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

HotChips 2007

Jason Trachewsky, Vijay Adusumilli, Carlos Aldana, Amit Bagchi, Arya Behzad, Keith Carter, Erol Erslan, Matthew Fischer, Rohit Gaikwad, Joachim Hammerschmidt, Min-Chuan Hoo, Simon Jean, Venkat Kodavati, George Kondylis, Joseph Lauer, Rajendra Tushar Moorti, Walter Morton, Eric Ojard, Ling Su, Dalton Victor, Larry Yamano

Broadcom Corporation

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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

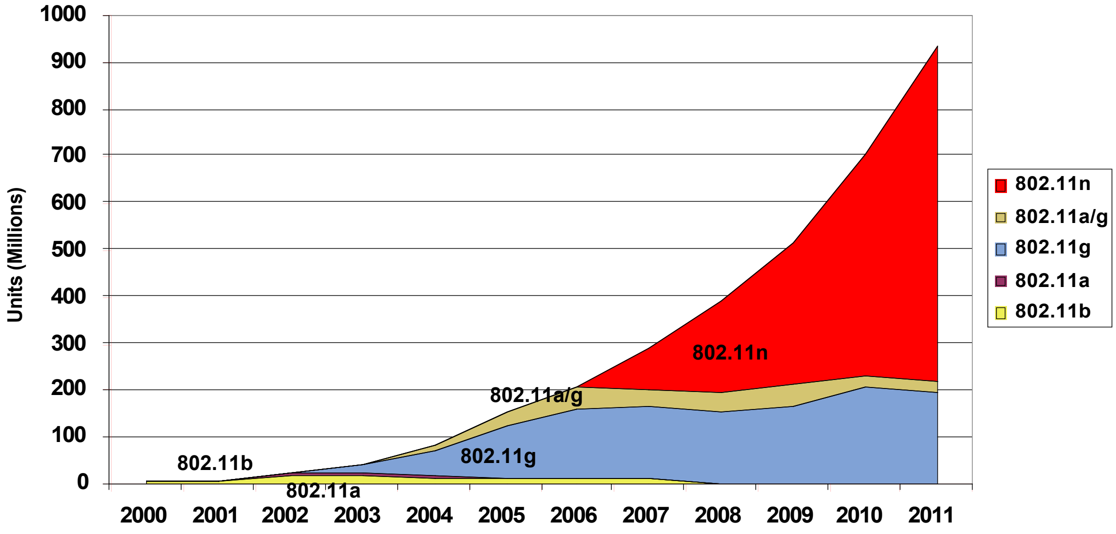
802.11g (2003)
- DSSS, CCK and OFDM
- 1 – 54 Mbps
- ~11 or ~17 MHz bandwidth
- 2.4-2.5 GHz

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.

Worldwide WLAN Volume by Standard

☐ 802.11n will dominate the market going forward (after a slow start) ☺



Source: ABI, October 2006

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.

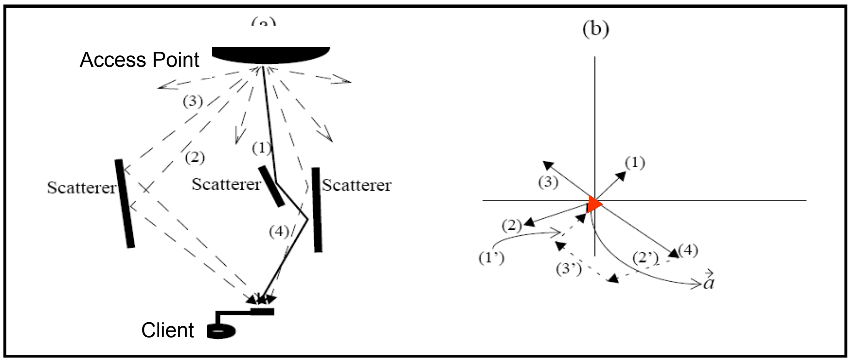


Fig. after ref [1]

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

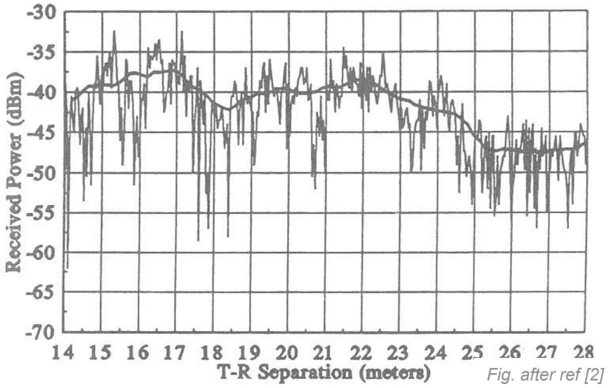


Fig. after ref [2]

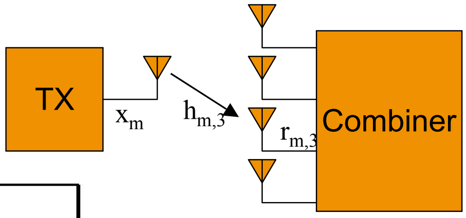
- **What can we do to mitigate the effects of spatial selectivity?**

Maximal Ratio Combining (MRC)

- **One can select "best" antenna(s) or combine antenna outputs.**
- **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:**

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

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



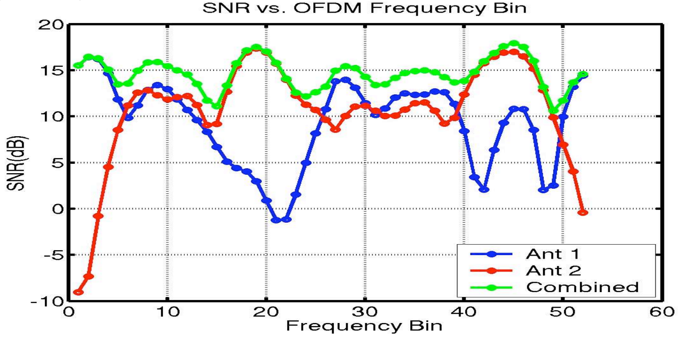
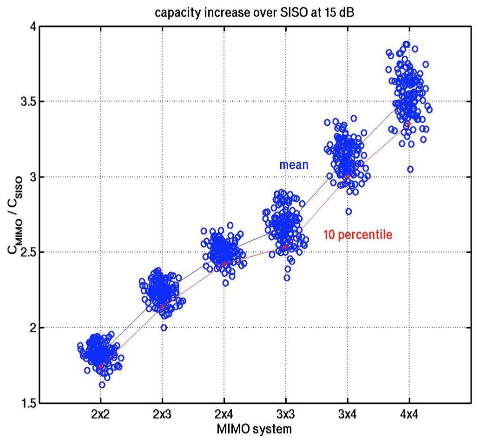
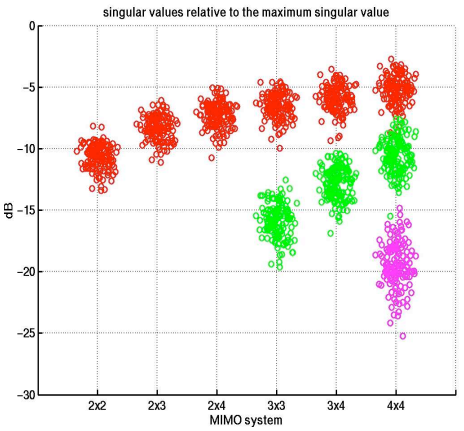


Fig. after ref [3]

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

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

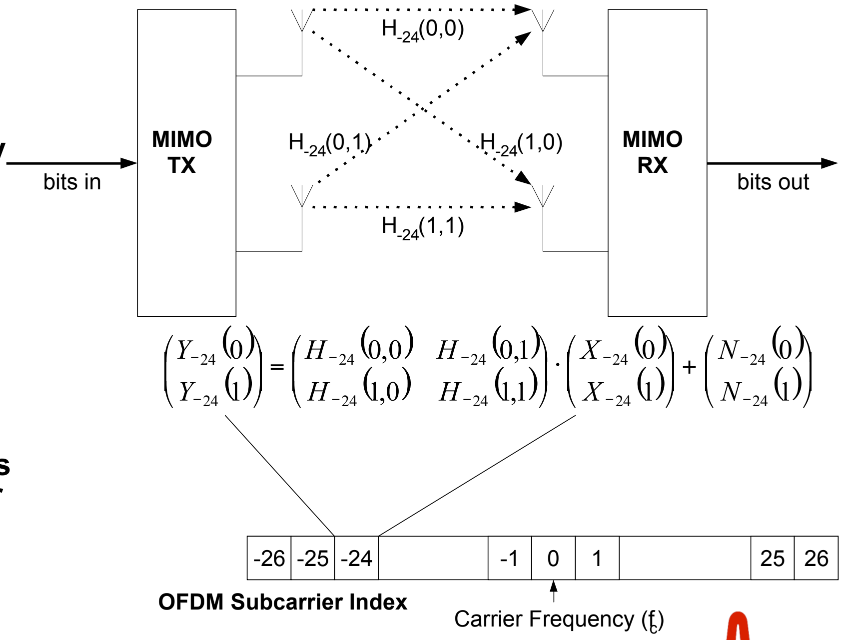
$$\eta_k = \log_2\left(\det\left[I_N + \frac{\rho}{N_{TX}}\cdot H_k \cdot H_k^*\right]\right) = \sum_{n=0}^{N_{RX}-1} \log_2\left(1+\frac{\rho}{N_{TX}}\cdot\sigma_{k,n}^2\right) \le \min\left(N_{TX}, N_{RX}\right)\cdot\log_2\left(1+\frac{\rho}{N_{TX}}\right)$$

Each circle represents a location on one floor of an office building with offices, cubicals and labs. Notice the roughly linear increase in capacity.

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.

MIMO-OFDM

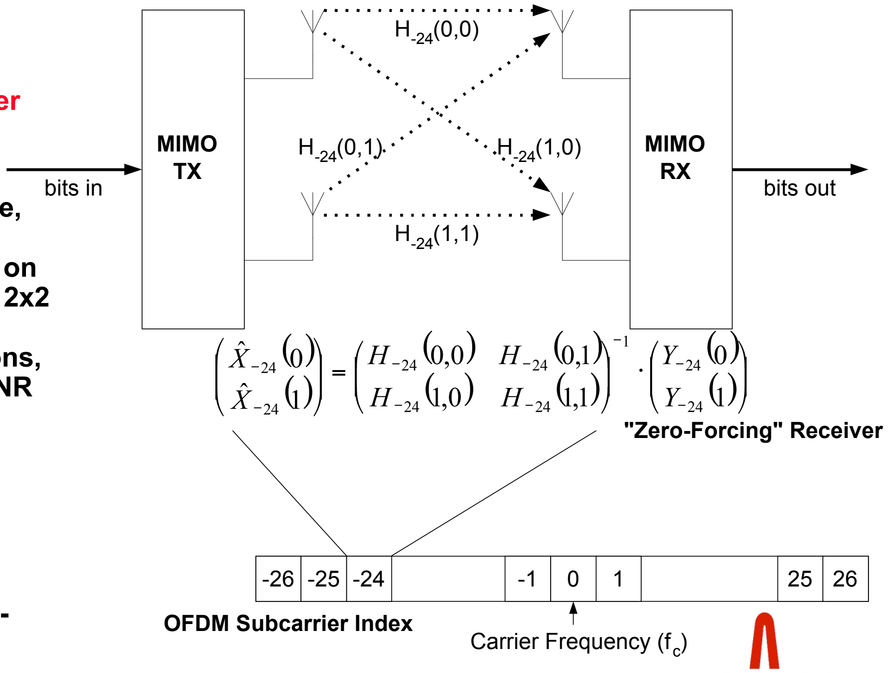
- **In OFDM, the channel is broken into L (in this case, 53) parallel flat-fading channels, each represented by a single complex coefficient.**
- **In MIMO OFDM, there is an NxM complex-valued matrix of channel coefficients per subcarrier, where M is the number of transmitter antennas and N is the number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

- 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”.**

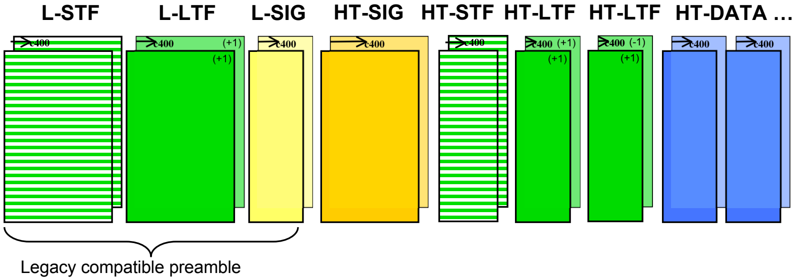


$$\begin{pmatrix}\hat{X}_{-24}(0)\\ \hat{X}_{-24}(1)\end{pmatrix} = \begin{pmatrix} H_{-24}(0,0) & H_{-24}(0,1)\\ H_{-24}(1,0) & H_{-24}(1,1)\end{pmatrix}^{-1}\cdot\begin{pmatrix}Y_{-24}(0)\\ Y_{-24}(1)\end{pmatrix}$$

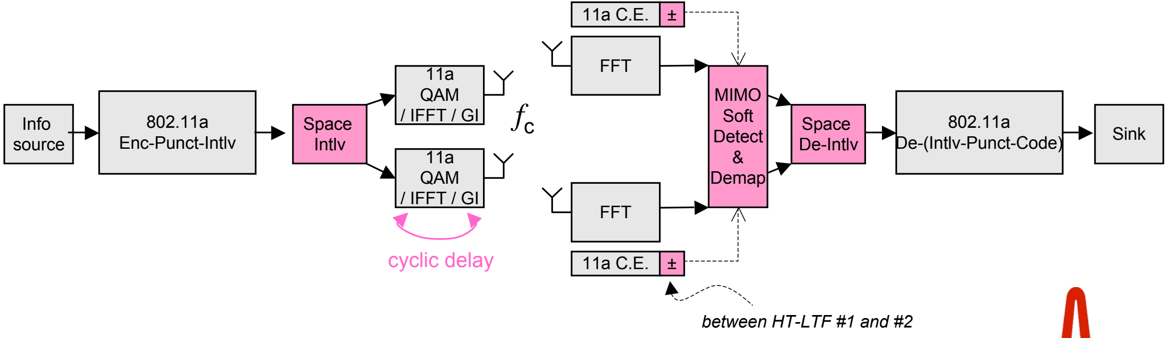
"Zero-Forcing" Receiver

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
  - High complexity

ML Detector and Complexity

- **2x2 MIMO system using M^2-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 , $k = 1,2$

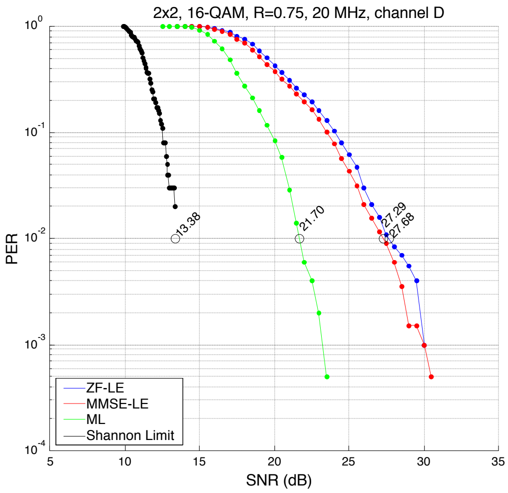
H is the channel matrix

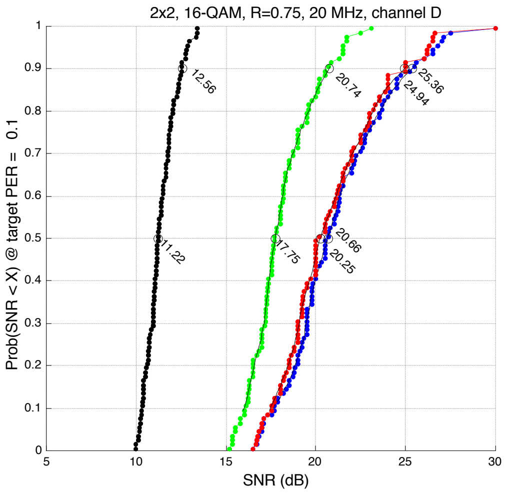
n is the noise: n_1 and n_2 are i.i.d. complex Gaussian random variables with mean 0 and variance σ^2

r is the received signal

- **Brute force MLD**
  - Log-likelihood ratio for bit k is $L_k = \frac{1}{\sigma^2}\left(\min\limits_{\mathbf{x}|b_k=-1} - \min\limits_{\mathbf{x}|b_k=1}\right)\|\mathbf{r} - \mathbf{H}\mathbf{x}\|^2$
  - 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 + 4log$_2$(M)]M^2+78 adds
  - Also need 4log$_2$M low-precision divisions for global scaling of each LLR by 1/Kσ^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 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

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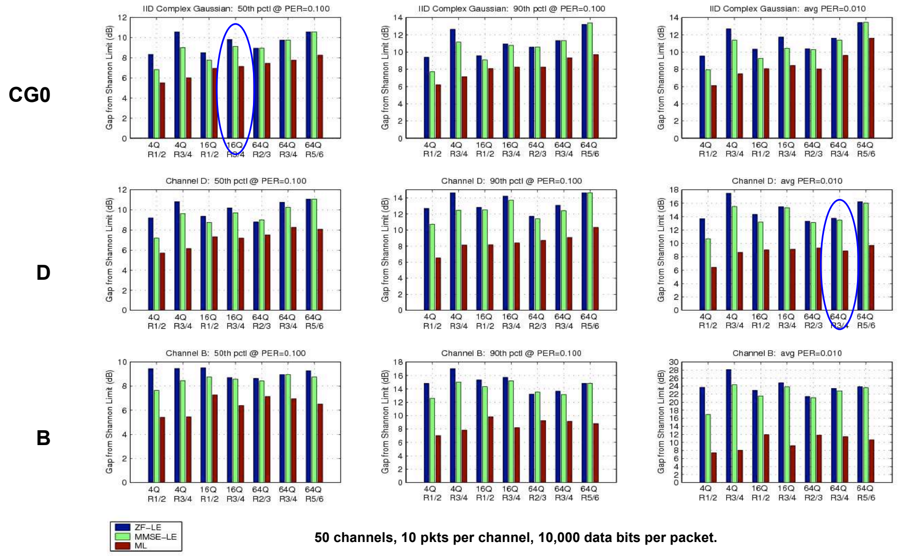
2x2 Performance Summary



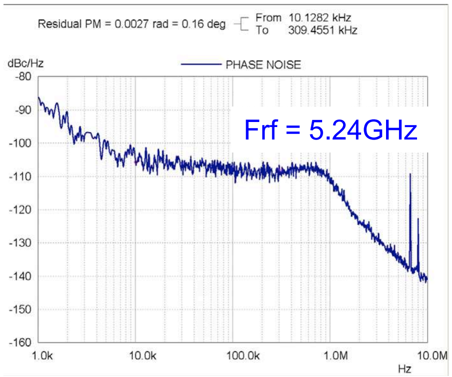
50 channels, 10 pkts per channel, 10,000 data bits per packet.

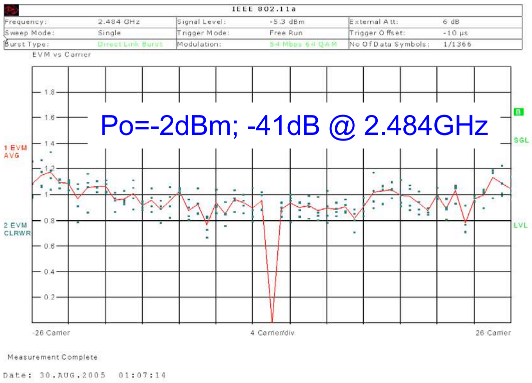
1. **ZF-LE to MMSE-LE gap is more pronounced at lower SNR (smaller constellations at fixed error rate).**
2. **MMSE-LE/ZF-LE to ML gap is more pronounced on channels with higher condition number (more correlated paths) and at higher code rates (weaker code due to puncturing).** ***I.e.,*** **ML helps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

Post-calibration Phase Noise and EVM Results



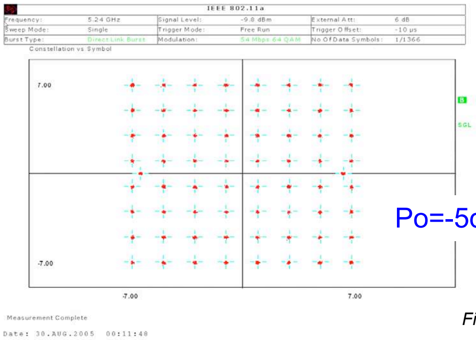


IEEE 802.11a

Frequency:	2.484 GHz	Signal Level:	-5.3 dBm	External Att:	6 dB
Sweep Mode:	Single	Trigger Mode:	Free Run	Trigger Offset:	-10 µs
Burst Type:	Direct Link Burst	Modulation:	54 Mbps 64 QAM	No Of Data Symbols:	1/1366

Measurement Complete

Date: 30.AUG.2005 01:07:14



IEEE 802.11a

Frequency:	5.24 GHz	Signal Level:	-9.8 dBm	External Att:	6 dB
Sweep Mode:	Single	Trigger Mode:	Free Run	Trigger Offset:	-10 µs
Burst Type:	Direct Link Burst	Modulation:	54 Mbps 64 QAM	No Of Data Symbols:	1/1366

Measurement Complete

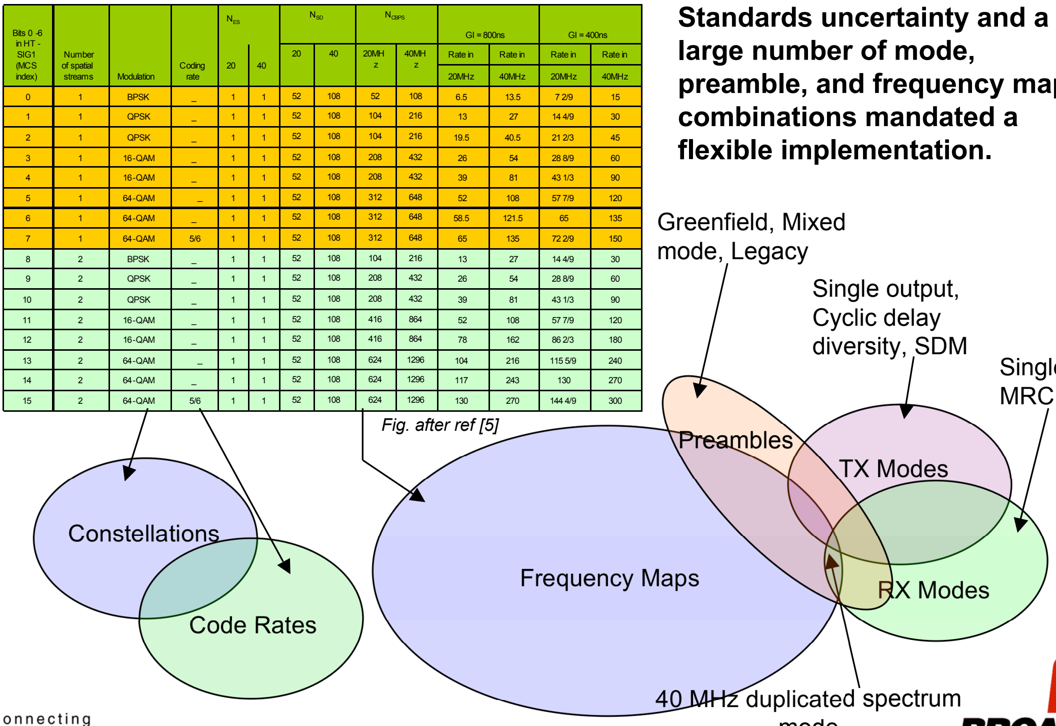
Date: 30.AUG.2005 00:11:48

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

Figs. after ref [4]

The Need for a Flexible Transceiver

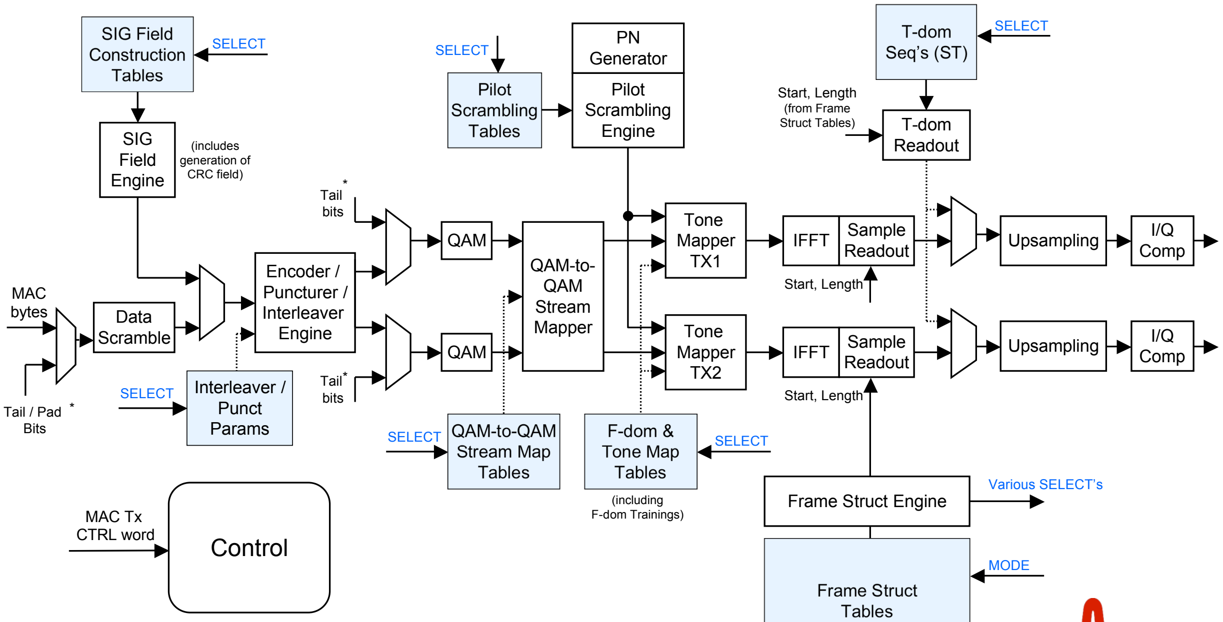
Standards uncertainty and a large number of mode, preamble, and frequency map combinations mandated a flexible implementation.



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	_	1	1	52	108	52	108	6.5	13.5	7 2/9	15
1	1	QPSK	_	1	1	52	108	104	216	13	27	14 4/9	30
2	1	QPSK	_	1	1	52	108	104	216	19.5	40.5	21 2/3	45
3	1	16-QAM	_	1	1	52	108	208	432	26	54	28 8/9	60
4	1	16-QAM	_	1	1	52	108	208	432	39	81	43 1/3	90
5	1	64-QAM	_	1	1	52	108	312	648	52	108	57 7/9	120
6	1	64-QAM	_	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	_	1	1	52	108	104	216	13	27	14 4/9	30
9	2	QPSK	_	1	1	52	108	208	432	26	54	28 8/9	60
10	2	QPSK	_	1	1	52	108	208	432	39	81	43 1/3	90
11	2	16-QAM	_	1	1	52	108	416	864	52	108	57 7/9	120
12	2	16-QAM	_	1	1	52	108	416	864	78	162	86 2/3	180
13	2	64-QAM	_	1	1	52	108	624	1296	104	216	115 5/9	240
14	2	64-QAM	_	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

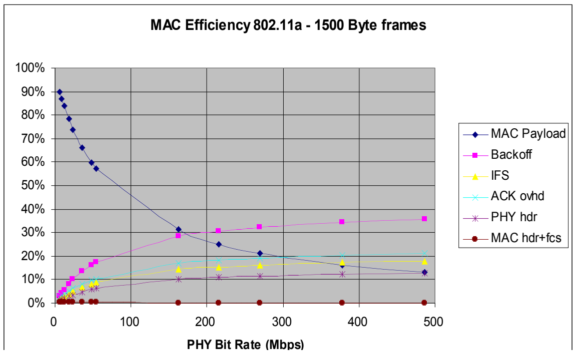
Fig. after ref [5]

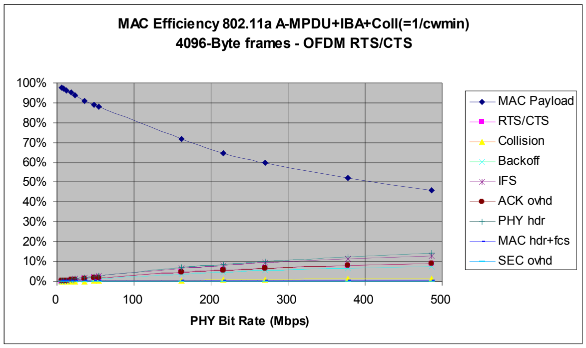
An Example: Programmable TX Engine



MAC Improvements: Why Aggregate Frames?

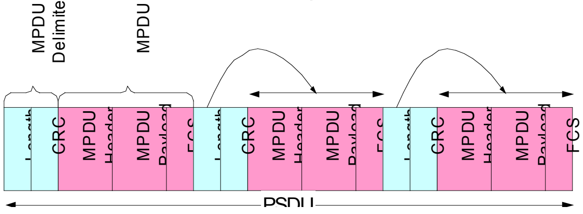
- **RTS/CTS/A-MPDU/IBA *vs.* DATA/ACK improvement**
  - At a 300 Mbps PHY rate, 60 Mbps throughput is the upper bound for a UDP-like flow with an unmodified DCF MAC.
  - Throughput is around 180 Mbps (or better) with A-MPDU and Immediate BA



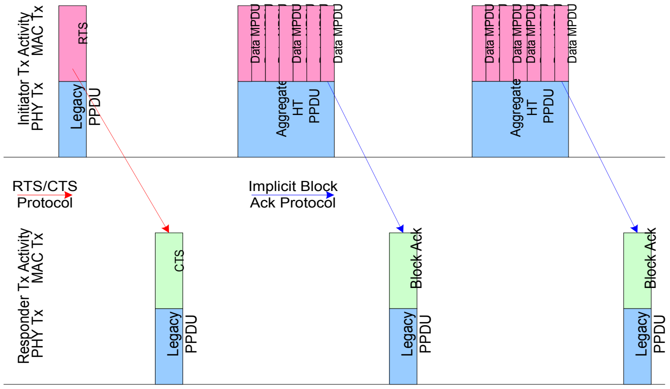


A-MPDU Aggregation

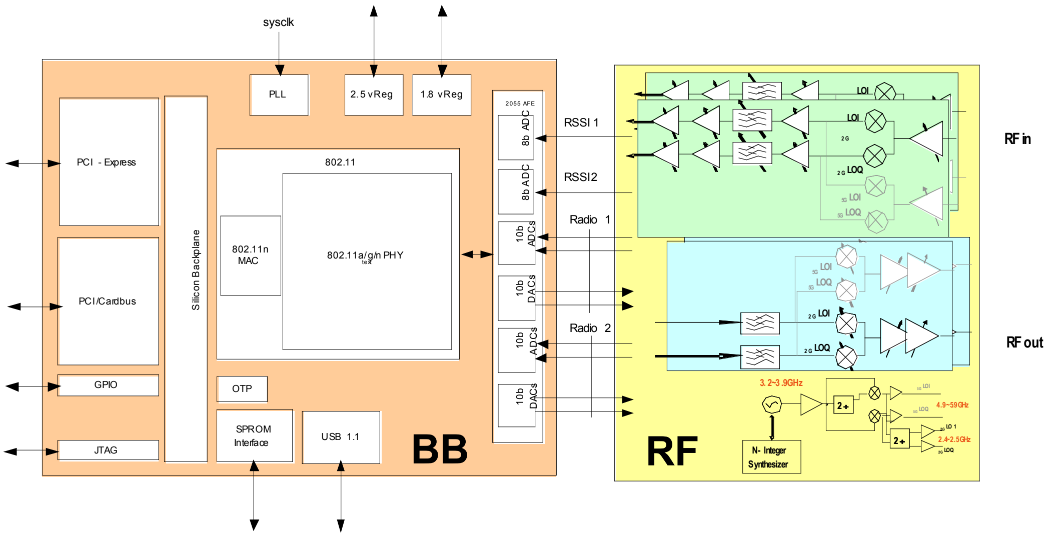
- **Control and data MPDUs (MAC Protocol Data Units) can be aggregated**
- **PHY has no knowledge of MPDU boundaries**



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

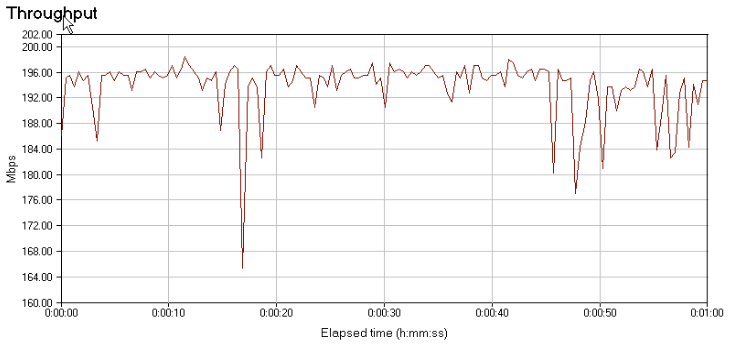


Baseband Block Diagram (Showing Radio Interconnections)

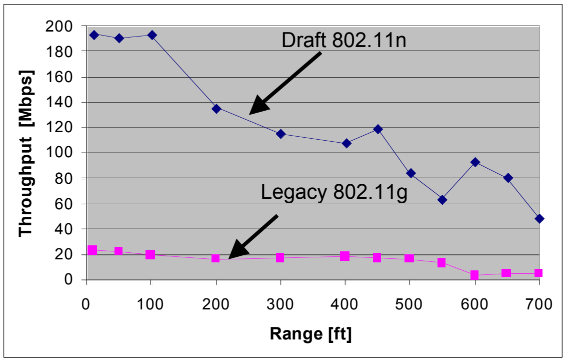


- Supported interfaces: JTAG (both for test and radio control), GPIOS, OTP interface, PCI/Cardbus, PCI-Express
- Maximum supported PHY rate: 270 Mbps (includes proprietary 256-QAM mode for test)
- Full hardware support for TKIP, AES and WEP
- Support for non-simultaneous activity in multiple bands (2.4-2.5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

TCP Throughput and Range



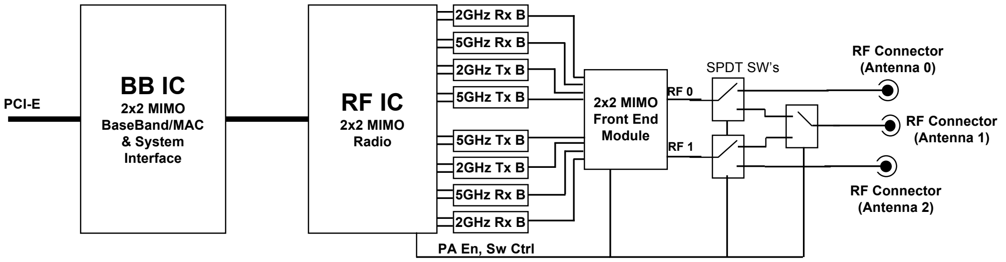
- Close-range (10-ft.) over the air test at 5.24 GHz
- 2x2 system
- Max TCP throughput: 198 Mbps
- Average throughput > 193 Mbps

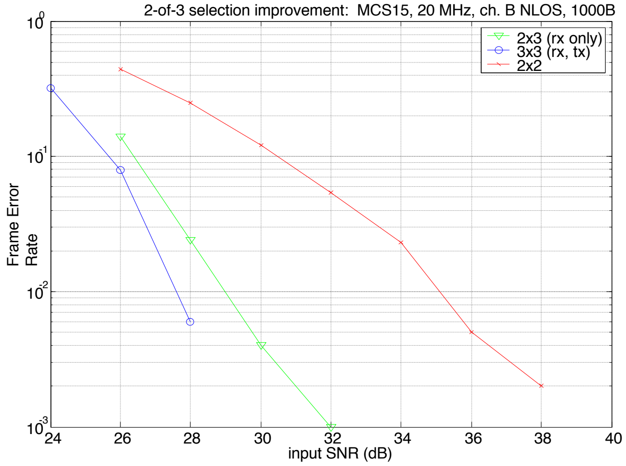


- 2.442 GHz
- 2x2 system
- Lowest level of office parking garage (LOS up to ~100m)

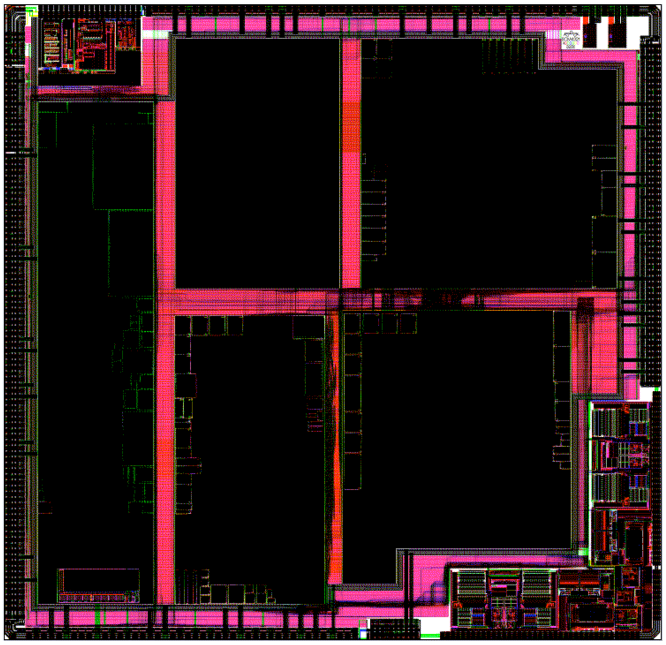
Figs. after ref [4]

3x3 with Selection Diversity





Baseband Die 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 active).

Acknowledgments

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

Dr. Ed Frank

Dr. Nambi Seshadri

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[1] A. Behzad, "The Implementation of a High Speed Experimental Transceiver Module with an Emphasis on CDMA Applications", Electronic Research Labs, U.C. Berkeley, 1994.

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[3] W.-J. Choi, et. al., "MIMO Technology for Advanced Wireless Local Area Networks", DAC, June 2005.

[4] A. Behzad, et. al., "A Fully Integrated Multiband Direct Conversion CMOS Transceiver for MIMO WLAN Applications (802.11n)", ISSCC 2006.

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Thank you