A 2x2 MIMO Baseband for High-Throughput Wireless Local-Area Networking (802.11n)

SCV-SSC Talk

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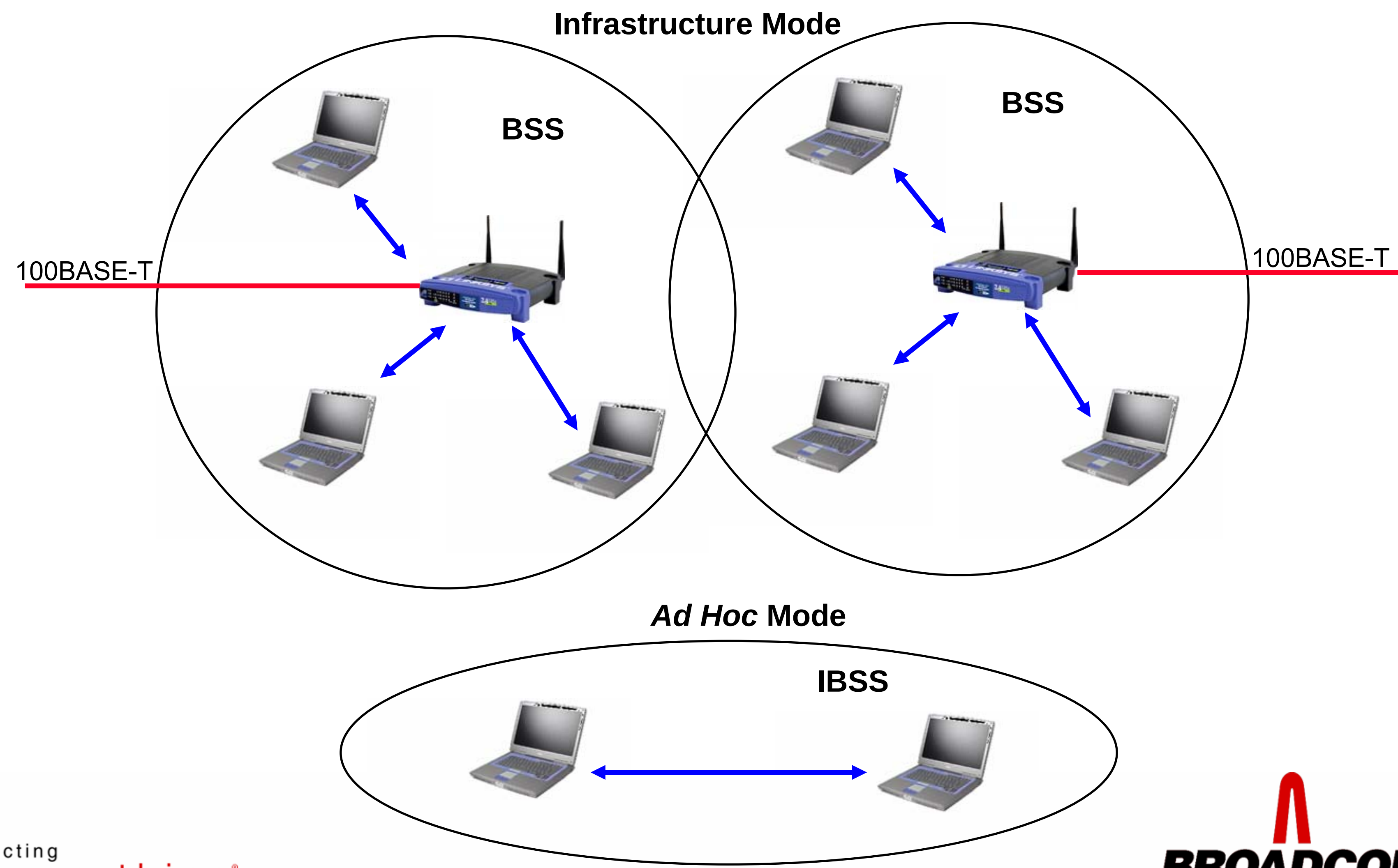
Outline

- **IEEE 802.11 Overview**
- The Indoor Wireless Channel
- Approaches to Improving Robustness and Data Rate
- More 802.11n Draft Details
- MIMO Transceiver Design Challenges and Solutions
- Broadcom's First MIMO Baseband IC

IEEE 802.11 Networks



WLAN Standards Evolution

802.11 (1997)	→	802.11b (1999)	+	802.11a (1999)	=	802.11g (2003)

802.11 (1997)
- FHSS and DSSS
- 1, 2 Mbps DSSS
- ~11 MHz bandwidth
- 2.4-2.5 GHz

802.11b (1999)
- DSSS and CCK
- 1, 2 Mbps DSSS
- 5.5, 11 Mbps CCK
- ~11 MHz bandwidth
- 2.4-2.5 GHz

802.11a (1999)
- OFDM
- 6, 9, 12, 18, 24, 36, 48, 54 Mbps
- ~17 MHz bandwidth
- (4.92-5.1) 5.15-5.825 GHz

802.11g (2003)
- DSSS, CCK and OFDM
- 1 – 54 Mbps
- ~11 or ~17 MHz bandwidth
- 2.4-2.5 GHz

802.11n (2008?)
- DSSS, CCK, OFDM, and MIMO-OFDM
- 1 – 600 Mbps (77 new modulation and coding sets)
  - Up to 1.1x rate through higher max code rate
  - Up to 4x through use of multiple antennas
- ~11, ~17 or ~35 MHz bandwidth
  - Up to 2.5x rate through bandwidth expansion
- 2.4-2.5, (4.92-5.1) 5.15-5.825 GHz
- Flexible transmitter and receiver PHY components
- MAC-layer aggregation

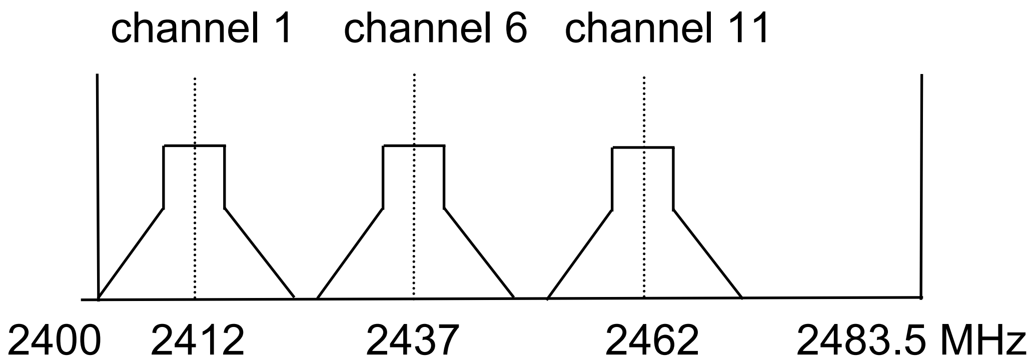
- **Transition from low (~0.1 bps/Hz) to high spectral efficiency (> 15 bps/Hz) in less than 10 years!**
  - The complexity in number of possible PHY rates and modes is vastly greater than it was at the end of the last century.

802.11, 802.11b/g/n Regulatory Landscape

In North America

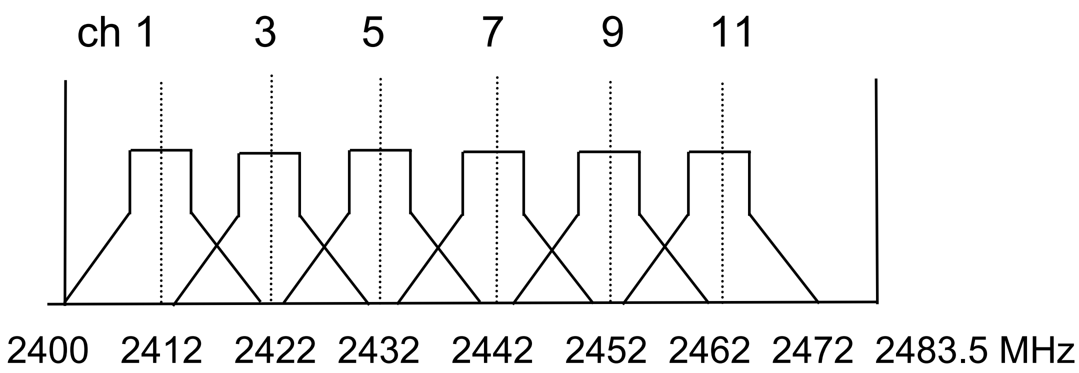
Set 1: Non-overlapping

5.5 & 11 Mbps

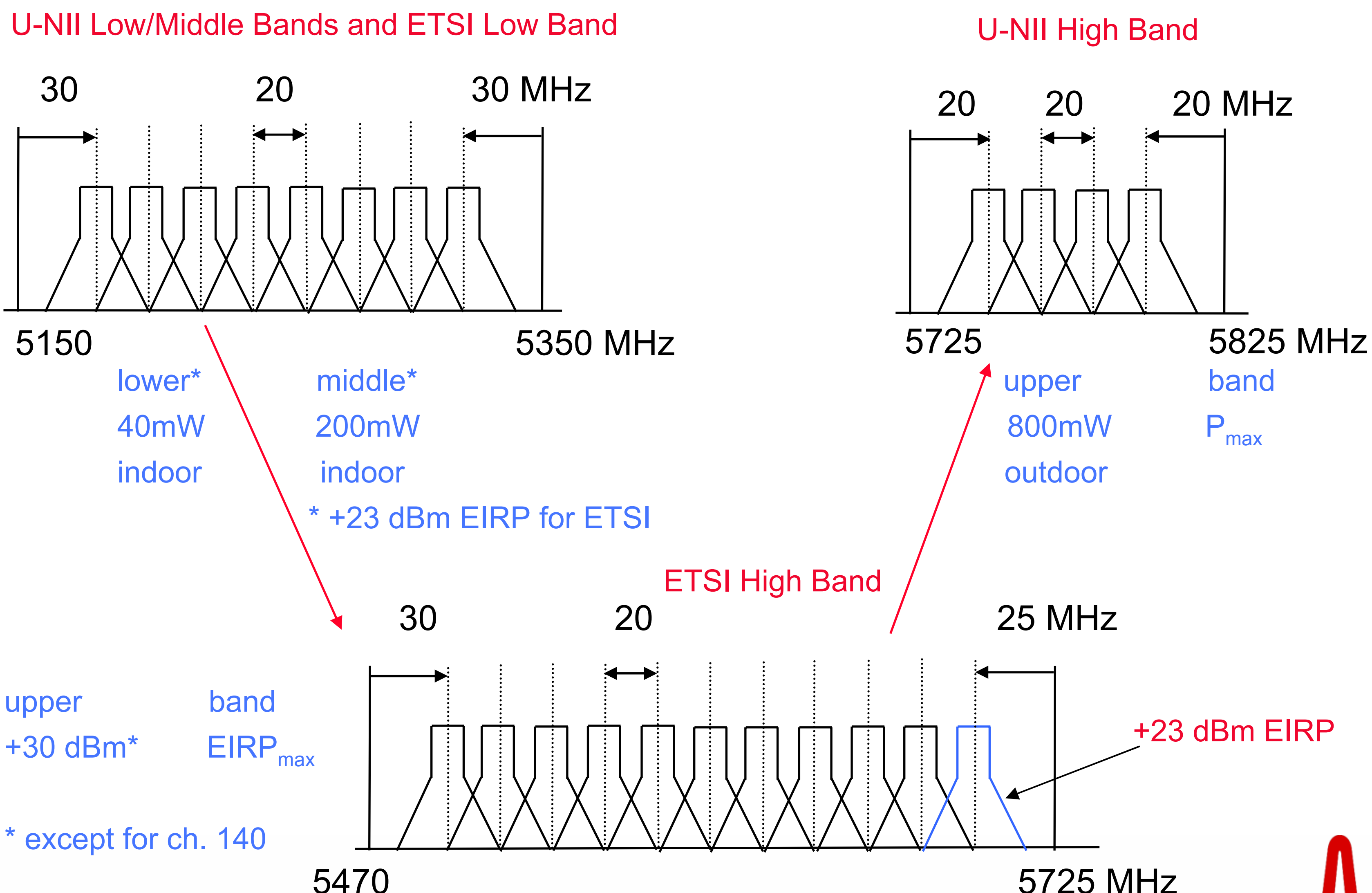


Set 2: Overlapping

1 & 2 Mbps



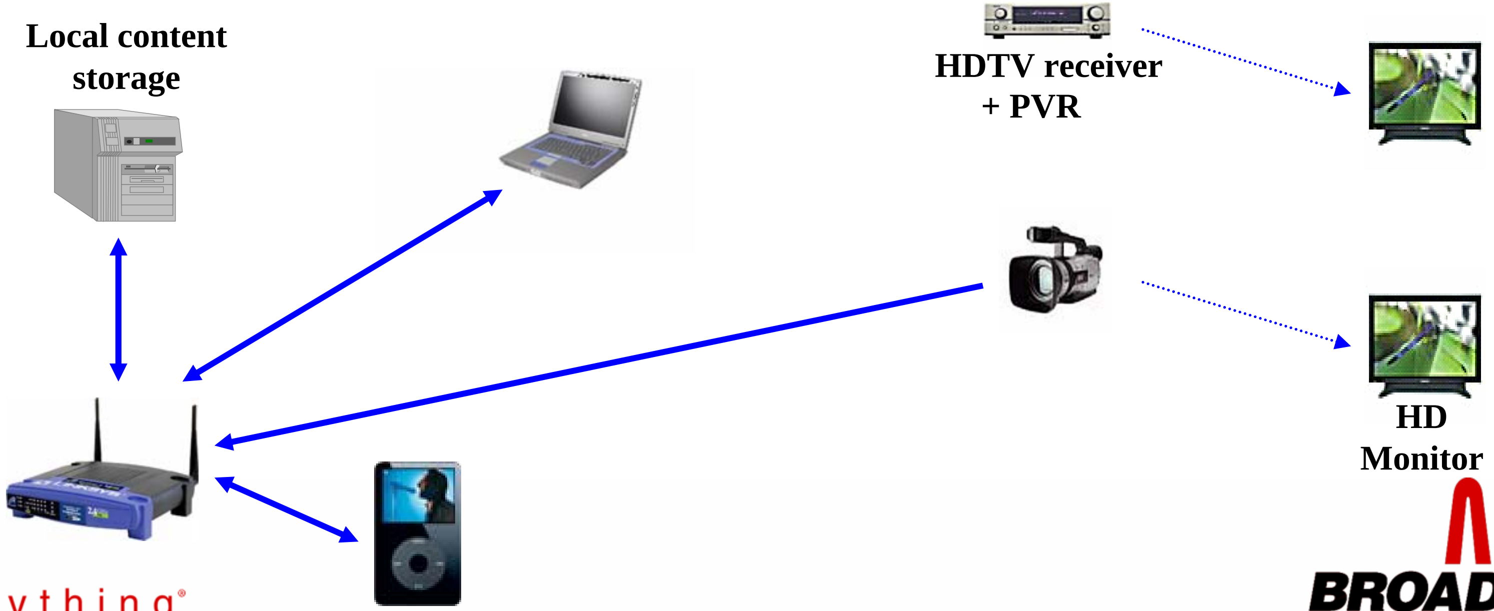
802.11a/n Regulatory Landscape



Additional channels from 4920 to 5080 MHz are defined only in Japan.

Why Do We Need > 54 Mbps?

- **First answer: very good question. ☺**
- **On second thought:**
  - For multiple-stream compressed video transmission
  - For wireless connections to content stored in one place in the home (NAS)
  - Because it's faster than what is available today and eventually will be of equivalent price. (Our experience: speed sells.)



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Multipath Channels: LOS

- **Multipath with Strong LOS**
  - Below is an example of a multipath channel in the presence of a strong LOS path
  - Vector *r* represents the *mean value* of the possible resultant vectors
  - The area of the circle indicates the 50% contour for the distribution
  - Vector magnitude indicates that probability of error is small
  - If the non-LOS components adhere to a Rayleigh distribution, the underlying distribution of the sum is Ricean.

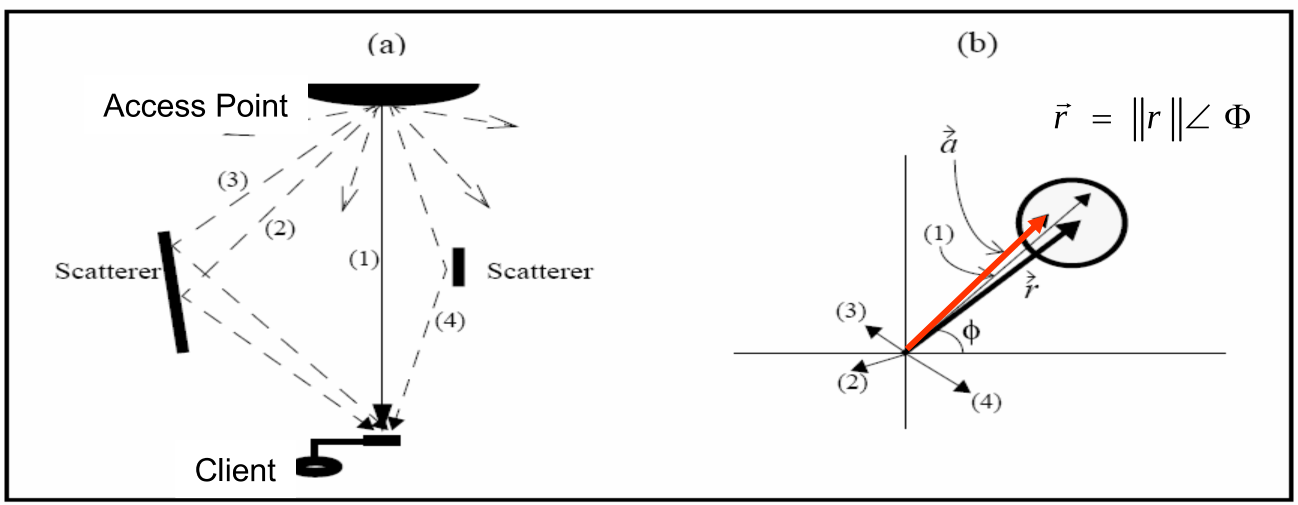

Fig. after ref [1]

Multipath Channels: Non-LOS

- **Multipath:**
  - Is caused by the multiple arrivals of the transmitted signal to the receiver due to reflections off "scatterers" (walls, cabinets, people, *etc*.).
  - For most indoor wireless systems, it is generally more problematic if a direct line-of-sight (LOS) path does *not* exist between the transmitter and the receiver
  - If incident waves are uniformly distributed over solid angle, the fade depth at any location is drawn from a Rayleigh distribution. Many real indoor environments approximate Rayleigh fading.

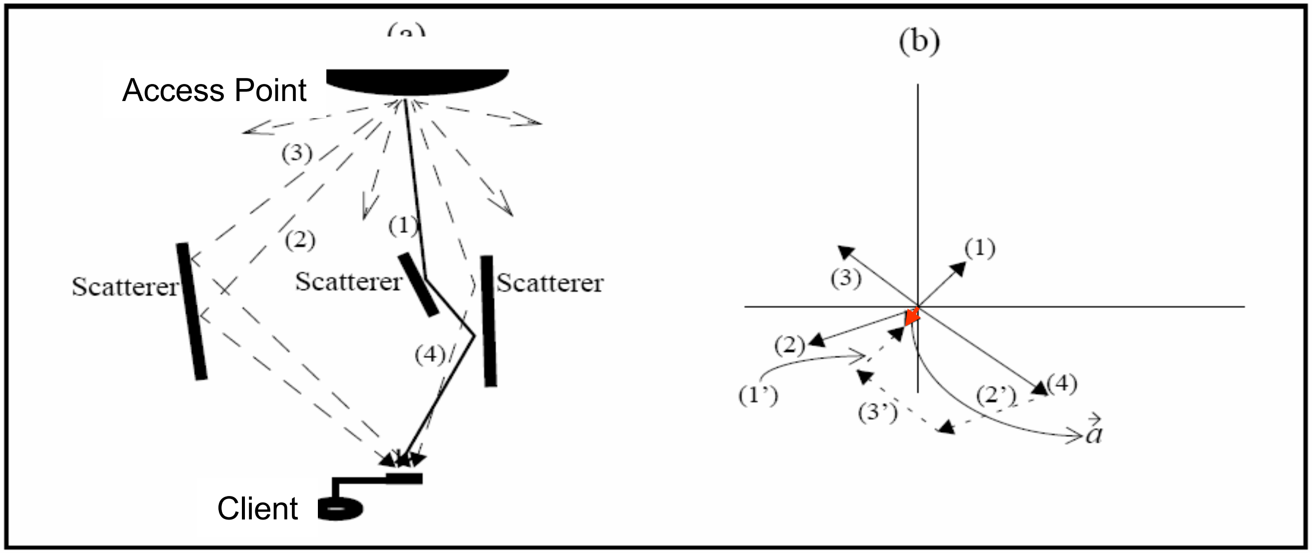

Fig. after ref [1]

Multipath Channels: Spatial Selectivity

- **Received signal power as a function of receiver-to-transmitter distance for a multi-GHz transmission in a multi-path indoor environment is shown below.**
  - Received signal power can vary quite significantly with a slight change in distance

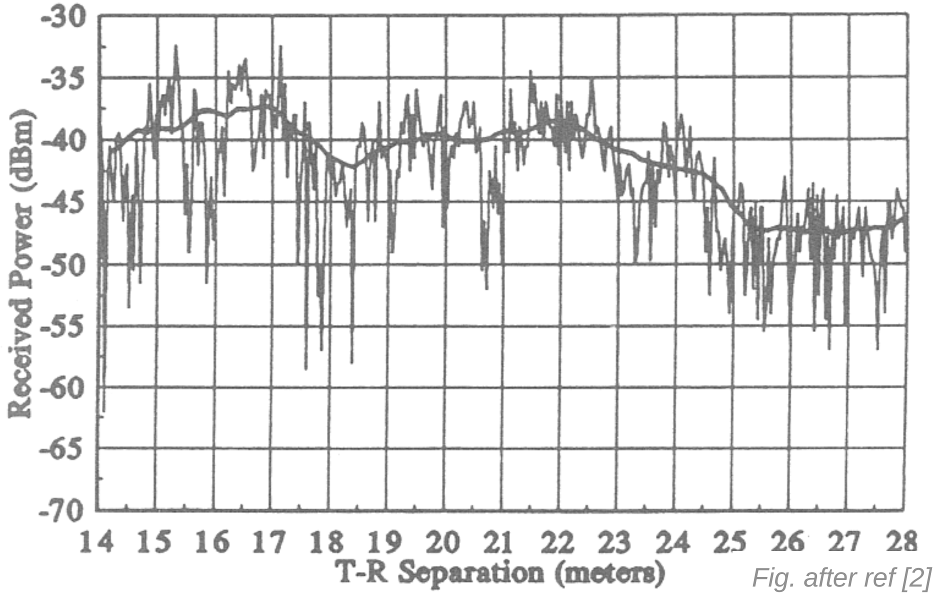

Fig. after ref [2]

- **The fade may be frequency selective if the channel impulse response (CIR) is long enough.**
- **What can we do to mitigate the effects of space and frequency selectivity?**

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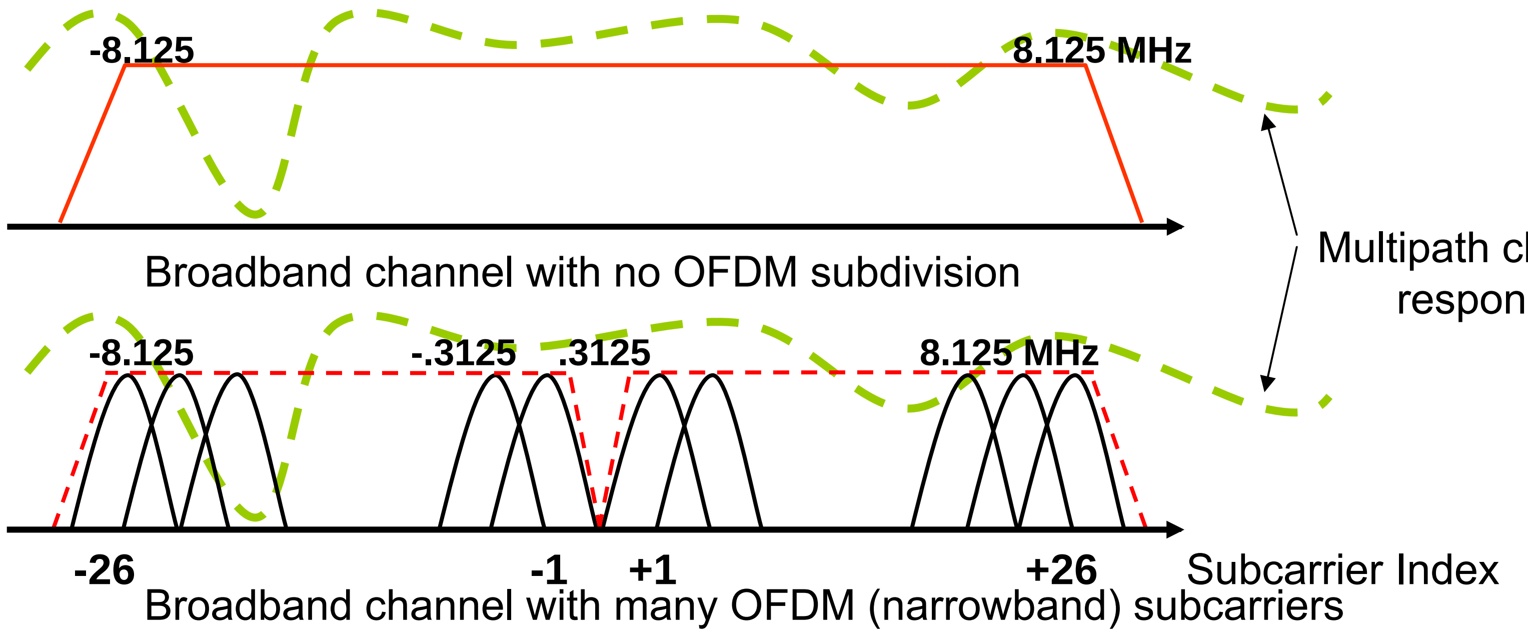
Diversity

- **One or more dimensions ("degrees of freedom") can be exploited in a fading wireless system for diversity.**
  - Time
    - Interleaving of coded symbols (not done in 802.11 systems due to high channel coherence time).
  - Frequency
    - when bandwidth of the modulated signal is wider than the coherence bandwidth of the channel
    - Can be implemented in the form of:
      - Spectrum spreading
      - Coding and interleaving across frequency
  - Space
    - Use of multiple Rx and/or Tx antennas
      - Selection diversity (tx or rx)
      - Space-time or space-frequency coding (tx)
      - Combining (rx)

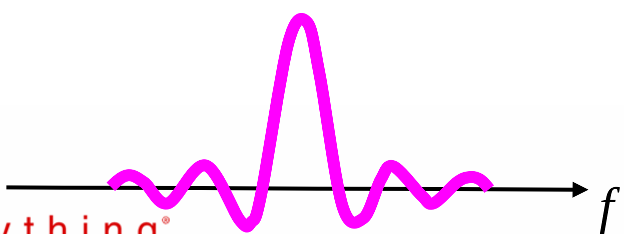
Wideband Modulation over the Wireless Channel

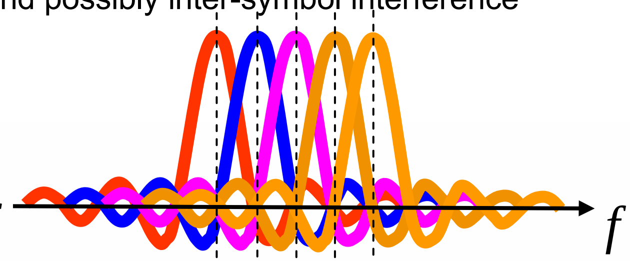
- **The received signal in a multi-path environment will suffer “fades” as shown below.**
- **For wideband channels (as in 802.11n) the fade is often frequency-selective.**
- **Orthogonal Frequency Division Multiplexing (OFDM) divides the frequency-selective channel into approximately frequency-flat bins through an orthogonal transform.**



OFDM and Frequncy Diversity in 802.11n

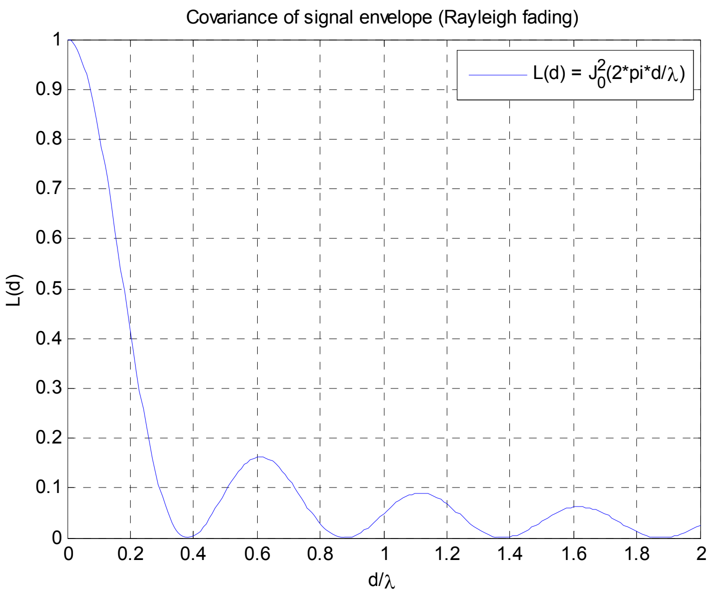
- **The 802.11n standard is based on OFDM.**
- **OFDM addresses multi-path frequency selectivity and introduces frequency diversity through subdivision of the channel into parallel approximately flat-fading sub-channels and coding+interleaving across frequency (*e.g.,* BICM).**
- **Signal is sub-divided into N sub-carriers, which are orthogonal to each other under certain conditions, through the use of an orthogonal transformation such as the DFT/IDFT.**
  - Typically, a cyclic prefix (CP) is defined to ensure orthogonality in the presence of a multipath channel.
    - The values of the CP may be the last M samples of the output of the IDFT.
    - The guard interval (GI), or duration of the CP, is chosen to be somewhat longer than typical long channel.
  - Orthogonality deteriorates because of long channels, phase noise, distortion, frequency inaccuracy, IQ imbalance, …
    - Causes inter-subcarrier interference and possibly inter-symbol interference

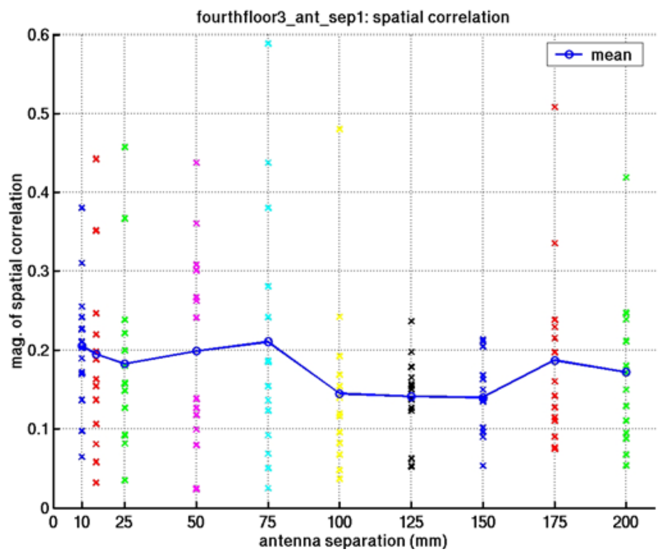




Multi-Antenna Systems: Spatial Diversity

- **Can be achieved by using multiple antennas at the transmitter or the receiver**
- **Antennas are required to be placed “sufficiently” far apart in order to**
  - Need to have uncorrelated signal envelope values at antenna inputs.
  - In an indoor environment, an antenna separation of greater than ½ carrier wavelength is often quoted as the minimum separation to exploit spatial diversity.
  - In practice, smaller separations may be used.





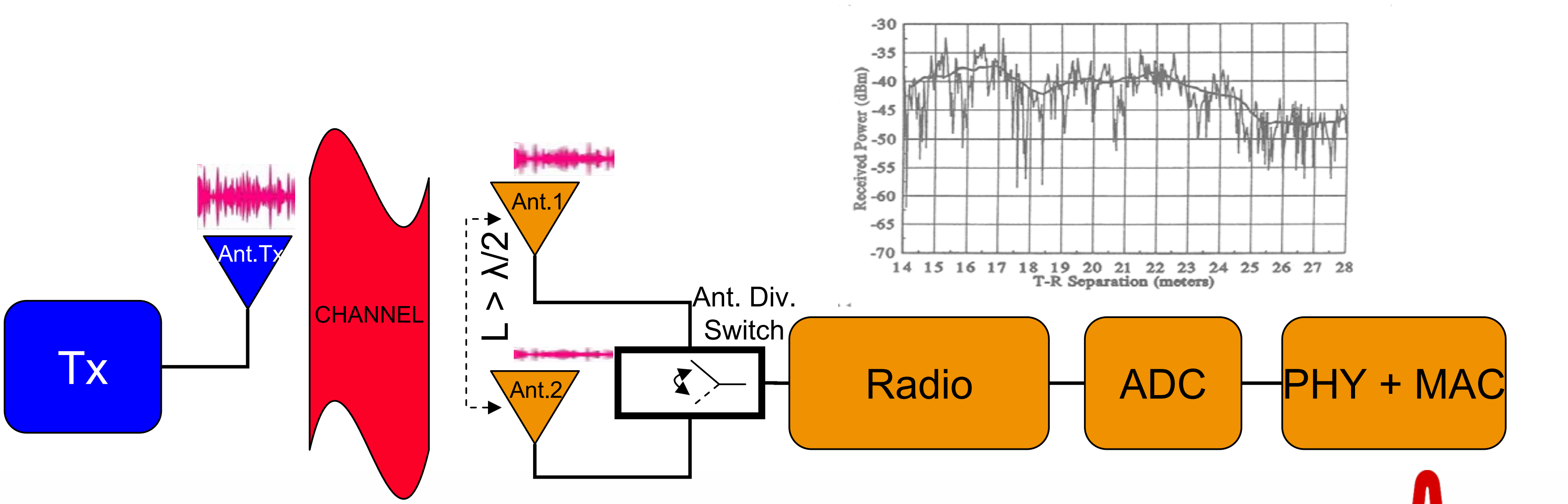
5.24 GHz measured indoor channels (40 MHz BW)

$$R^{rx}_{m,l} = \frac{\sum_{k=0}^{K-1}\sum_{i=0}^{N-1} \hat{H}_k(i,m)\cdot \hat{H}_k^*(i,l)}{\left(\sum_{k=0}^{K-1}\sum_{i=0}^{N-1} \hat{H}_k(i,m)\cdot \hat{H}_k^*(i,m)\right)^{1/2}\cdot\left(\sum_{k=0}^{K-1}\sum_{i=0}^{N-1} \hat{H}_k(i,l)\cdot \hat{H}_k^*(i,l)\right)^{1/2}}$$

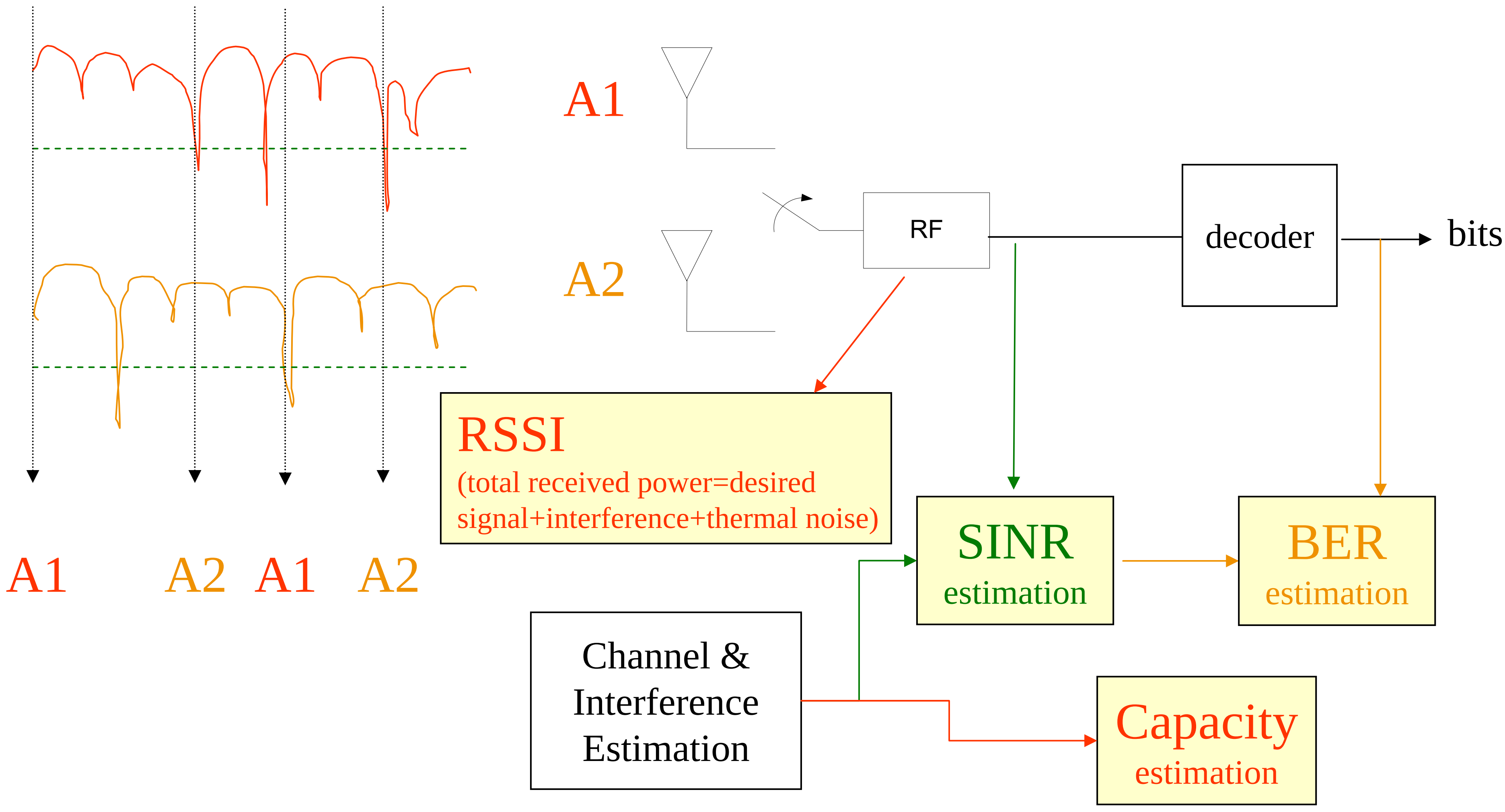
$$\hat{H}_k(i,j) = H_k(i,j) - \frac{1}{K\cdot N}\cdot\sum_{k=0}^{K-1}\sum_{n=0}^{N-1} H_k(n,j)$$

Selection Diversity Using RSSI

- **In a simple Rx *selection-diversity* system:**
  - – Received power at each antenna is examined in turn (during preamble processing, for example)
    - Often a “diversity switch” is used to multiplex the antennas to the common receiver block
  - – The antenna path with the largest signal strength is selected



Antenna Selection Criteria

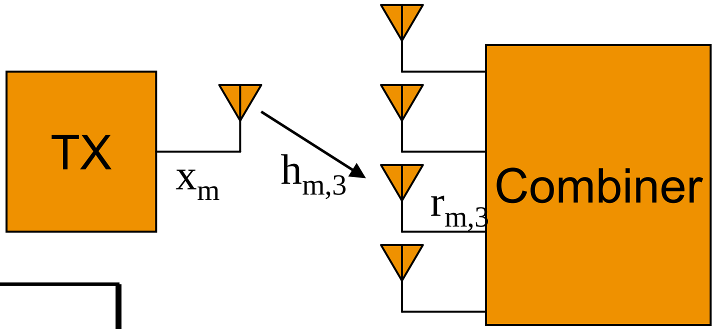


Maximal Ratio Combining (MRC)

- **One can also combine antenna outputs instead of selecting the “best” set.**
- **In OFDM, MRC may be performed on a per subcarrier (m=1..num_subcarriers) basis to help reduce multipath deep nulls.**
- **The combiner weights from each branch are adjusted independently from other branches according to its branch SNR:**

$$r_{m,k} = h_{m,k} \cdot x_m + \eta_m, \qquad y_m = \sum_{k=1}^{M} w_{m,k}^H \cdot r_{m,k}$$

$$w_{m,k} = h_{m,k}$$



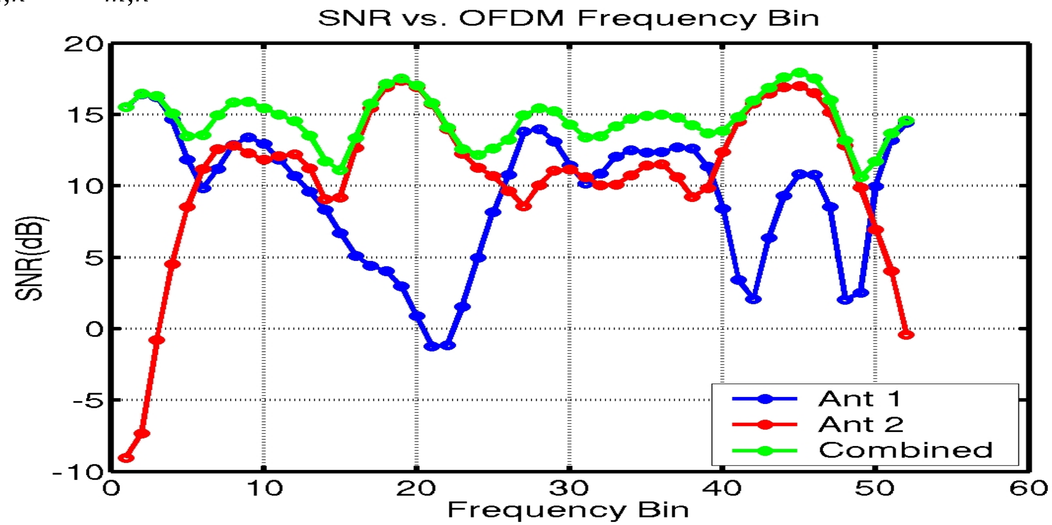
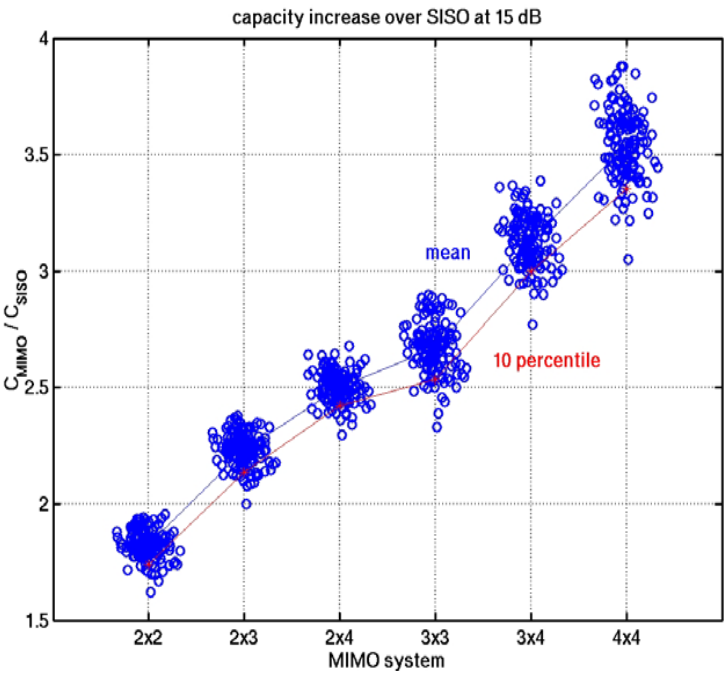


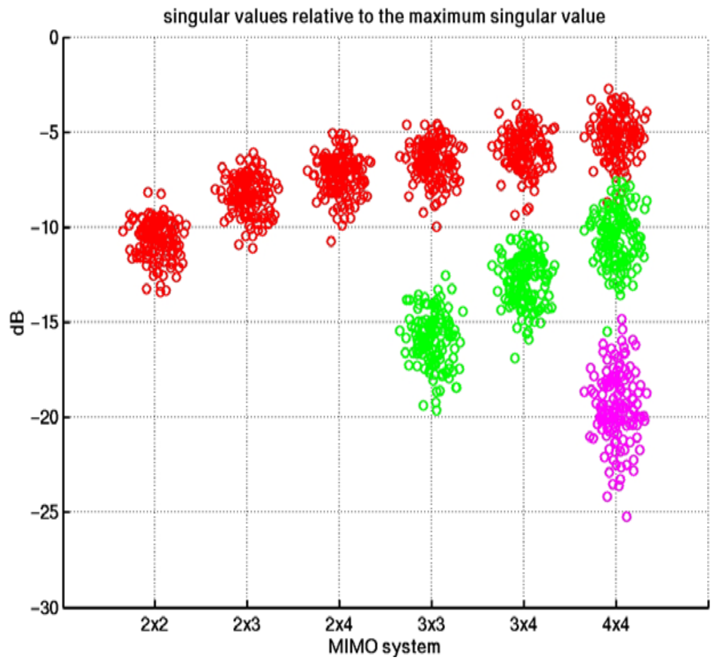
Fig. after ref [3]

Now, can we exploit multipath propagation to increase data rates?

Connecting everything®

Exploiting Multipath for Higher Rates: Constant-energy Capacity Increase





Red: ratio of 2nd to 1st singular value

Green: ratio of 3rd to 1st singular value

Magenta: ratio of 4th to 1st singular value

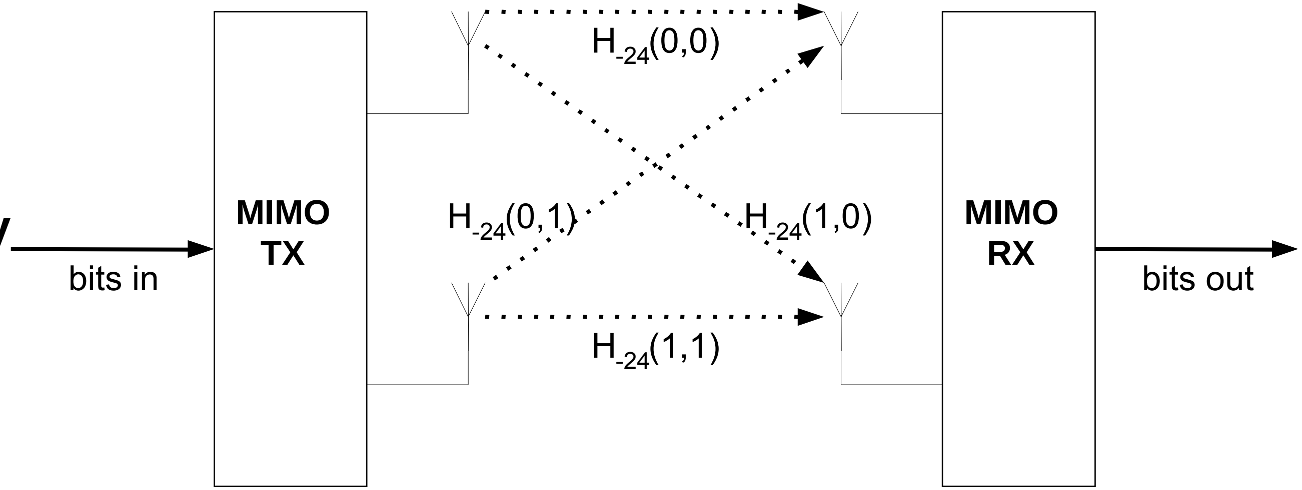
$$\eta_k = \log_2\left(\det\left[I_N + \frac{\rho}{N_{TX}} \cdot H_k \cdot H_k^{*}\right]\right) = \sum_{n=0}^{N_{RX}-1} \log_2\left(1 + \frac{\rho}{N_{TX}} \cdot \sigma_{k,n}^2\right) \le \min(N_{TX}, N_{RX}) \cdot \log_2\left(1 + \frac{\rho}{N_{TX}}\right)$$

Each circle represents a location on one floor of an office building with offices, cubicles and labs. Notice the roughly linear increase in capacity. σ are the singular values of H.

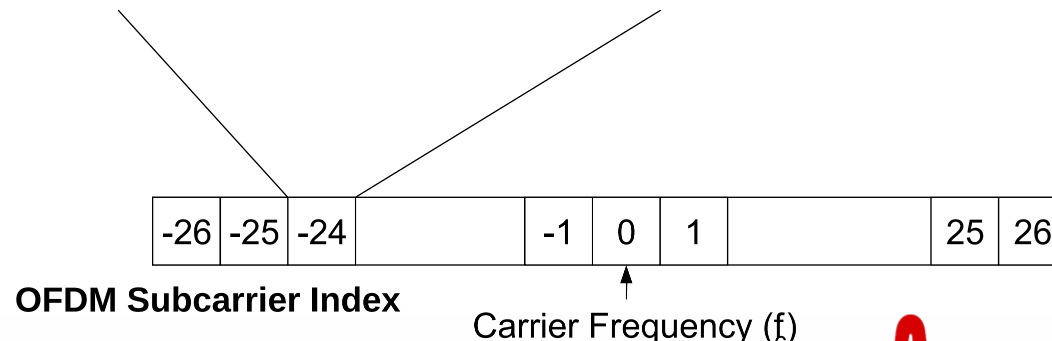
The ratio of the first to second singular value decreases as M and N increase → There is always a benefit to using more antennas for k <= min(M,N) spatial streams, though the benefit diminishes.

Space Division Multiplexing (SDM) with MIMO-OFDM

- **In OFDM, the channel is broken into L (in this case, 53) parallel flat-fading channels, each represented by a single complex coefficient.**
- **In MIMO OFDM, there is an NxM complex-valued matrix of channel coefficients per subcarrier, where M is the number of transmitter antennas and N is the number of receiver antennas.**

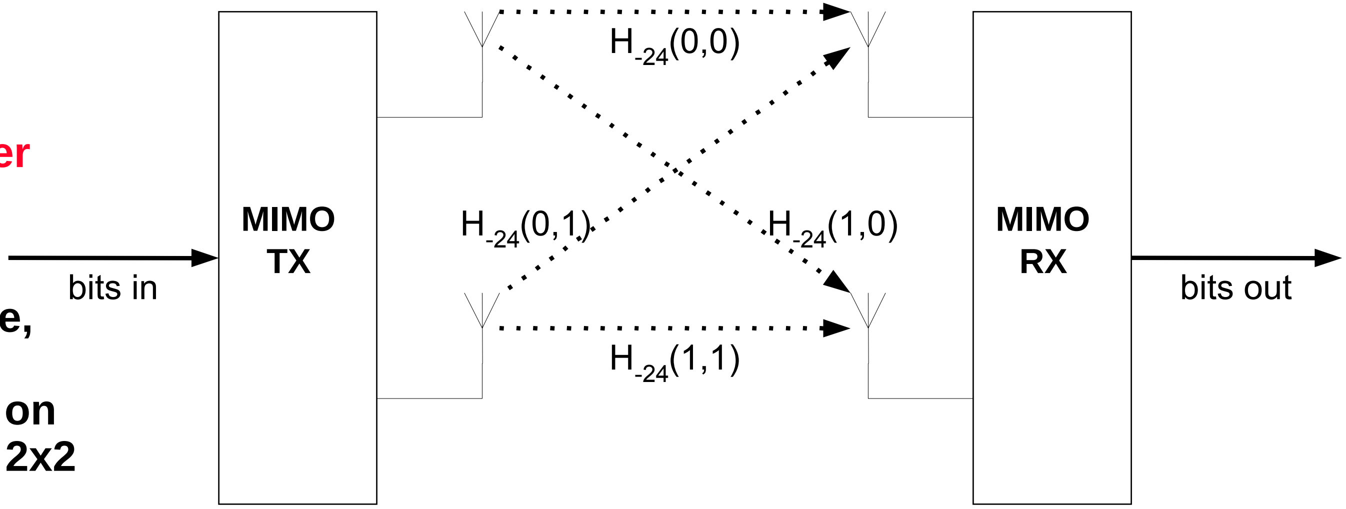


$$\begin{pmatrix} Y_{-24}(0) \\ Y_{-24}(1) \end{pmatrix} = \begin{pmatrix} H_{-24}(0,0) & H_{-24}(0,1) \\ H_{-24}(1,0) & H_{-24}(1,1) \end{pmatrix} \cdot \begin{pmatrix} X_{-24}(0) \\ X_{-24}(1) \end{pmatrix} + \begin{pmatrix} N_{-24}(0) \\ N_{-24}(1) \end{pmatrix}$$



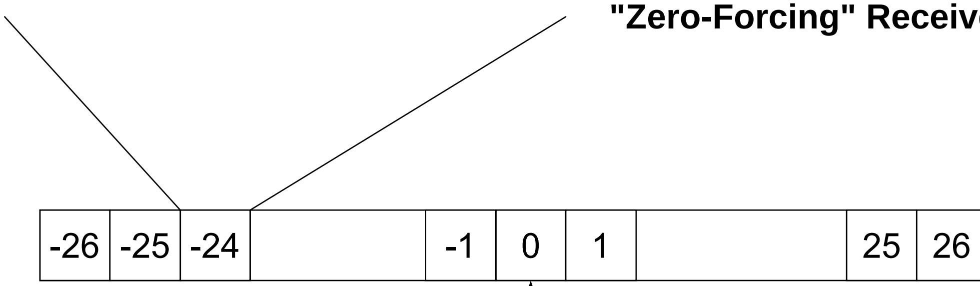
Space Division Multiplexing (SDM) Receivers

- **One can transmit an independent data stream on each transmit antenna provided the receiver has at least two antennas.**
- **In this 2x2 SDM case, the data may be recovered perfectly on any subcarrier if its 2x2 channel matrix is invertible (2 equations, 2 unknowns) and SNR is high enough.**
- **The simplest linear receiver inverts the channel matrix to recover transmitted symbols and is referred to as “Zero-Forcing”.**



$$\begin{pmatrix} \hat{X}_{-24}(0) \\ \hat{X}_{-24}(1) \end{pmatrix} = \begin{pmatrix} H_{-24}(0,0) & H_{-24}(0,1) \\ H_{-24}(1,0) & H_{-24}(1,1) \end{pmatrix}^{-1} \cdot \begin{pmatrix} Y_{-24}(0) \\ Y_{-24}(1) \end{pmatrix}$$

"Zero-Forcing" Receiver



OFDM Subcarrier Index

Carrier Frequency (f_c)

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Throughput-Enhancing Features of 802.11n

- **Space Division Multiplexing (SDM)**
- **Higher code rate (up to 5/6)**
- **Greater signal bandwidth**
- **MAC-layer aggregation and block acknowledgment (Block ACK)**

Rate-increasing Modulation and Coding Schemes

- **Constructing a basic rate table**
  - 8 modulation+coding sets (MCSs) for 1 spatial stream
  - Range from BPSK rate ½ to 64-QAM rate 5/6
  - Data rates range from 6.5 Mbps to 65 Mbps (72.2 Mbps with short GI)
- **Additional streams are added in a similar manner for SDM**
  - *E.g.*, MCS 8 is BPSK rate=1/2 for each of two streams (13 Mbps).
  - And, so on..

Index	Modulation	Code Rate	Data Rate (Mbps)
0	BPSK	½	6.5
1	QPSK	½	13
2	QPSK	¾	19.5
3	16-QAM	½	26
4	16-QAM	¾	39
5	64-QAM	2/3	52
6	64-QAM	¾	58.5
7	64-QAM	5/6	65

Fragment of the 802.11n Draft Modulation/Coding Set (MCS)

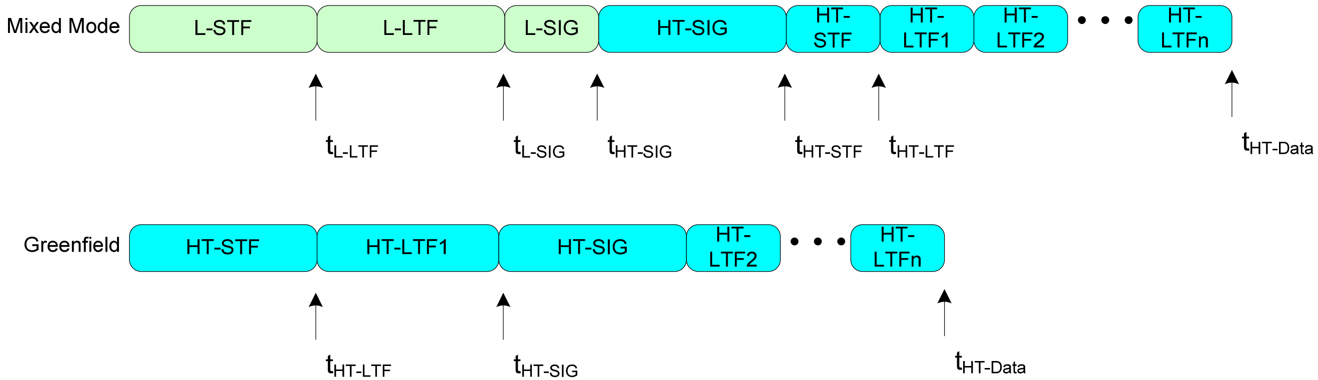
Bits 0-6 in HT-SIG1 (MCS index)	Number of spatial streams	Modulation	Coding rate	N_{ES}		N_{SD}		N_{CBPS}		GI = 800ns		GI = 400ns	
				20	40	20	40	20MHz	40MHz	Rate in 20MHz	Rate in 40MHz	Rate in 20MHz	Rate in 40MHz
0	1	BPSK	½	1	1	52	108	52	108	6.5	13.5	7 2/9	15
1	1	QPSK	½	1	1	52	108	104	216	13	27	14 4/9	30
2	1	QPSK	¾	1	1	52	108	104	216	19.5	40.5	21 2/3	45
3	1	16-QAM	½	1	1	52	108	208	432	26	54	28 8/9	60
4	1	16-QAM	¾	1	1	52	108	208	432	39	81	43 1/3	90
5	1	64-QAM	⅔	1	1	52	108	312	648	52	108	57 7/9	120
6	1	64-QAM	¾	1	1	52	108	312	648	58.5	121.5	65	135
7	1	64-QAM	5/6	1	1	52	108	312	648	65	135	72 2/9	150
8	2	BPSK	½	1	1	52	108	104	216	13	27	14 4/9	30
9	2	QPSK	½	1	1	52	108	208	432	26	54	28 8/9	60
10	2	QPSK	¾	1	1	52	108	208	432	39	81	43 1/3	90
11	2	16-QAM	½	1	1	52	108	416	864	52	108	57 7/9	120
12	2	16-QAM	¾	1	1	52	108	416	864	78	162	86 2/3	180
13	2	64-QAM	⅔	1	1	52	108	624	1296	104	216	115 5/9	240
14	2	64-QAM	¾	1	1	52	108	624	1296	117	243	130	270
15	2	64-QAM	5/6	1	1	52	108	624	1296	130	270	144 4/9	300

Maximum rate in shipping products today.

MCS indices 16-31 cover 3- and 4-spatial-stream symmetric encodings. MCS 32 is a special frequency-diverse mode. MCS indices 33-77 cover asymmetric encodings.

802.11n Frame Formats

- **The 802.11n Draft defines a "greenfield" and a "mixed mode" format.**
  - "Greenfield" frames are used for channels and time periods during which all legacy devices are inactive.
  - "Mixed mode" frames include a legacy prefix to trigger physical carrier sense of legacy devices.
- **The "high-throughput" (HT) and legacy short training fields (HT-STF and L-STF) use the 802.11a short symbols with cyclic shifts on additional antennas.**
  - Different shifts are used on HT and legacy portions.
- **The HT long training fields use the 802.11a long symbols with cyclic shifts on additional antennas and multiplication by a matrix with orthogonal columns.**
  - [1 1; 1 -1] for 2 spatial mapper inputs.
  - [1 -1 1 1; 1 1 -1 1; 1 1 1 -1; -1 1 1 1] for 3 and 4 spatial mapper inputs.
  - STBC 2x1 is defined in the spec. as "2 spatial-mapper inputs" (N_{SMI} = 2).



n is 1, 2, and 4 for N_{SMI} = 1, 2, and 4 and 4 for N_{SMI} = 3.

HT-LTF Construction

- **The HT-LTFs are constructed using the following base matrix:**

$$P_{HTLTF} = \begin{pmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 \end{pmatrix}$$

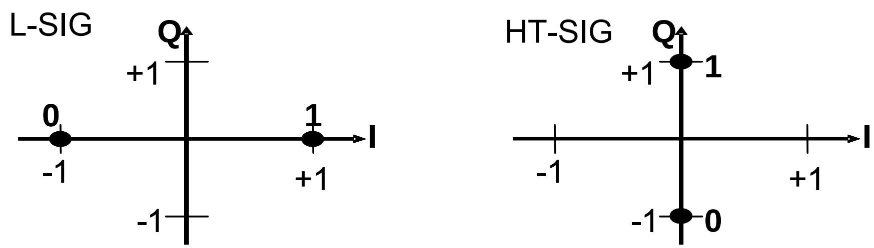
- **The following table shows the number of HT-LTFs transmitted for frames using 1-4 spatial mapper inputs:**

Number of spatial mapper inputs (N_{SMI})	Number of HT-LTFs
1	1
2	2
3	4
4	4

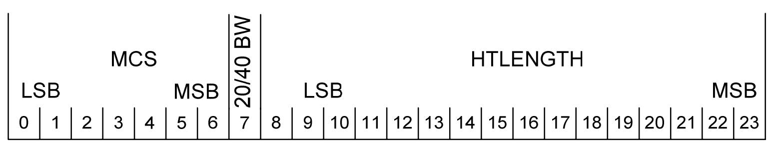
- **For 1-3 spatial streams, the bottom row(s) of the $P_{HT\text{-}LTF}$ matrix shown above is (are) deleted.**

High-Throughput SIGNAL Field (HT-SIG)

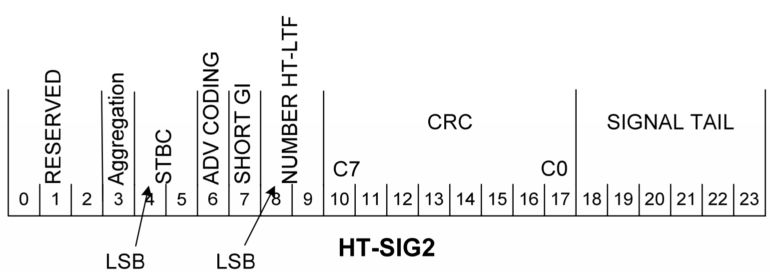
- **Each 4-usec symbol in the HT-SIG field is encoded as +90-degree rotated BPSK.**
  - Distinguishing HT-SIG in from legacy transmissions is straightforward.



- **HT-SIG1 is the first HT-SIG symbol transmitted in time.**

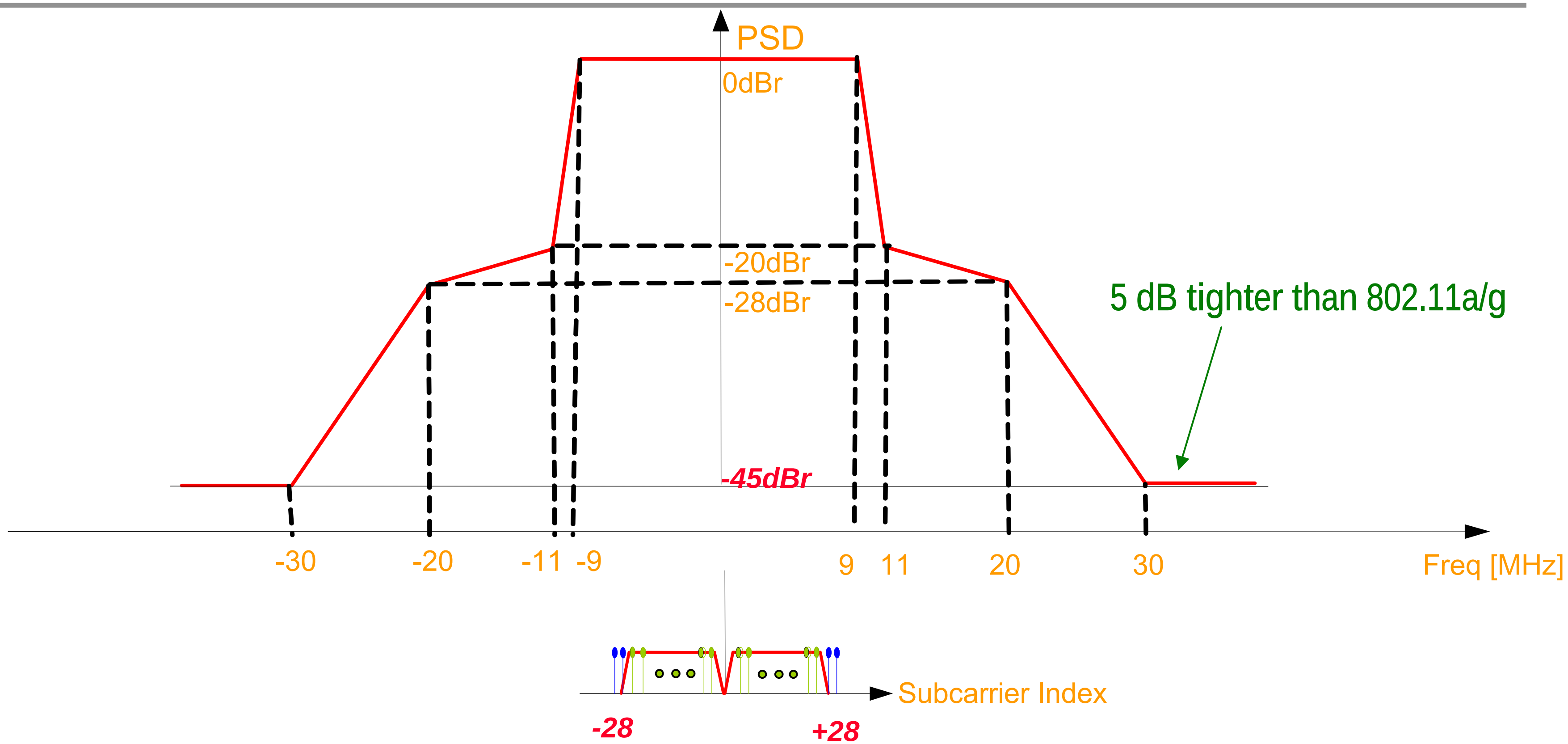


HT-SIG1



HT-SIG2

Bandwidth Extension: 802.11n 20MHz Mode Spectral Mask

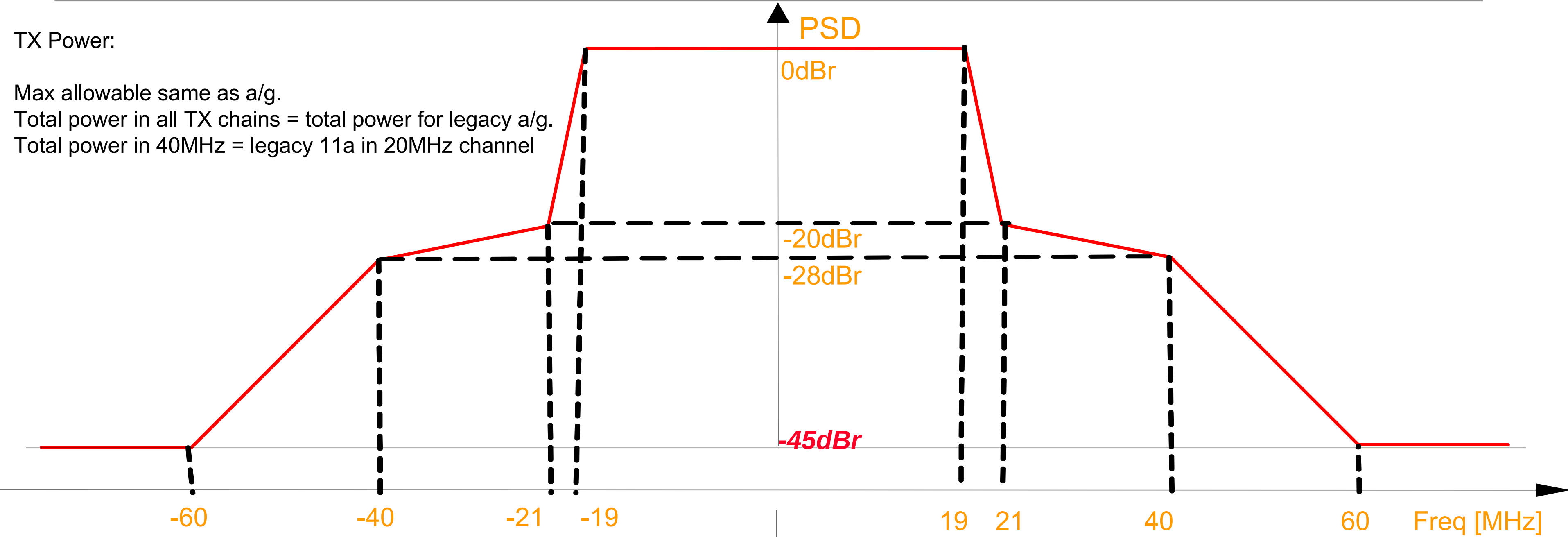


- **For 802.11n 20MHz mode, the spectral mask floor is set to -45dBr.**
- **For 802.11n 20MHz mode, there are a total of 56 subcarriers (indices-28 through 28 with 0 excluded)**
  - 8% increase in PHY rate relative to legacy A/G

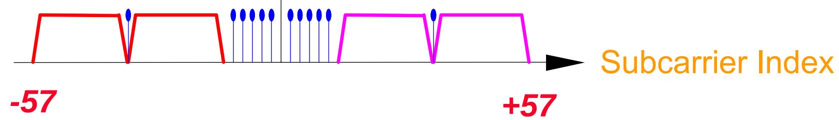
Bandwidth Extension: 802.11n 40MHz Mode Spectral Mask

TX Power:

Max allowable same as a/g.
Total power in all TX chains = total power for legacy a/g.
Total power in 40MHz = legacy 11a in 20MHz channel



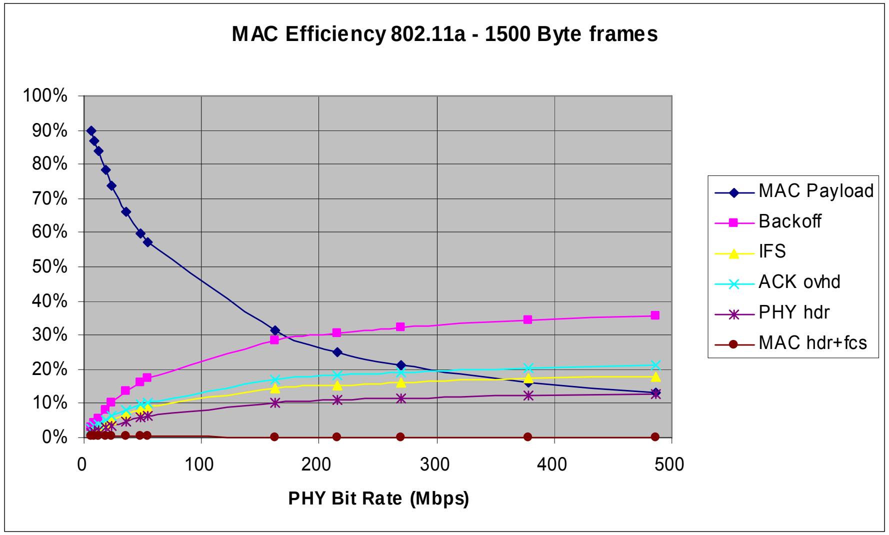
20MHz-mode tones moved up and down by 20MHz, the DC tones filled and additional tones are added in the middle (added tones shown in blue)

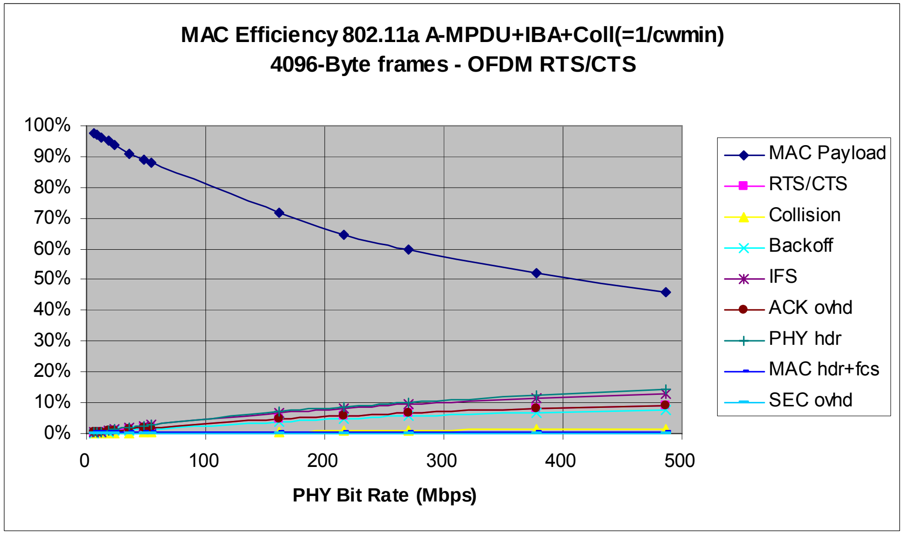


- **For 802.11n 40MHz mode, the spectral mask floor is set to -45dBr.**
- **For 802.11n 40MHz mode, there are a total of 114 subcarriers (indices -57 through +57 with 0 excluded)**
  - Use of 108 data subcarriers increases PHY rate by 2.25x relative to legacy A/G

MAC Improvements: Why Aggregate Frames?

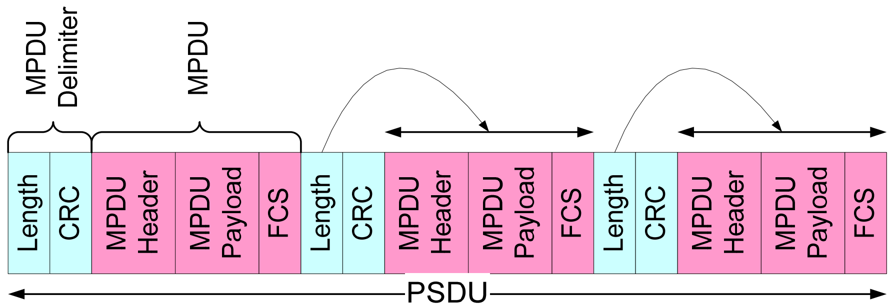
- **RTS/CTS/A-MPDU/IBA *vs.* DATA/ACK improvement**
  - At a 300 Mbps PHY rate, 60 Mbps throughput is the upper bound for a UDP-like flow with an unmodified DCF MAC.
  - Throughput is around 180 Mbps (or better) with A-MPDU and Immediate BA



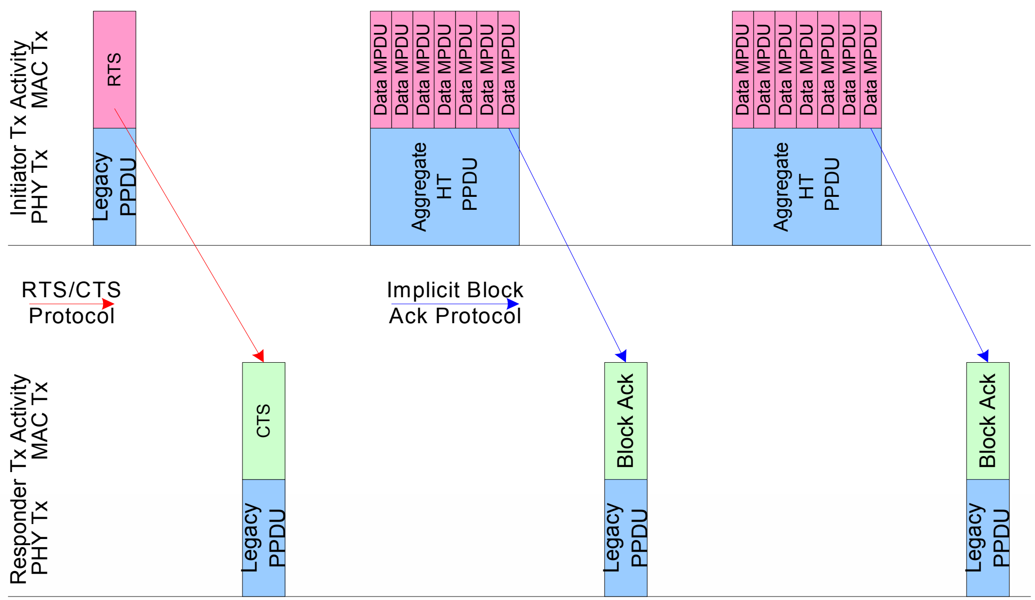


A-MPDU Aggregation

- **Control and data MPDUs (MAC Protocol Data Units) can be aggregated**
- **PHY has no knowledge of MPDU boundaries**

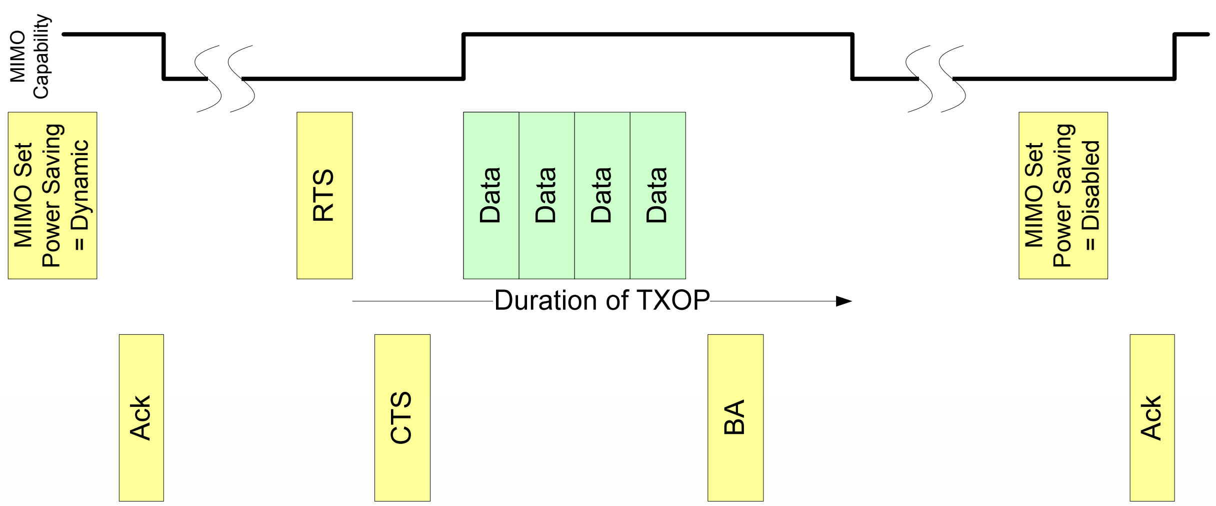


A-MPDU + Block ACK provide the most significant boost to MAC efficiency.



MIMO Power Save

- **Allows RX to remain in steady state with one RX chain**
- **Modes: Disabled (fully MIMO capable), Static, Dynamic**
- **Dynamic MIMO Power save mode**
  - Move to multiple RX chains when it gets RTS directed to it
  - Switch back after sequence ends
  - STA or AP can request partner to issue RTS in front of MIMO frame sequence
- **Static MIMO Power save mode (Reduce MIMO capability)**
  - STA requests AP to not send MIMO frames to it
- **Signalled:**
  - HT Capabilities Element
  - MIMO Power Save management action frame

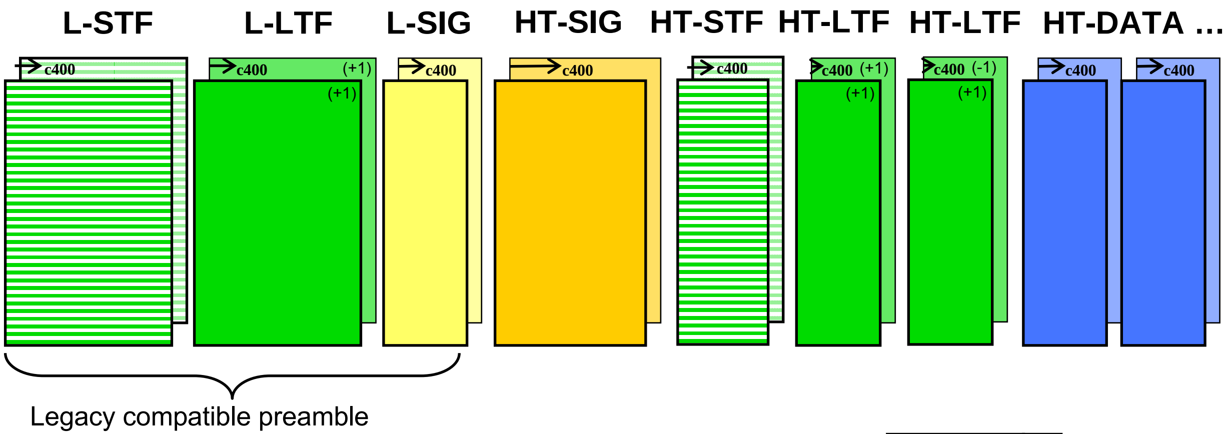


Outline

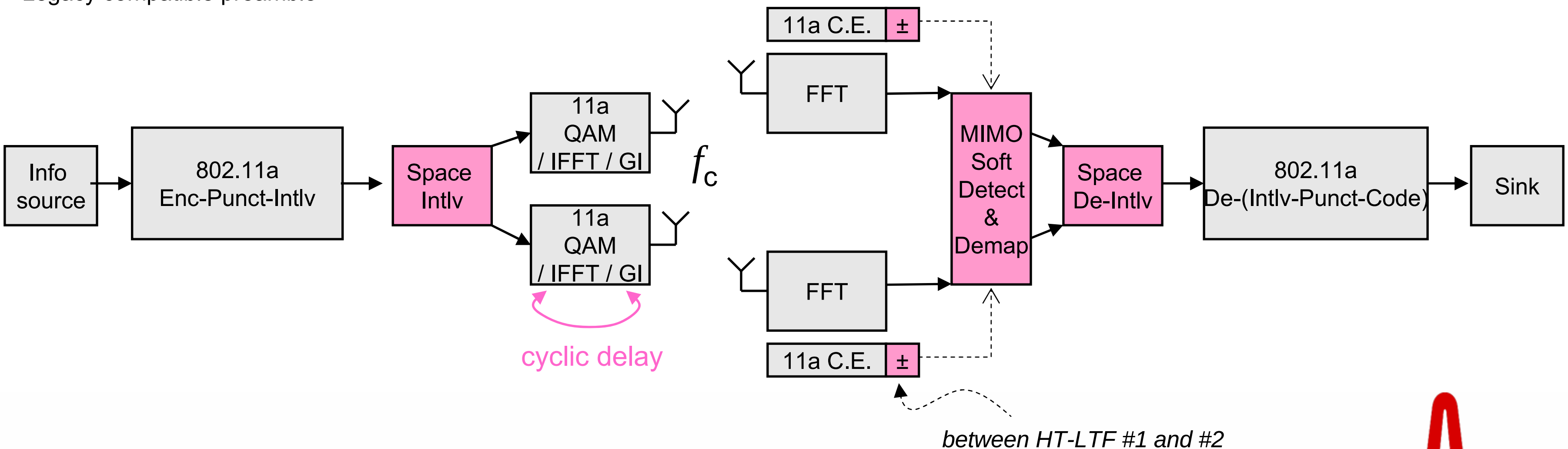
- IEEE 802.11 Overview
- The Indoor Wireless Channel
- Approaches to Improving Robustness and Data Rate
- More 802.11n Draft Details
- **MIMO Transceiver Design Challenges and Solutions**
- Broadcom's First MIMO Baseband IC

2x2 SDM In the Context of an OFDM Transmitter/Receiver

“Mixed Mode” High Throughput (HT) Frame Format



- Space Division Multiplexing (SDM) up to 130 Mbps in 20 MHz bandwidth or 270 Mbps in 40 MHz bandwidth (64-QAM, 5/6 rate)
- Use 400ns cyclic advance on Short Training and 400ns cyclic advance on Long Training, SIGNAL fields and DATA.
- Long Training using time orthogonality between HT-LTF #s 1 and 2; channel estimation in frequency domain reusing 11a/g blocks



Receiver Types for SDM

- **Zero Forcing (ZF)**
  - Simplest receiver type (covered in intro to SDM)
  - Poor performance on channels with high condition number and at low SNR
    - Nrx > Nss in general for decent performance
- **MMSE-LE**
  - Incorporates knowledge of input SNR
  - Far higher complexity than ZF but better performance at low SNR
  - Poor performance on channels with high condition number
    - Nrx > Nss in general for decent performance
- **Interference-cancelling**
  - Suffers large losses from error propagation with one FEC encoder
    - Generally a poor choice for 802.11n
- **ML Detector**
  - Best performance achievable open-loop while also meeting rx-tx timing requirement
  - Achieves full diversity
  - High complexity without clever tricks

ML Detector and Complexity

- **2x2 MIMO system using M²-QAM modulation**

$$\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_{1,I} + jx_{1,Q} \\ x_{2,I} + jx_{2,Q} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

where

x is the transmitted symbol, with $x_{k,\mathrm{I}}$ the in-phase component and $x_{k,\mathrm{Q}}$ the quadrature component of x_k , $k = 1,2$

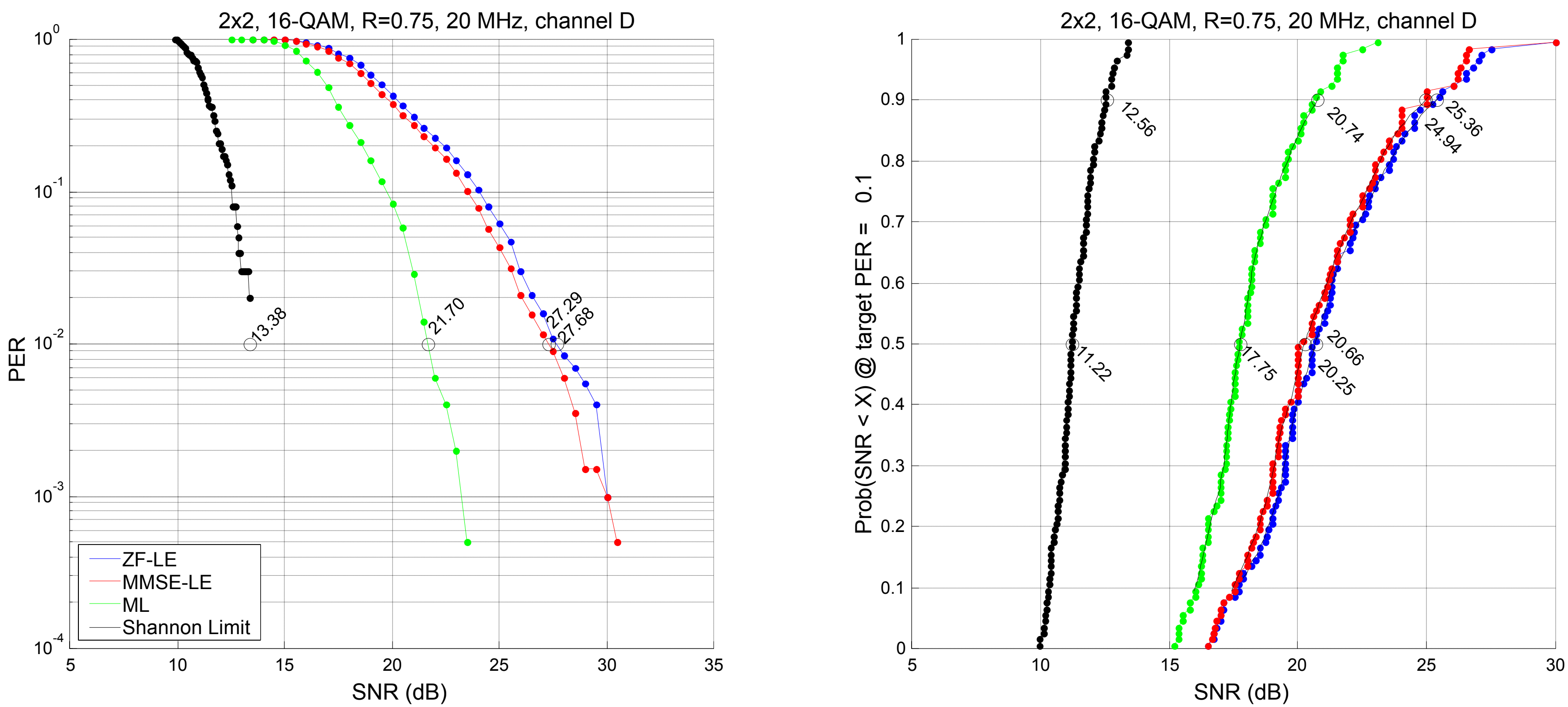
H is the channel matrix

n is the noise: n_1 and n_2 are i.i.d. complex Gaussian random variables with mean 0 and variance σ^2

r is the received signal

- **Brute force MLD**
  - Log-likelihood ratio for bit k is $L_k = \frac{1}{\sigma^2}\left(\min_{\mathbf{x}|b_k=-1} - \min_{\mathbf{x}|b_k=1}\right)\|\mathbf{r}-\mathbf{H}\mathbf{x}\|^2$
  - Must compute $\|\mathbf{r}-\mathbf{H}\mathbf{x}\|^2$ for each M^4 possible combination of QAM symbols
  - Requires $20M^4$ multiplies and $12M^4$ adds per subcarrier per 4D symbol
  - Provides receiver diversity order 2 with two antenna outputs
- **Complexity of efficient approach (per subcarrier per 4D symbol):**
  - $M^2/8 + M/4 + 73$ multiplies, $[18 + 4\log_2(M)]M^2+78$ adds
  - Also need $4\log_2 M$ low-precision divisions for global scaling of each LLR by $1/K\sigma^2$
  - Comparisons for 64-QAM (M=8)
    - Brute force ML -- 81920 multiplies and 49152 adds plus overhead
    - Efficient ML -- 83 multiplies, 1998 adds including overhead

2x2 Nss=2 ML Performance – Channel D NLOS



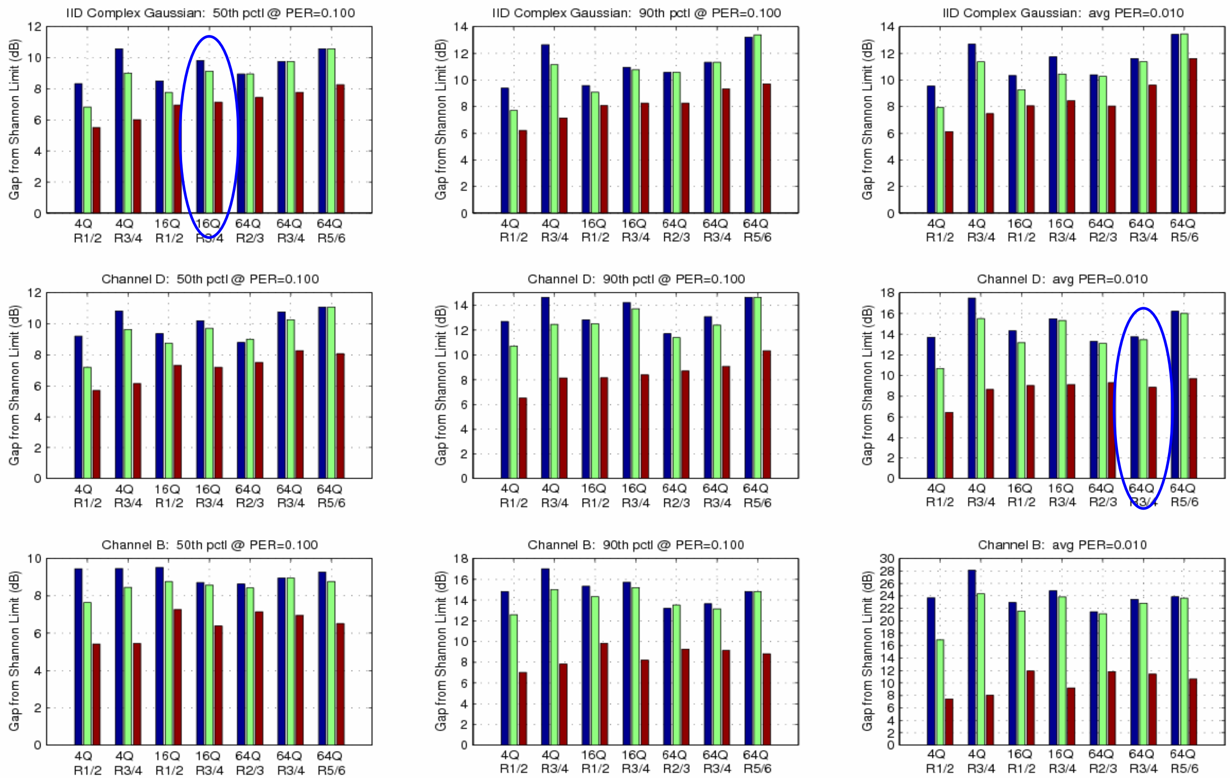
test1_M4_R75_2x2_D_SL: 3.48 minutes, 100 channels X 20 pkts, avg 3.42 SNR pts per pkt, 0.06 dB resolution, avg 0.03 sec per demod
test1_M4_R75_2x2_D_ZF: 136.83 minutes, 100 channels X 20 pkts, avg 3.41 SNR pts per pkt, 0.50 dB resolution, avg 1.20 sec per demod
test1_M4_R75_2x2_D_LE: 140.64 minutes, 100 channels X 20 pkts, avg 3.49 SNR pts per pkt, 0.50 dB resolution, avg 1.21 sec per demod
test1_M4_R75_2x2_D_ML: 172.67 minutes, 100 channels X 20 pkts, avg 3.24 SNR pts per pkt, 0.50 dB resolution, avg 1.60 sec per demod

2x2 Nss=2 Performance Summary

CG0

D

B



ZF–LE
MMSE–LE
ML

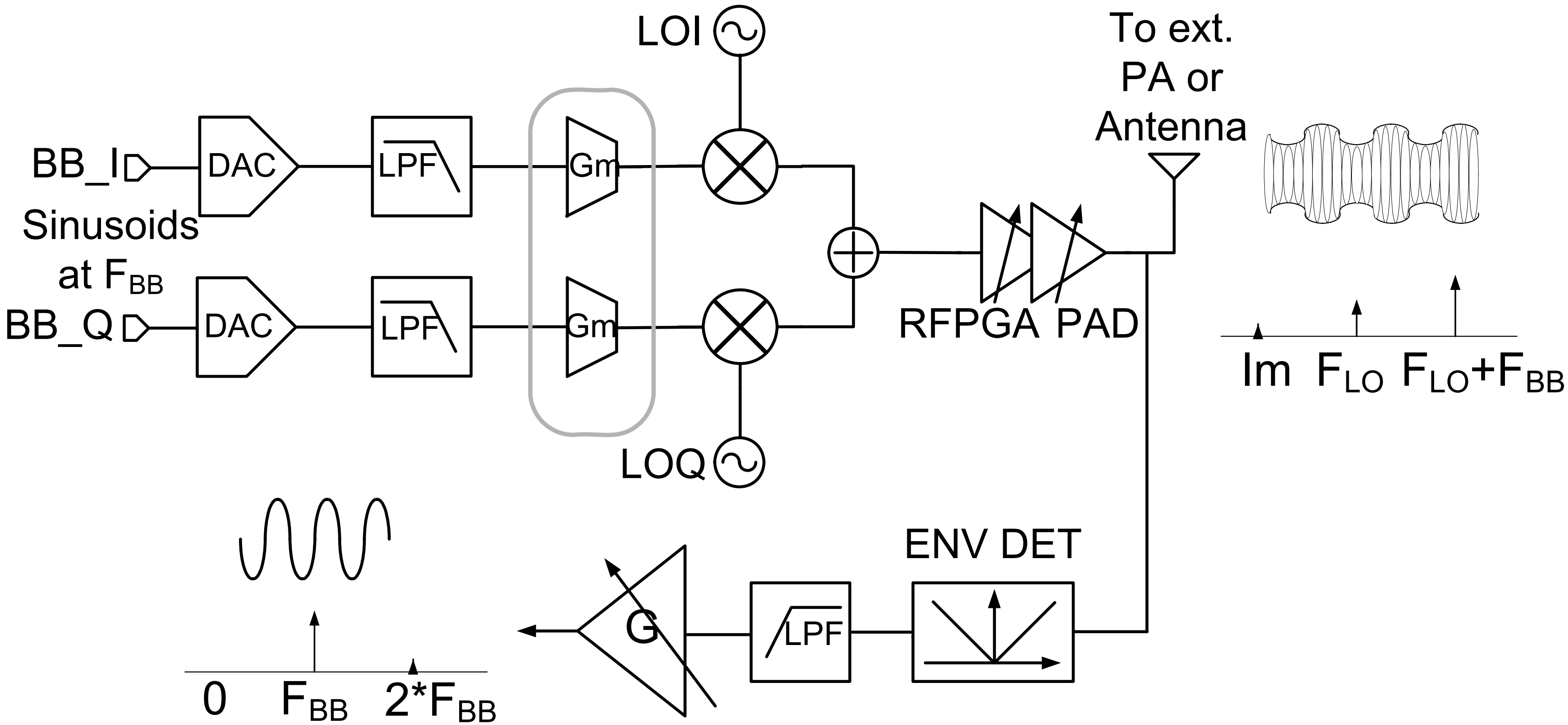
50 channels, 10 pkts per channel, 10,000 data bits per packet.

1. **ZF-LE to MMSE-LE gap is more pronounced at lower SNR (smaller constellations at fixed error rate).**
2. **MMSE-LE/ZF-LE to ML gap is more pronounced on channels with higher condition number (more correlated paths) and at higher code rates (weaker code due to puncturing). *I.e.,* ML helps on poor channels at the highest data rates.**

802.11n Radio Design Challenges and Baseband Solutions

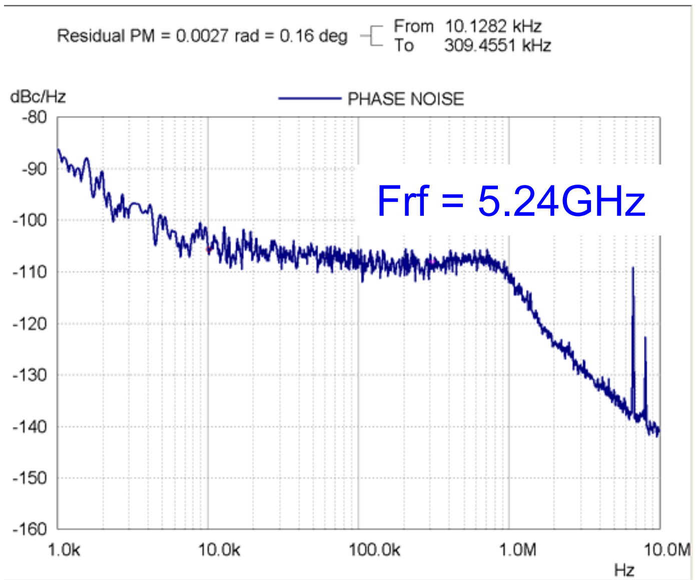
- **Receiver dynamic range**
  - Must deal with desired signals from roughly +5 to almost -100 dBm at the LNA input
  - Must deal with blockers with carrier frequency offset as little as 25 MHz away and power as much as 35 dB greater than desired signal
  - Requires high-dynamic-range AGC and sensitive carrier detector.
- **Transmit error vector magnitude (EVM)**
  - Must meet tight EVM requirements for highest OFDM rate (< -28 dB)
    - Requires minimizing phase noise and I-Q imbalance (nonlinear impairments)
    - Requires tight control of output power to avoid PA saturation region
- **Additional challenges for compact direct-conversion receivers**
  - Receiver DC offset
  - Local oscillator (LO) feedthrough at transmitter
  - I-Q imbalance

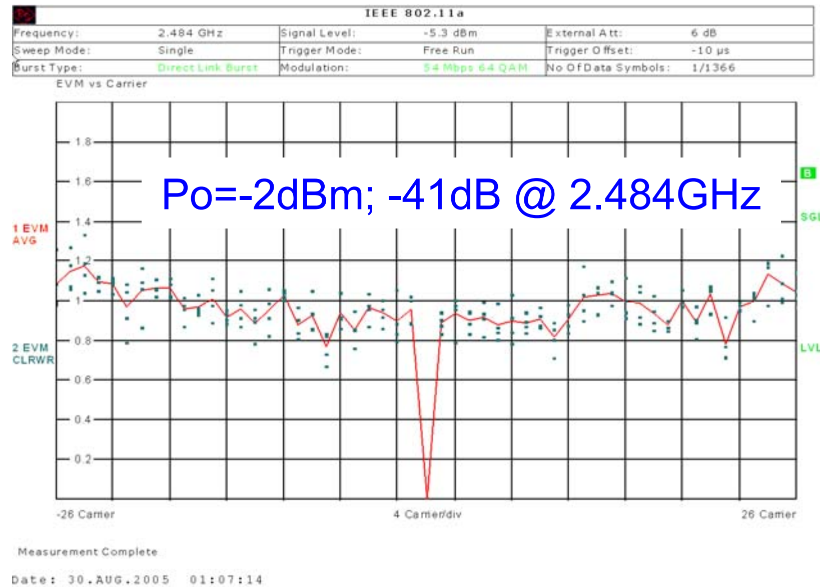
Using the Baseband to Detect/Mitigate LOFT and I-Q Imbalance in Tx

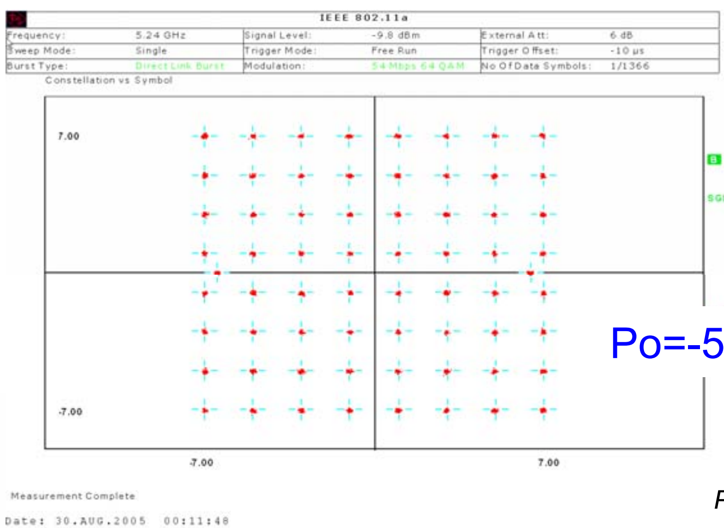


- **Only LOFT shown for simplicity.**
- **Inject Sinusoid at F_{BB}.**
- **ADC+FFT to detect F_{BB} or $2*F_{BB}$.**
- **LOFT at F_{BB}, I/Q imbalance at $2*F_{BB}$.**

Post-calibration Phase Noise and EVM Results







Po=-5dBm; EVM= -40dB @ 5.24GHz

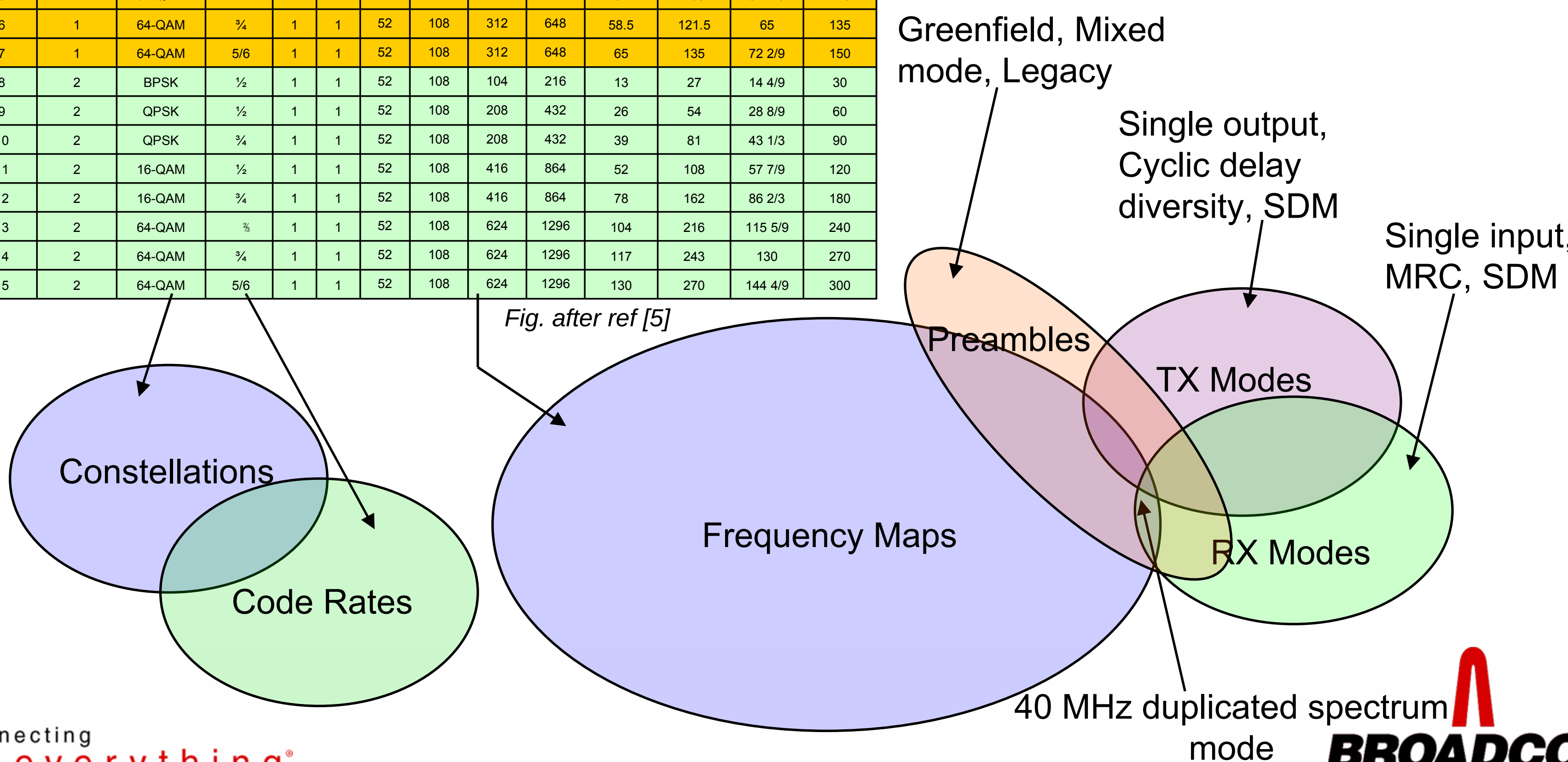
Figs. after ref [4]

The Need for a Flexible Transceiver

Bits 0-6 in HT-SIG1 (MCS index)	Number of spatial streams	Modulation	Coding rate	N_{ES}		N_{SD}		N_{CBPS}		GI = 800ns		GI = 400ns	
				20	40	20	40	20MHz	40MHz	Rate in 20MHz	Rate in 40MHz	Rate in 20MHz	Rate in 40MHz
0	1	BPSK	½	1	1	52	108	52	108	6.5	13.5	7 2/9	15
1	1	QPSK	½	1	1	52	108	104	216	13	27	14 4/9	30
2	1	QPSK	¾	1	1	52	108	104	216	19.5	40.5	21 2/3	45
3	1	16-QAM	½	1	1	52	108	208	432	26	54	28 8/9	60
4	1	16-QAM	¾	1	1	52	108	208	432	39	81	43 1/3	90
5	1	64-QAM	⅔	1	1	52	108	312	648	52	108	57 7/9	120
6	1	64-QAM	¾	1	1	52	108	312	648	58.5	121.5	65	135
7	1	64-QAM	5/6	1	1	52	108	312	648	65	135	72 2/9	150
8	2	BPSK	½	1	1	52	108	104	216	13	27	14 4/9	30
9	2	QPSK	½	1	1	52	108	208	432	26	54	28 8/9	60
10	2	QPSK	¾	1	1	52	108	208	432	39	81	43 1/3	90
11	2	16-QAM	½	1	1	52	108	416	864	52	108	57 7/9	120
12	2	16-QAM	¾	1	1	52	108	416	864	78	162	86 2/3	180
13	2	64-QAM	⅔	1	1	52	108	624	1296	104	216	115 5/9	240
14	2	64-QAM	¾	1	1	52	108	624	1296	117	243	130	270
15	2	64-QAM	5/6	1	1	52	108	624	1296	130	270	144 4/9	300

Fig. after ref [5]

Standards uncertainty and a large number of mode, preamble, and frequency map combinations mandated a flexible implementation.



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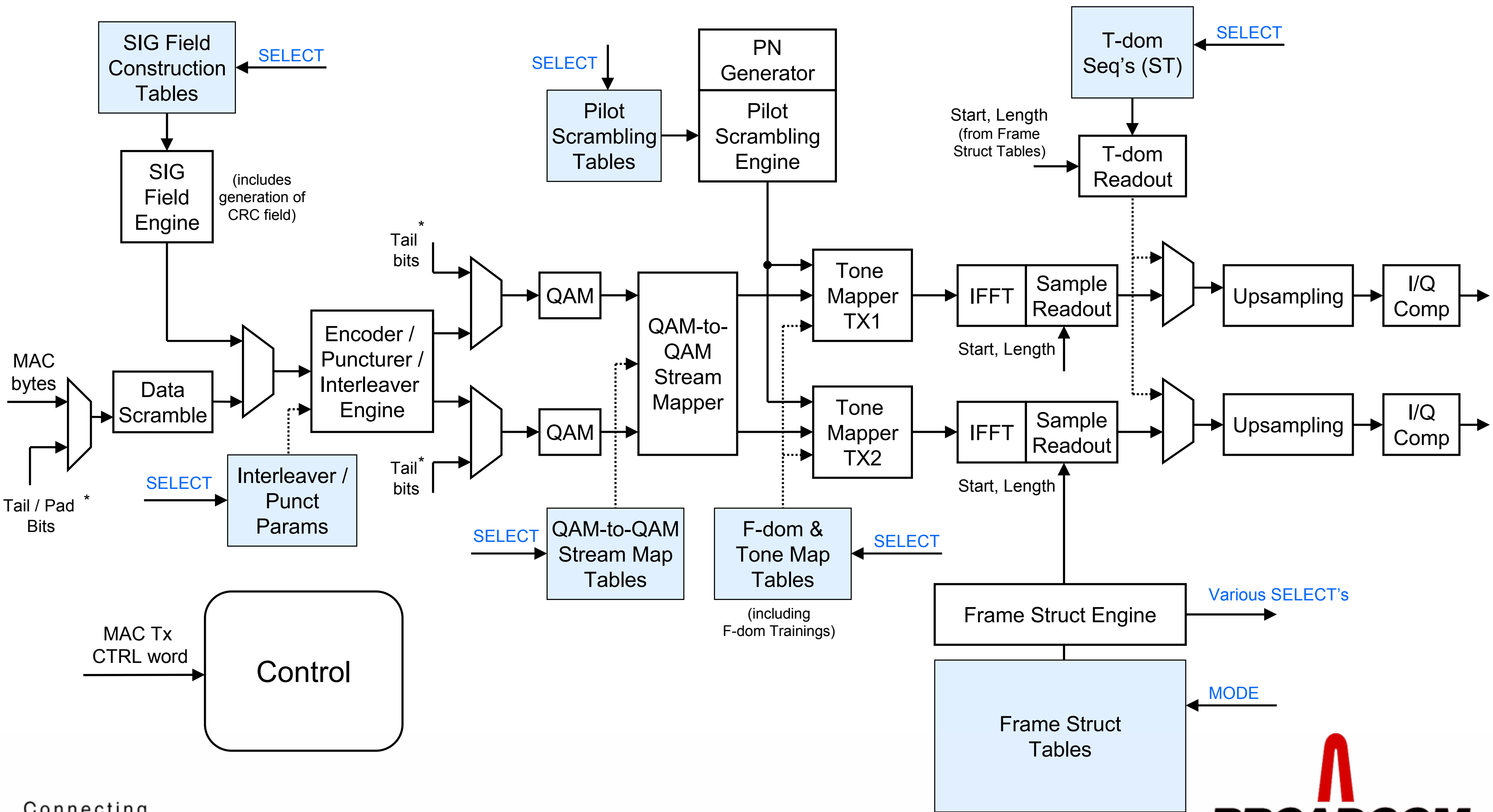
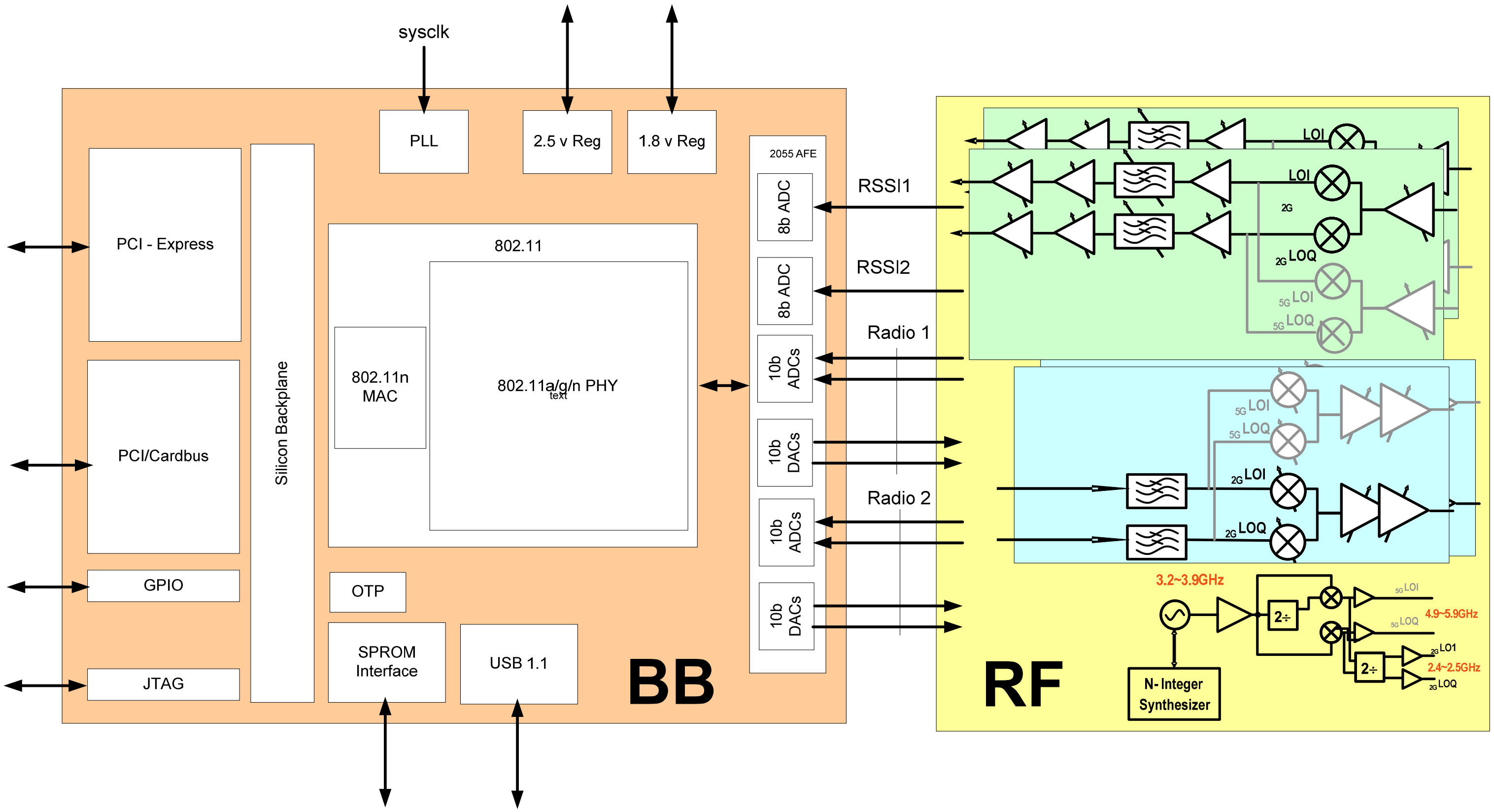
An Example: Programmable TX Engine

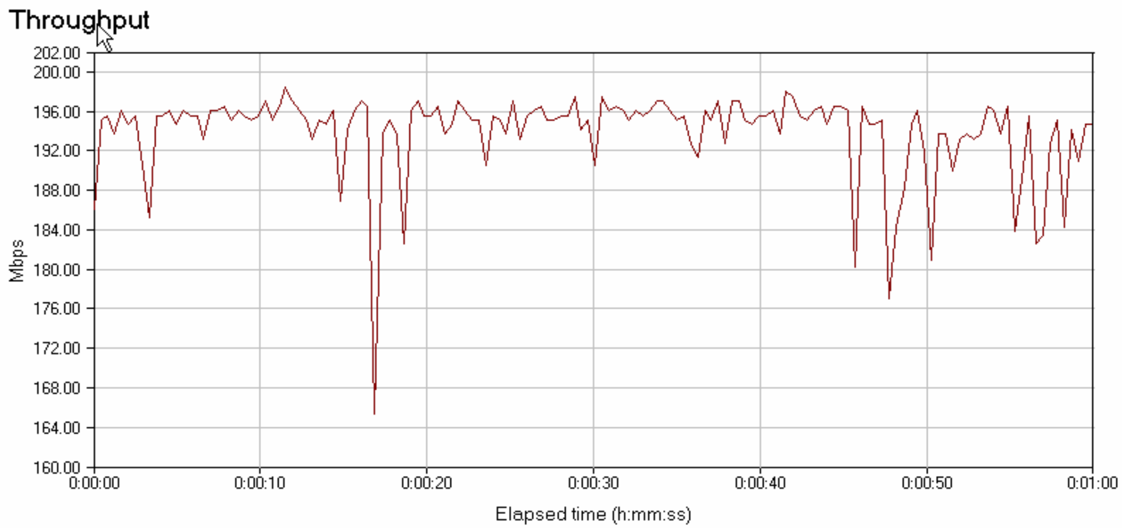


Baseband Block Diagram (Showing Radio Interconnections)

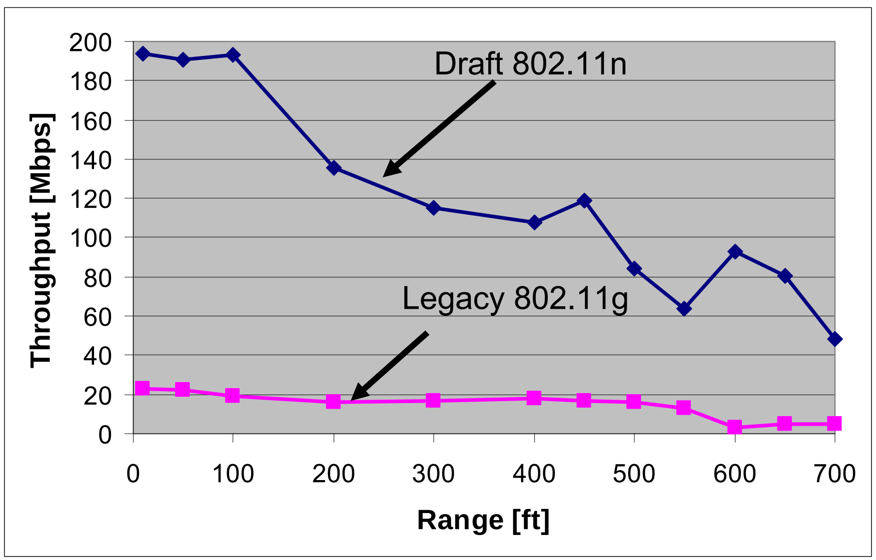


- **Supported interfaces: JTAG (both for test and radio control), GPIOS, OTP interface, PCI/Cardbus, PCI-Express**
- **Maximum supported PHY rate: 270 Mbps (includes proprietary 256-QAM mode for test)**
- **Full hardware support for TKIP, AES and WEP**
- **Support for non-simultaneous activity in multiple bands (2.4-2.5 and 4.92-5.925 GHz)**

TCP Throughput and Range



- **Close-range (10-ft.) over the air test at 5.24 GHz**
- **2x2 system**
- **Max TCP throughput: 198 Mbps**
- **Average throughput > 193 Mbps**



Figs. after ref [4]

- **2.442 GHz**
- **2x2 system**
- **Lowest level of office parking garage (LOS up to ~100m)**

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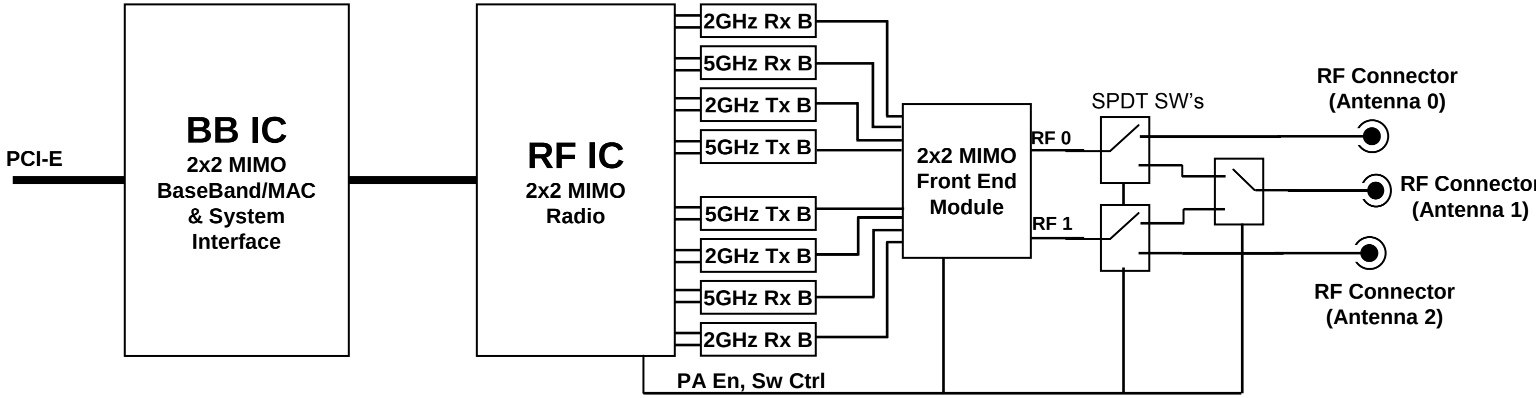
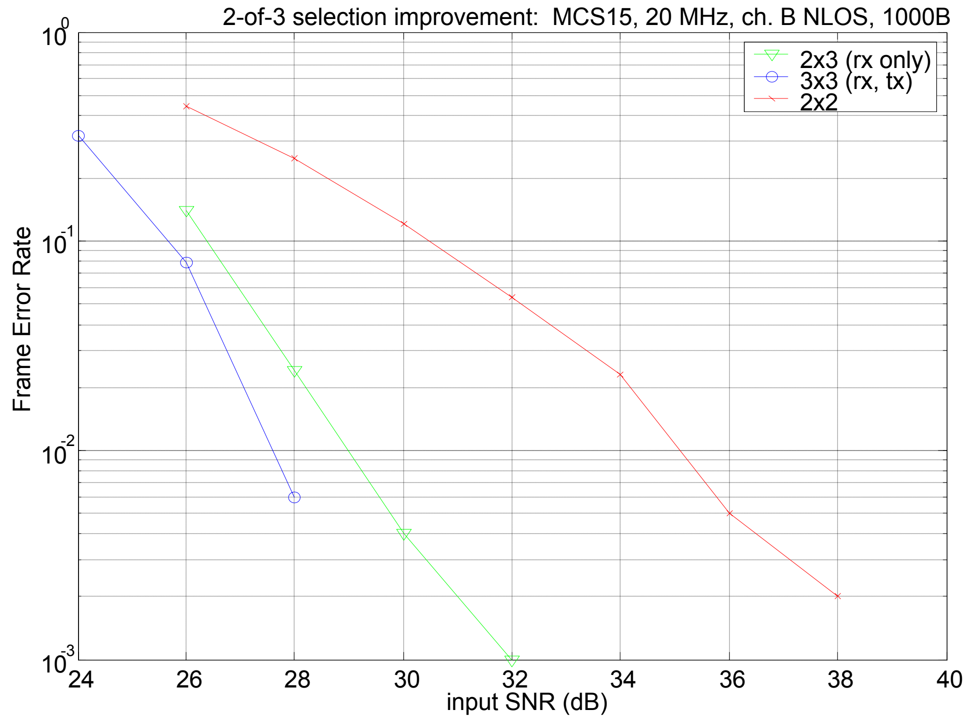
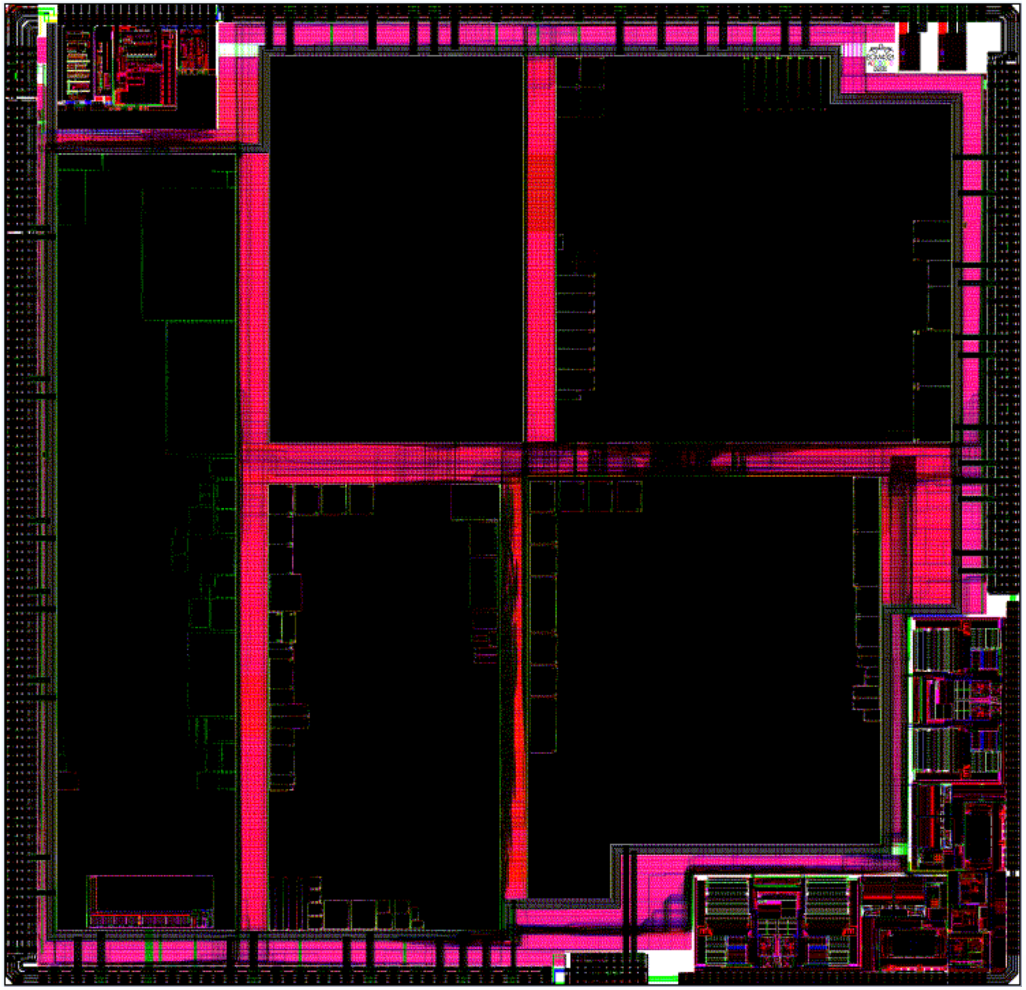
3x3 with Selection Diversity





Baseband Plot and Summary



- **Configurable static and dynamic power down modes (per RF path)**
- **Power consumption:**
  - Driver down, PCI-E clkreq + ASPM: 29 mA from 3.3V supply*
  - Driver up, associated, either PM1 or PM2, PCI-E clkreq + ASPM: 37 mA from 3.3V supply*
  - Driver up, associated, PM0, PCI-E clkreq + ASPM: 470 mA from 3.3V supply*
  - Driver up, associated, full-rate 270 Mbps data, PM0: 820 mA from 3.3V supply*
- **Sensitivity limits: -69 dBm at 270 Mbps (40 MHz bandwidth)**
- **Max. TCP throughput: 200 Mbps**
- **Operational temperature range: 0 to 75 deg C**
- **3-16 dB (typ: 4-6 dB) gain over PER range of interest through ML detection, with additional gain possible through antenna selection**
- **130 nm CMOS, 57.1 mm^2**
- **Packages:**
  - 256-ball FBGA (PCI)
  - 282-ball FBGA (PCI-E)

*** Including radio current (radio is ~193 mA off 3.3V supply when actively receiving a 40 MHz BW signal).**

Acknowledgments

With many thanks to the following individuals who have contributed to the slides and/or reviewed the material:

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Dr. Nambi Seshadri

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Thank you