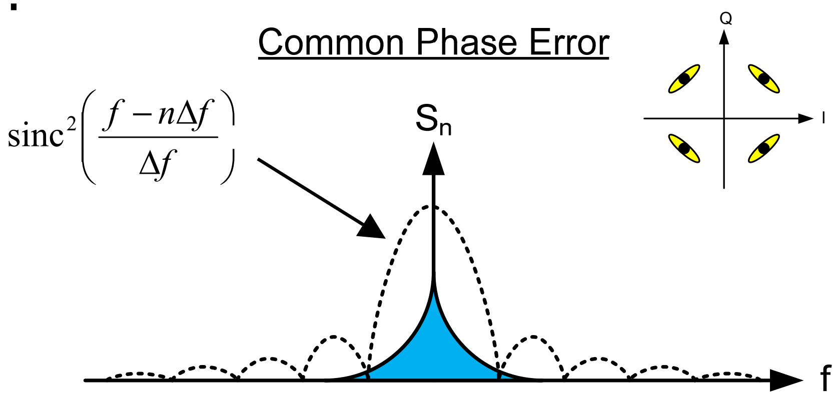
$$f_n = \frac{1}{T_s}\int_0^{T_s} x(t)\, e^{j2\pi n\Delta f t}\, dt$$

- Equivalent frequency-domain power weighting function:

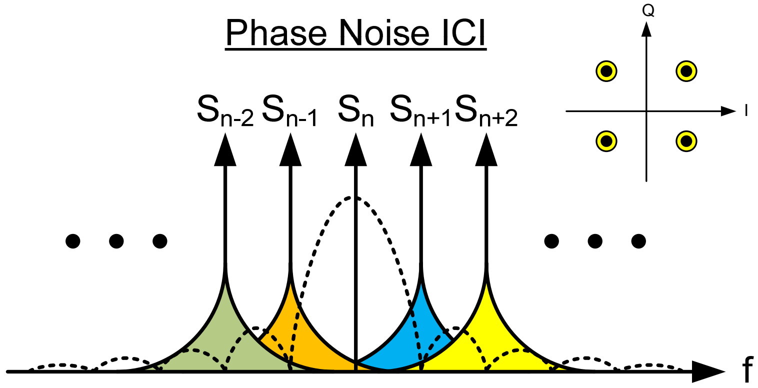
$$\sigma_n^2 = \int_{-\infty}^{\infty} \left|X(f)\right|^2 \operatorname{sinc}^2\left(\frac{f - n\Delta f}{\Delta f}\right) df$$

- Phase noise produces two effects
  - Common Phase Error
    - ➢Phase noise impressed on each sub-carrier causes symbol rotation of that sub-carrier
    - ➢Net noise correlated among all sub-carriers
  - Phase Noise ICI (Reciprocal Mixing)
    - ➢Phase noise impressed on each sub-carrier causes ICI to neighboring sub-carriers
    - ➢Net noise is uncorrelated between sub-carriers

Common Phase Error



Phase Noise ICI



Calculating RCE Due to Phase Noise

- Assume that the data on each subcarrier is random and uncorrelated among subcarriers.
- RMS noise falling on n^th^ subcarrier is the superposition of ICI due to subcarriers to the left and right.
- Number of subcarriers on each side varies with n
- Define an effective SSB P/N weighting function

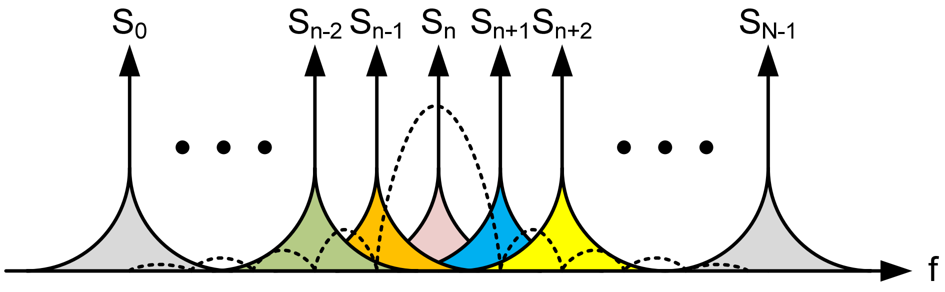
- Total RCE is approx. given by:

$$\boxed{\sigma_{\varepsilon}^{2} = 2\int_{f_{\min}}^{N\Delta f} L(f)W_{eff}(f)df}$$

where fmin is set by the Rx carrier frequency tracking loop bandwidth.

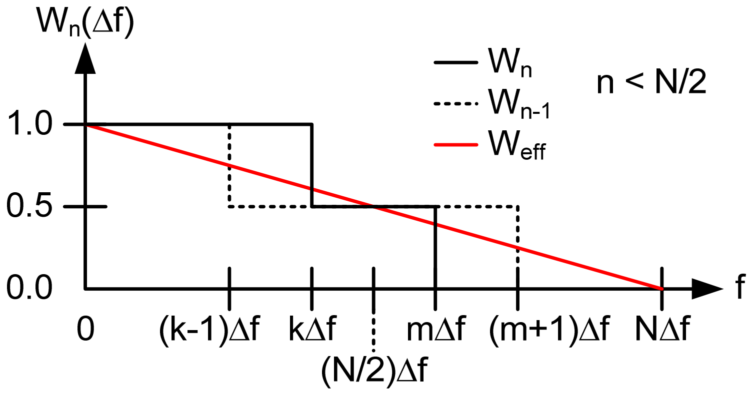
- In practice, RCE is slightly less, accounting for pilot boosting.

Aggregate Phase Noise



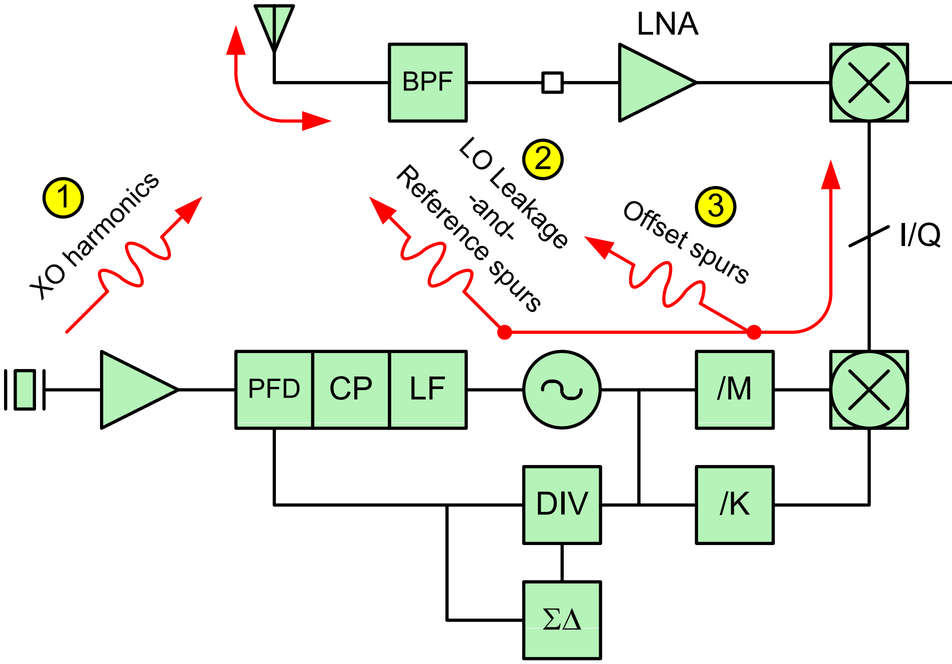
SSB P/N Weighting Functions

(100% subcarriers allocated)



$$k = N/2 - |n - N/2| \qquad m = N/2 + |n - N/2|$$

Rx Spurious Emissions



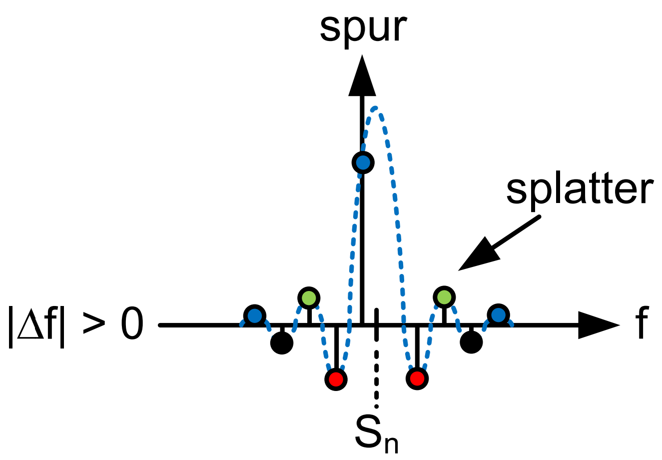
$$f_C = f_{VCO}\left(\frac{1}{M} \pm \frac{1}{K}\right)$$

Type	**Spur Frequency**
1	$n \cdot f_{XO}$
2	$n \cdot f_C \pm m \cdot f_{XO}$
3	$n \cdot f_C \pm m \cdot f_{VCO}/M \pm p \cdot f_{VCO}/K$

- In a direct-conversion Rx, VCO typically runs at a large frequency offset from carrier to avoid time-varying DC offsets
- Many sources of spurs need to be managed
  - In-band: XO harmonics and reference spurs
  - Out-of-band: Offset LO generation spurs (radiated and conducted)

Rx Spurious Limits

- Emissions
  - Limits are specified in CEPT/ERC recommendation 74-01E
- Reception
  - Spurs received by the Rx chain have to be compared to the sub-carrier sensitivity level @ -129dBm / S.C.
  - If spurs are off-frequency, then spectral splatter results.
  - A single spur can effect multiple sub-carriers!
  - XO harmonics are particularly vexing.



WiMAX Specification	Conditions	Min	Typ	Max	Units
In-Band Spurious	Ref. LNA Input			-135	dBm
Out-of-Band Spurious	Ref. LNA Input			-59	dBm

Outline

- Wireless Channels
- OFDM Modulation
- OFDMA Multiple Access in WiMAX Systems
- Implementation Challenges: What Limits Orthogonality
- Summary

Summary

- Wireless channels present a challenging environment for broadband communication where signals are scattered in time and frequency
  - Time-variance / mobility
  - Multipath
  - Fading (shadow and Rayleigh)
- OFDM modulation is well-suited to broadband communication over wireless channels
  - Tolerant of multipath delay-spread
  - Tolerant of Rayleigh fading
- OFDMA modulation provides a scalable solution for multiple-access in broadband wireless systems
  - Flexible bandwidth allocation / multiple access
  - Flexible network frequency planning
  - Compatible with advanced diversity / MIMO techniques
- Transciever challenges for maintaining orthogonality were outlined
  - Timbase accuracy
  - Spurious interference (self- or external-)
  - PLL phase noise

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