Radio Design for MIMO Systems with an Emphasis on IEEE 802.11

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IEEE DL Series
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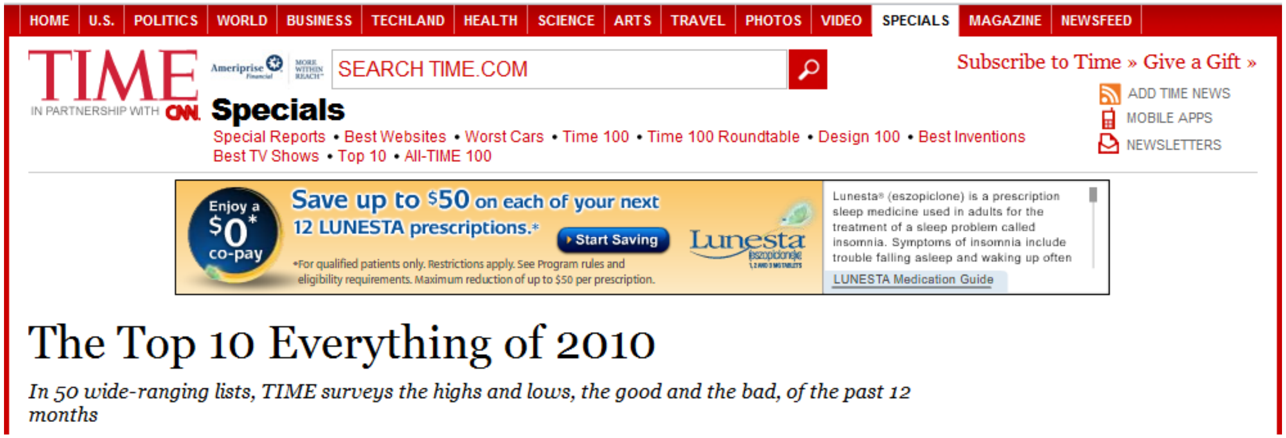
Outline

- ❑ Introduction, Market Overview & Market Trends
- ❑ Communication System Performance in a Multipath Channel:
  - ➢ The problem with multipath
  - ➢ Mitigation methods for multipath
  - ➢ Taking advantage of multipath
- ❑ WLAN Evolution & 802.11
  - ➢ Additions in 802.11n PHY and impacts on radio
  - ➢ 802.11n Sensitivity and EVM requirements
  - ➢ Some optional modes of 802.11n
  - ➢ Key features of TGac
- ❑ Some 802.11 Radio Requirements
  - ➢ Impacts of some radio impairments on system performance
- ❑ Examples of Circuit Techniques and Architectures Used in 802.11n Radios
- ❑ Evolution of Radios: SISO to MIMO
- ❑ Real World Performance
- ❑ Conclusion

WLAN in Top Gadgets

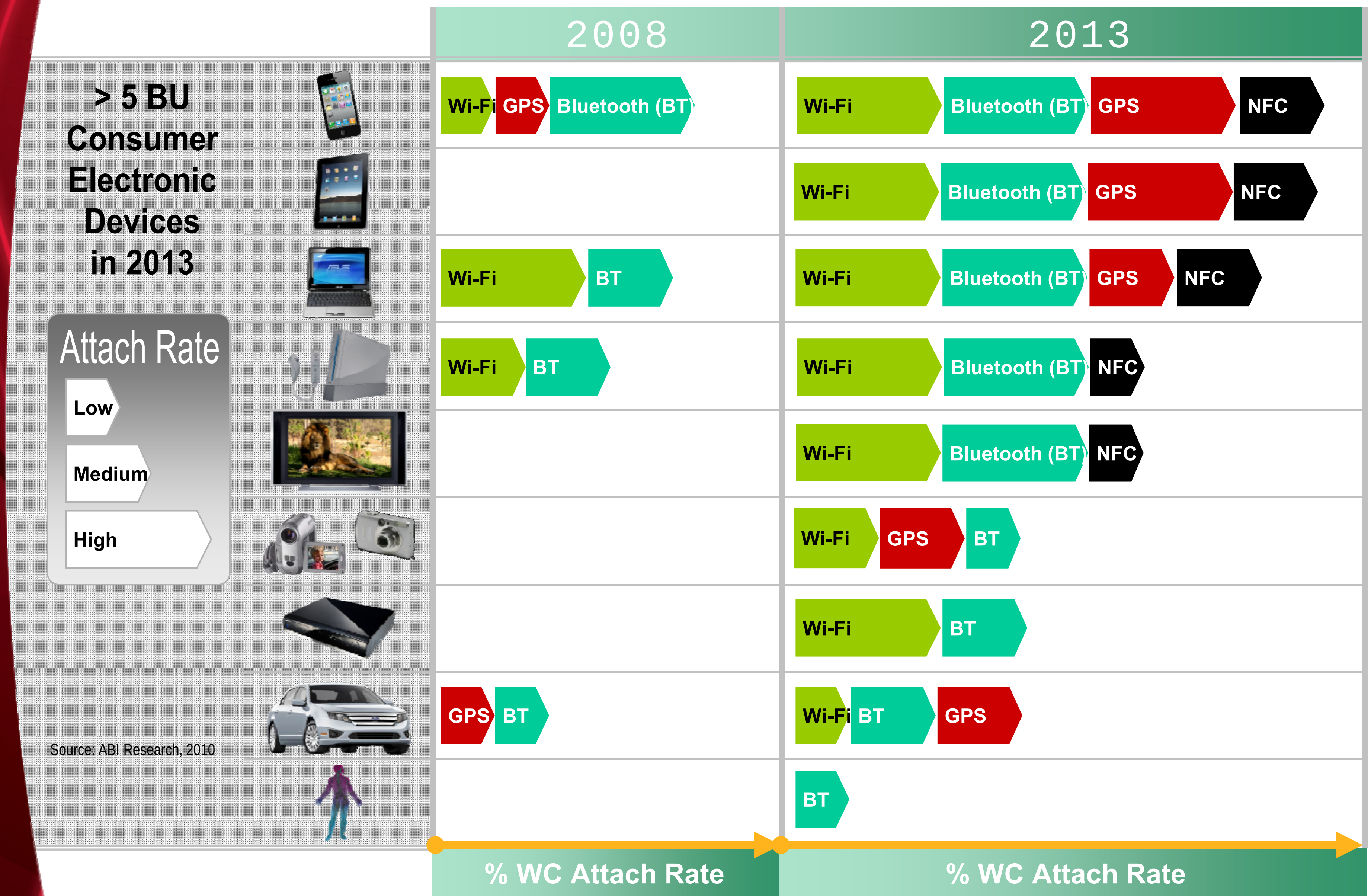


TOP 10 GADGETS

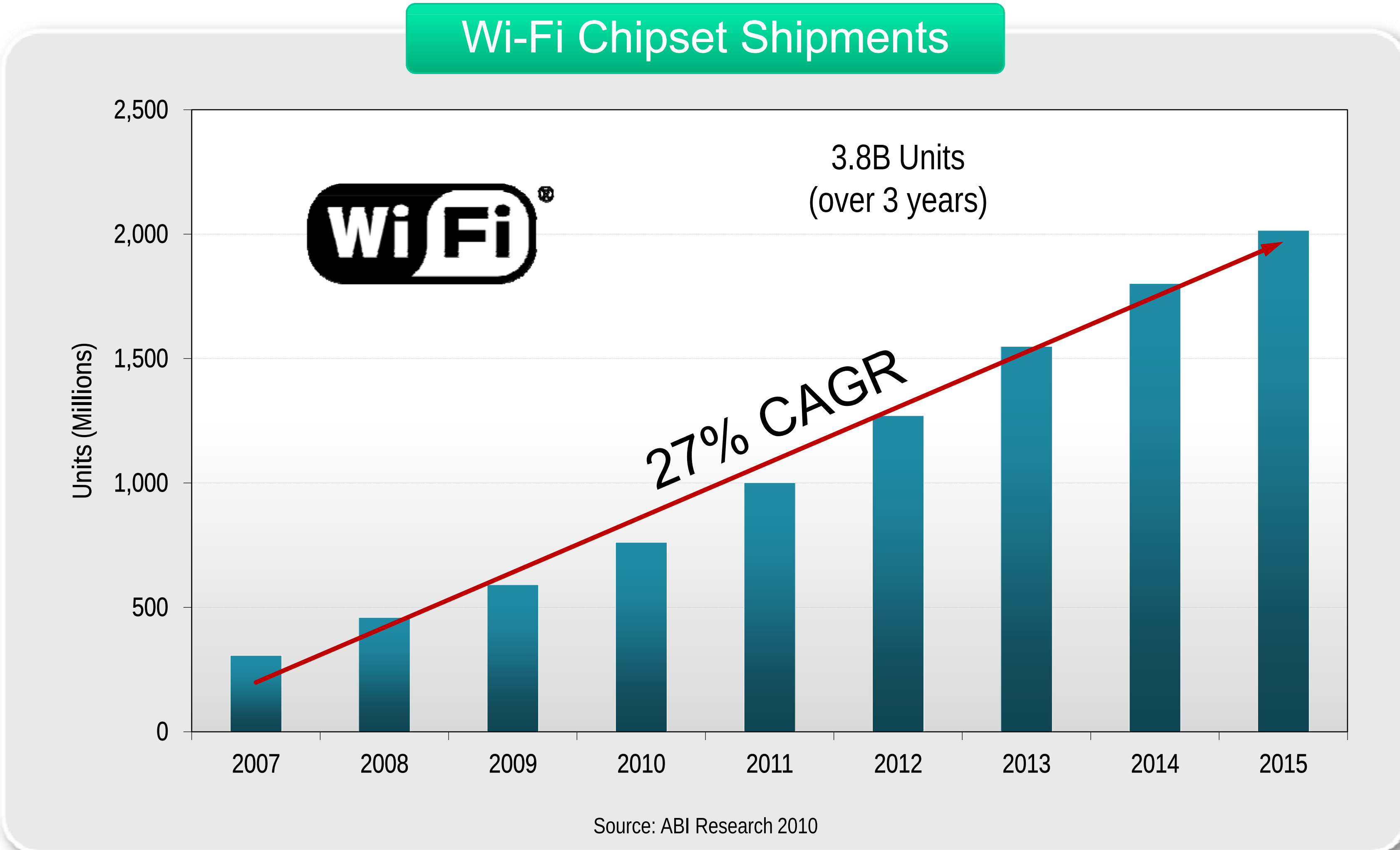
- iPad
- Samsung Galaxy S
- 11-In. MacBook Air
- Google TV Via Logitech Revue
- Nexus One
- iPhone 4
- Apple TV
- Toshiba Libretto Dual-Screen Laptop
- Kinect
- Nook Color

- ❑ 9 of 10 have integrated WiFi

Wireless Connectivity Attach Rates: Up, Up, & Away!

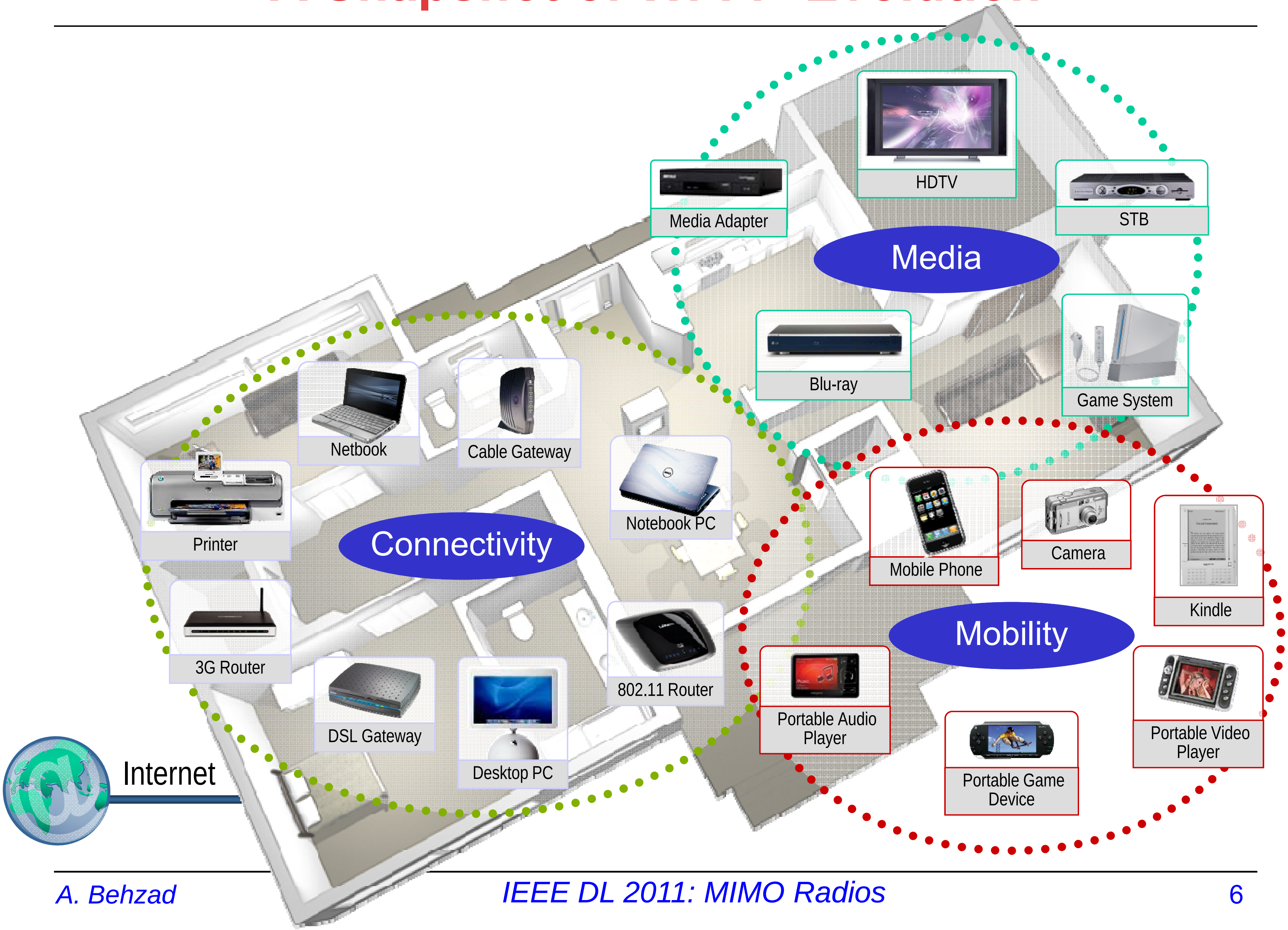


Wi-Fi Growth Driven by CE Adoption and its Utility!



Wi-Fi Device Demand Expected to Surpass Cellular in 2014!

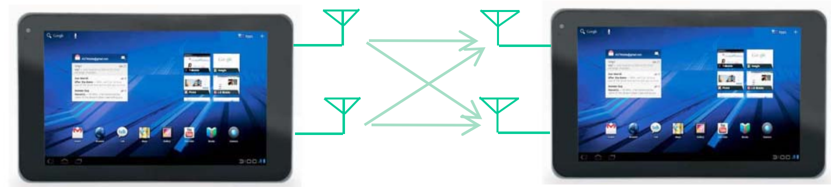
A Snapshot of Wi-Fi® Evolution



Mobility Trend in 2011

Number 1 - Speed

802.11n 2x2 MIMO
- Higher Speed Over 150Mbps
- Connect to 47% of 2.4GHz MIMO APs
- Perfect for "Tablet Application"

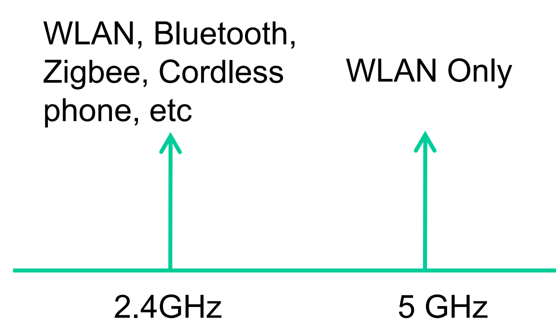


Number 2 - Connection

Convenient P2P Connection
- WiFi Direct
-SoftAP Modem

Number 3 - 2.4GHz Traffic

2.4GHz is getting congested
- Smart Coexistence Required
- 2.4GHz band for Internet Access
- 5GHz band off-load for P2P



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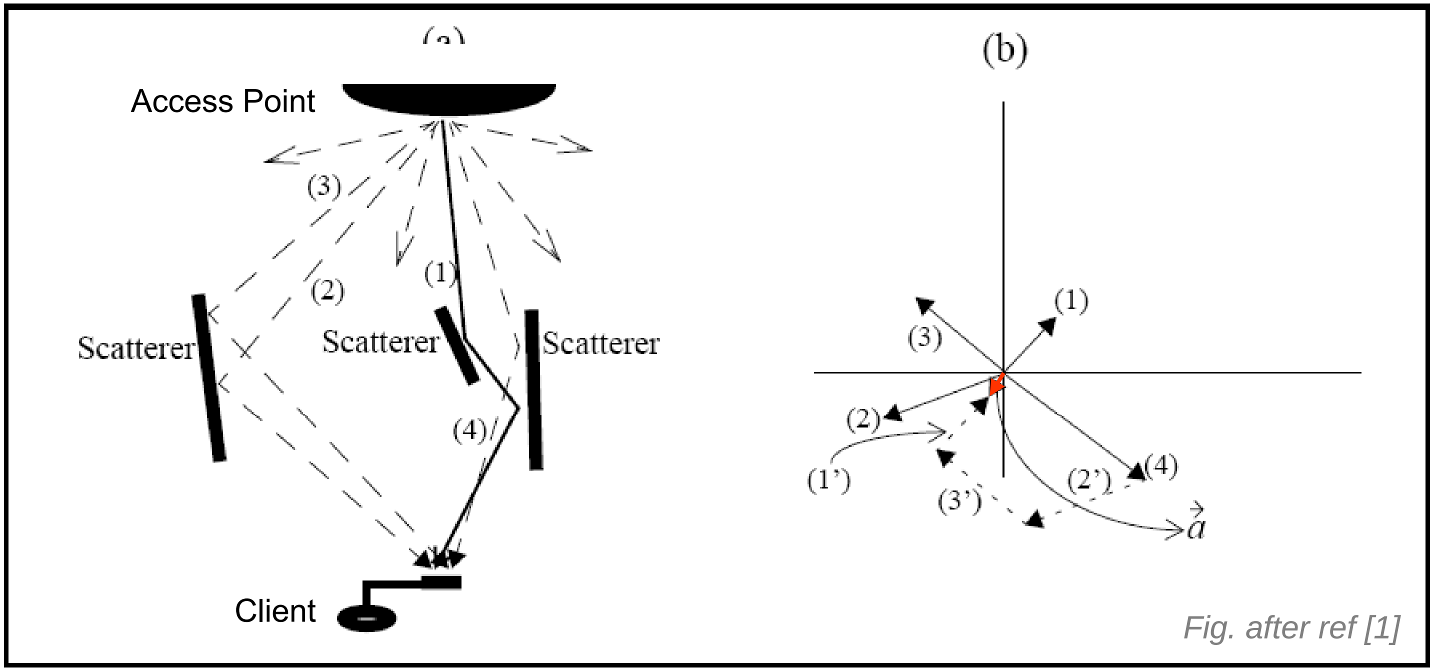
- Conclusion

Multipath Channels

- Multipath (Rayleigh fading):
  - Is a phenomena caused by the multiple arrivals of the transmitted signal to the receiver due to reflections off of “scatterers”
  - For traditional wireless systems, more problematic if a direct line-of-sight (LOS) path does *not* exist between the transmitter and the receiver (Rayleigh Fading)
  - Example and vector-magnitude representation shown below



Multipath Channels

- 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

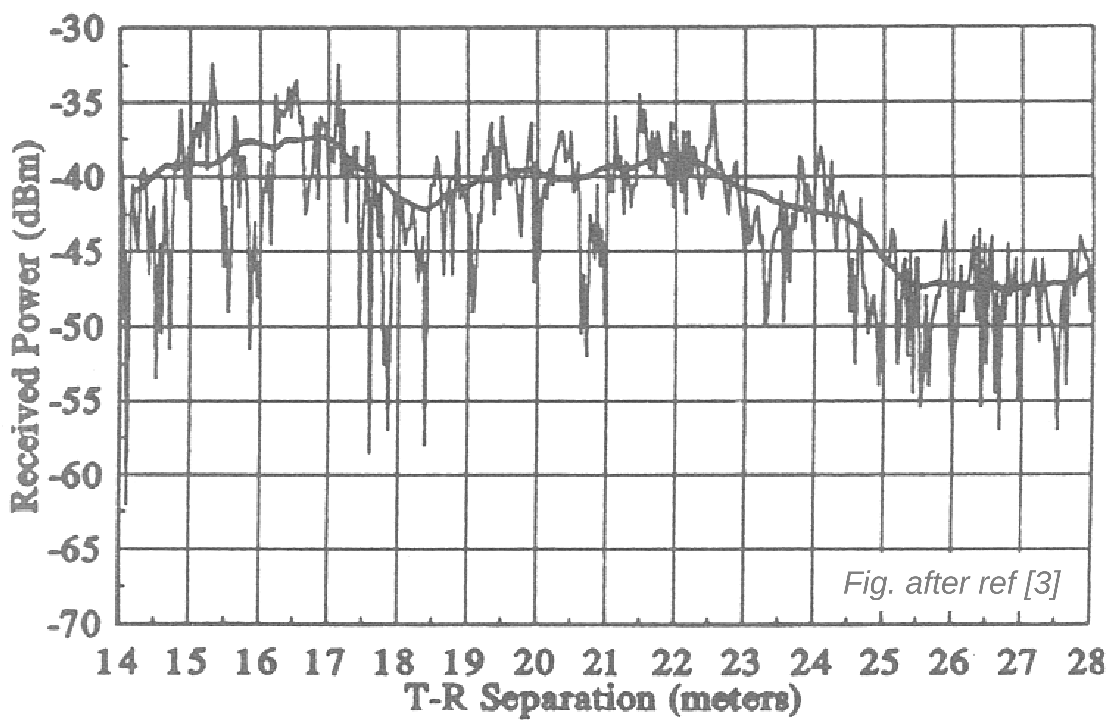
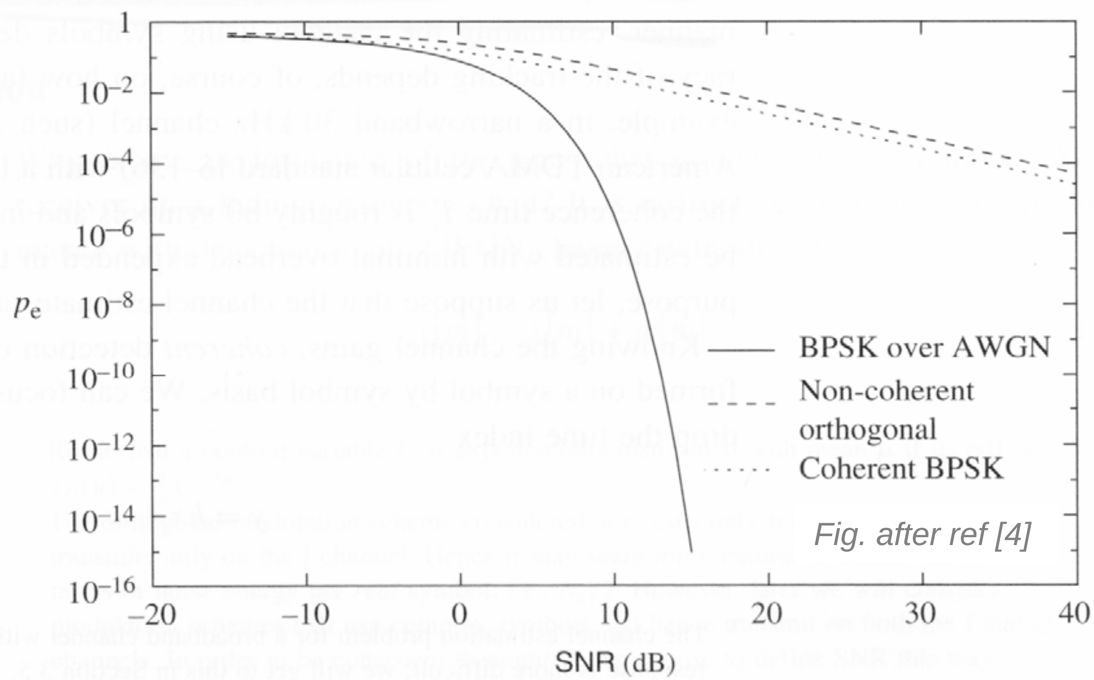


Fig. after ref [3]

Performance in a Multipath Channels

- In an AWGN channel, a "reasonable" SNR is sufficient for obtaining a low probability of error
  - The only factor that can impact an error is large additive noise
- In a faded environment, a very large SNR would be required for a low probability of error
  - Not a significant difference between a coherent or non-coherent scheme
  - Probabilistically, in the high SNR region, errors often occur due to the deep fade present in the channel



Diversity

- Without the use of some kind of diversity, performance in a faded environment is quite poor
  - Error probabilities decay quite slowly with an increase in SNR
  - The fundamental reason is that the reliability of the link is dependent on a single net “path” (i.e. no “diversity”)
    - High probability that this single net path will be in a deep fade
  - The technique used to improve the situation by providing multiple independently faded signal paths is “diversity”
  - As long as at least one of the signal paths has a reasonable SNR, reliable communication can be achieved

Diversity

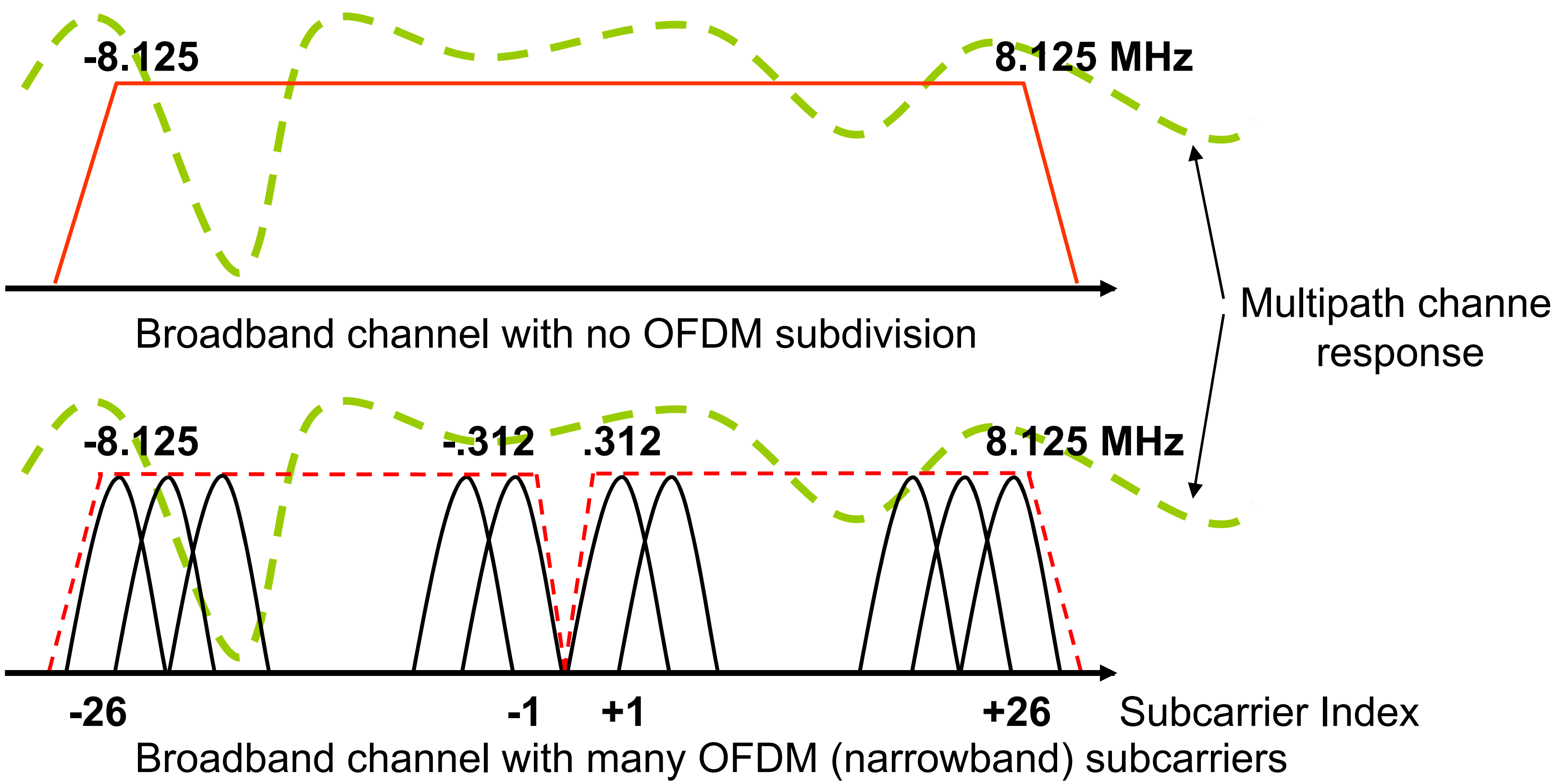
- One or more dimensions ("degrees of freedom") can be exploited in a faded wireless system to enable diversity
  - Time
    - Interleaving of coded symbols
  - Frequency
    - Can be applied when bandwidth of the modulated signal is wider than the coherence bandwidth of the channel
      - Frequency response of the channel is not flat over the bandwidth of the signal
    - Can be implemented in the form of:
      - Inter-symbol equalization
      - Spread-spectrum techniques
      - OFDM
  - Space
    - Use of multiple Rx and/or Tx antennas
      - Selection diversity
      - Space-time coding

Diversity

- Diversity can be utilized to improve the reliability of the link
  - Repetition coding is the simplest form of diversity
    - Same information is communicated over multiple signal paths
    - Can be applied to time, frequency or space diversity
    - Is quite wasteful of the degrees of freedom of the channel
- Using more sophisticated coding techniques allows to obtain diversity gain as well as a “coding gain”

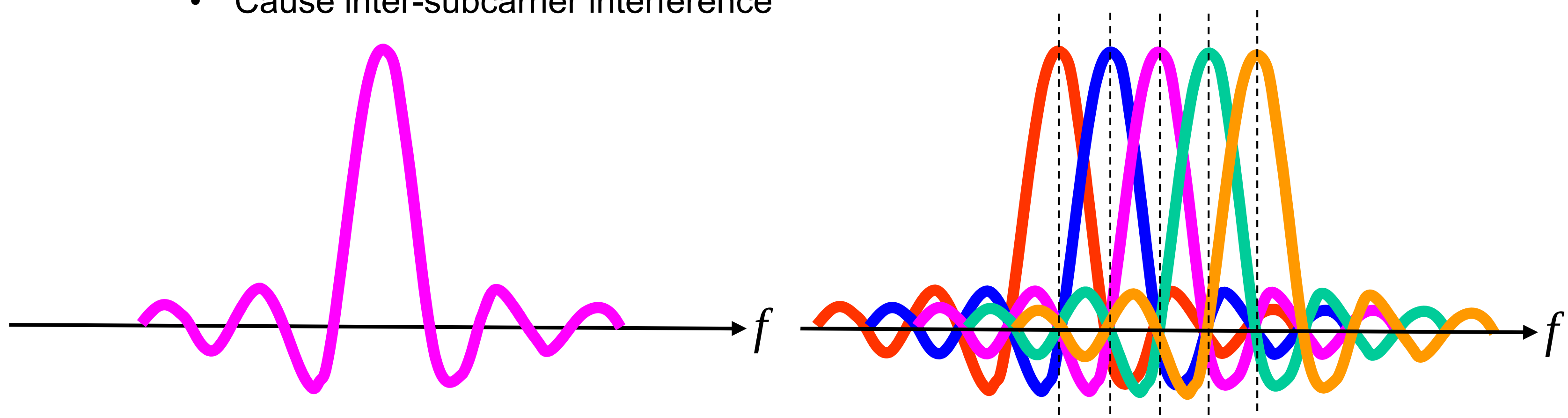
OFDM Subdivision of Wideband Modulation

- The received signal in a multi-path environment will suffer “fades”
- For wideband channels (often required for high data rate communications), the fade is often frequency-selective
- OFDM coding is a very effective method of combating frequency-selective fades



OFDM Coding

- 802.11a/g standards are based on Orthogonal Frequency Division Multiplexing (OFDM)
- The OFDM concept has been around for a long time
- OFDM provides some immunity to multi-path
- Orthogonality:
  - Obtained through the use of multiples of a sub-carrier frequency over an integer cycle (property of transform used DFT/IDFT)
  - Sub-carrier over-lap is allowed
    - Better spectral efficiency can be achieved
  - Is deteriorated by phase noise, distortion, frequency inaccuracy, IQ imbalance, …
    - Cause inter-subcarrier interference



Multi-Antenna Systems

- The use of multiple-antennas is a very popular technique and the subject of very active research
- Multiple antennas can provide:
  - Power gain
    - Can be achieved with SIMO, MISO, or MIMO
    - Rx Maximum ratio combining
    - Tx beam forming
  - Diversity gain
    - Can be achieved with SIMO, MISO, or MIMO
    - Selection diversity
    - Space-time coding
  - "Degree of freedom" gain
    - Can ***only*** be achieved with MIMO
      - Requires far-apart transmitter antennas OR far-apart receiver antennas in a non multi-path environment
      - Reasonably closely spaced Rx and Tx antennas can be used as long as scatterers and reflectors are placed far apart in the environment
        - We are *taking advantage* of the multi-path environment!!
    - Allows use of spatial multiplexing to increase the capacity of the channel

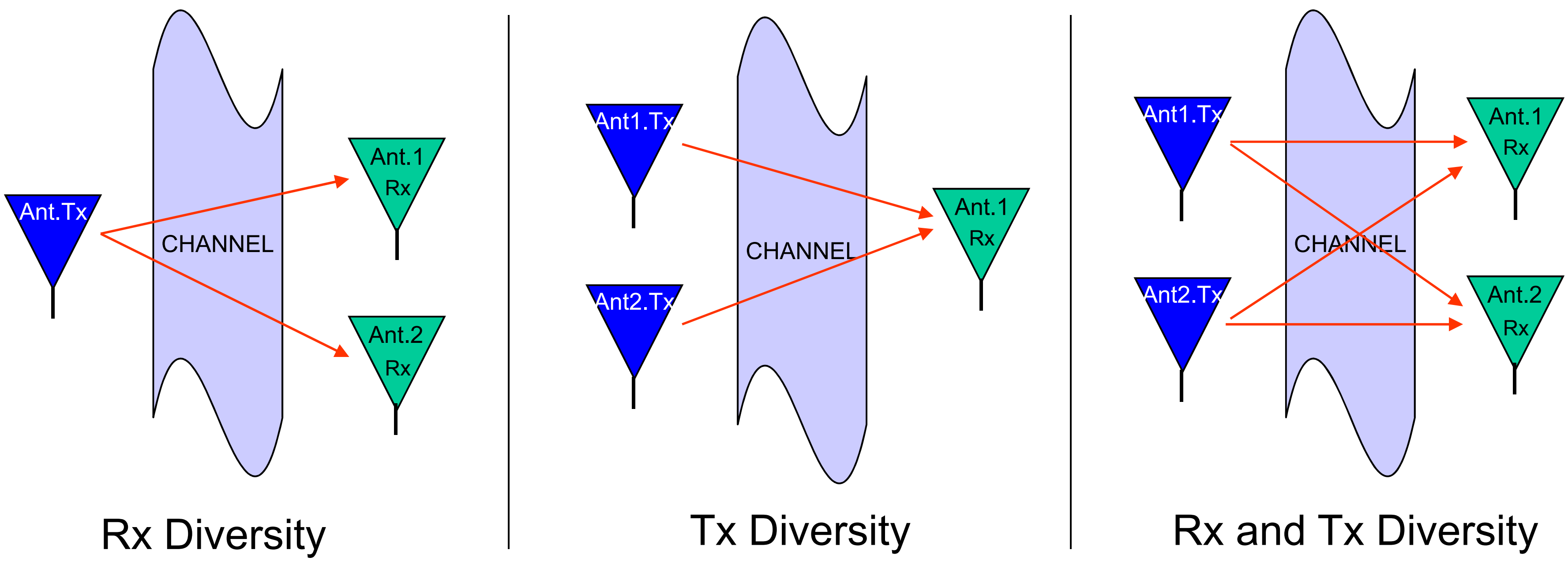
Multi-Antenna Systems: Spatial Diversity

- Antenna Diversity is also referred to as 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 create (reasonably) independent fading channels
  - Antenna separation is a function of the carrier wave length and the scattering environment
    - For an indoor environment, an antenna separation of greater than ½ carrier wavelength is typically required
- Systems with multiple transmit *and* multiple receive antennas offer more than just diversity.
  - They offer degrees of freedom which can be exploited for increasing the channel capacity

For an excellent detailed discussion of the communication theory aspects of multi-antenna systems see ref. [4]

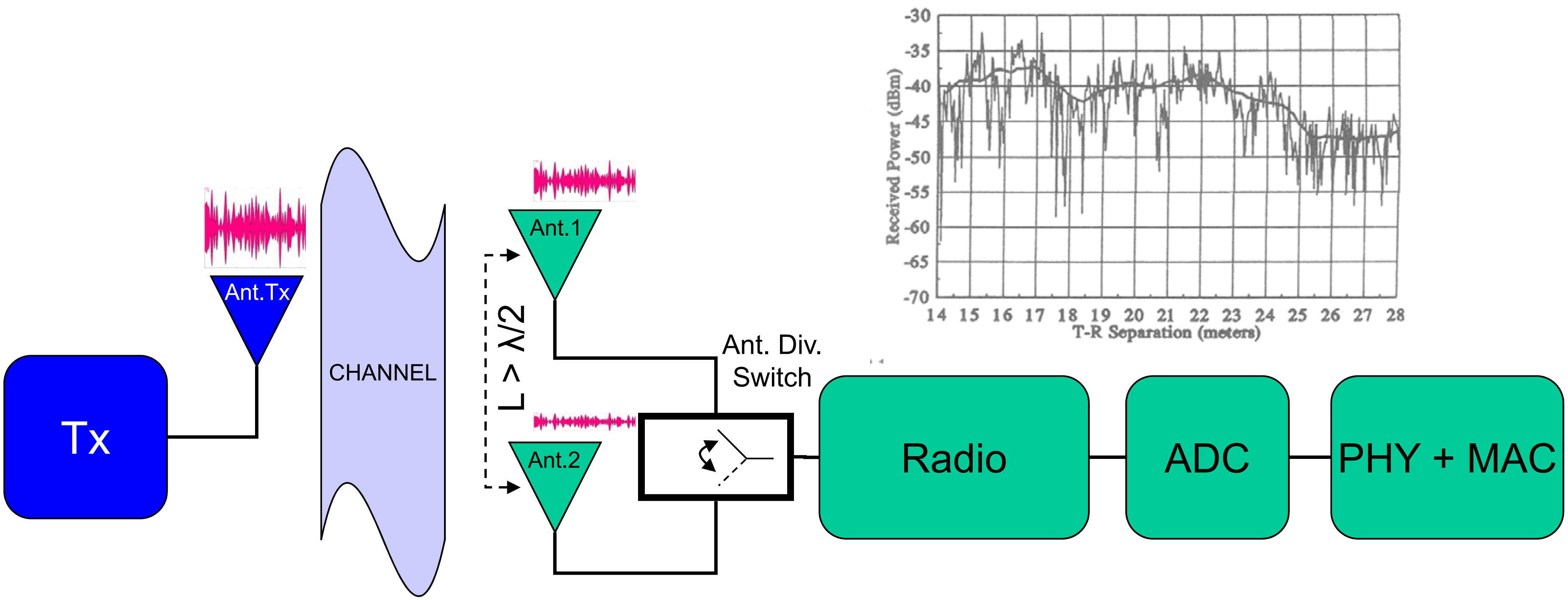
Multi-Antenna Systems: Spatial Diversity

- Multi-Antenna systems can be implemented with Rx and/or Tx diversity
  - If each Rx antenna has a complete analog path to digital, Rx Diversity is often referred to as single-in, multi-out (SIMO)
  - If each Tx antenna has a complete analog path from digital, Tx Diversity is often referred to as multi-in, single-out (MISO)
  - If each Rx and Tx antenna has a complete analog path to and from digital, Rx and Tx Diversity is often referred to as multi-in, multi-out (MIMO)



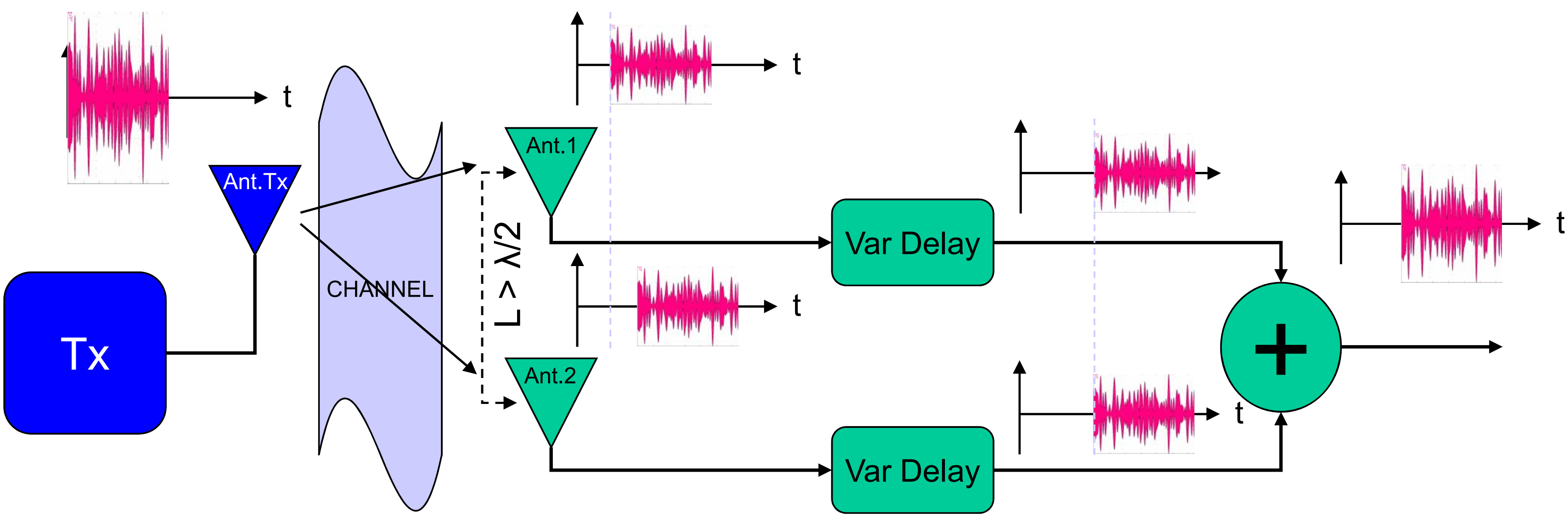
Selection Diversity

- In a simple Rx *selection-diversity* system:
  - Received power at each antenna is examined one after another (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



Analog Maximum Ratio Combining (MRC)

- MRC is a form of Rx diversity that is more sophisticated than Rx selection diversity
  - MRC works by simultaneously enabling multiple receive antennas, equalizing the gain on each path, and aligning the delays of the received signals before (coherently) combining them
  - If gain is not equalized (only delays are aligned) system is often referred to as a “single weight combiner” or SWC.



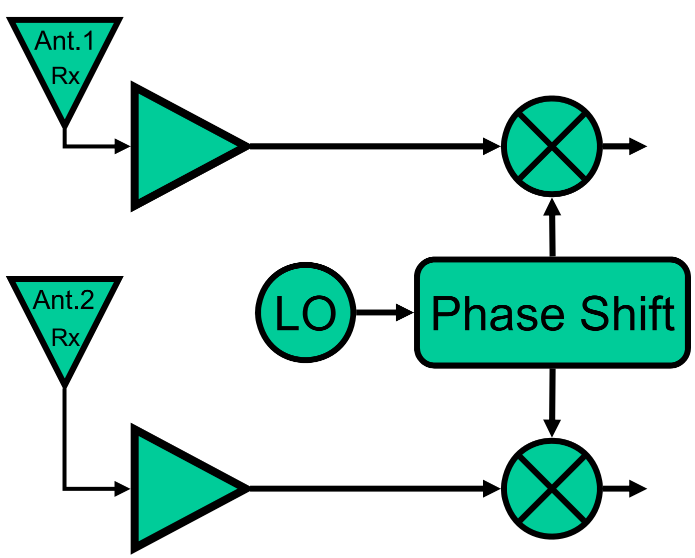
Analog Maximum Ratio Combining (MRC)

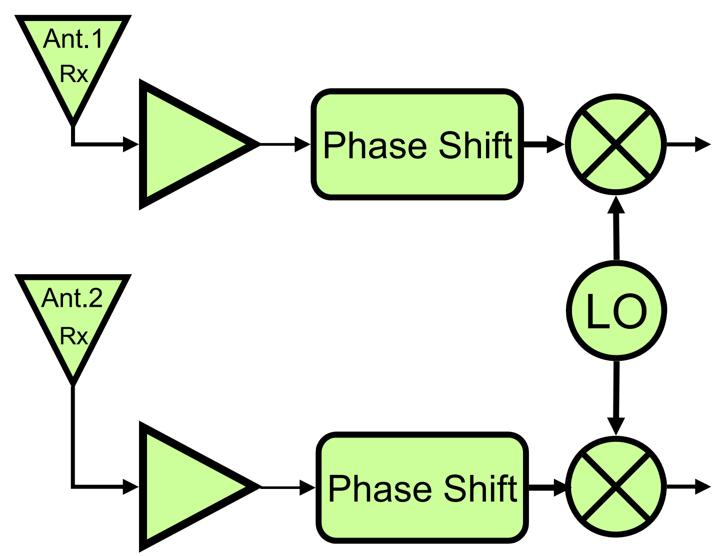
- In an MRC system, signals on each path are added coherently, whereas noise for each path is added incoherently
  - MRC allows for an SNR improvement of up to [10 log(m)] over a Rx selection diversity scheme, where m is the number of Rx antennas
    - 3dB SNR improvement for 2 antenna system

- MRC can be performed in the digital domain also (with full independent Rx paths to baseband)
  - More on this later

Analog Maximum Ratio Combining (MRC)

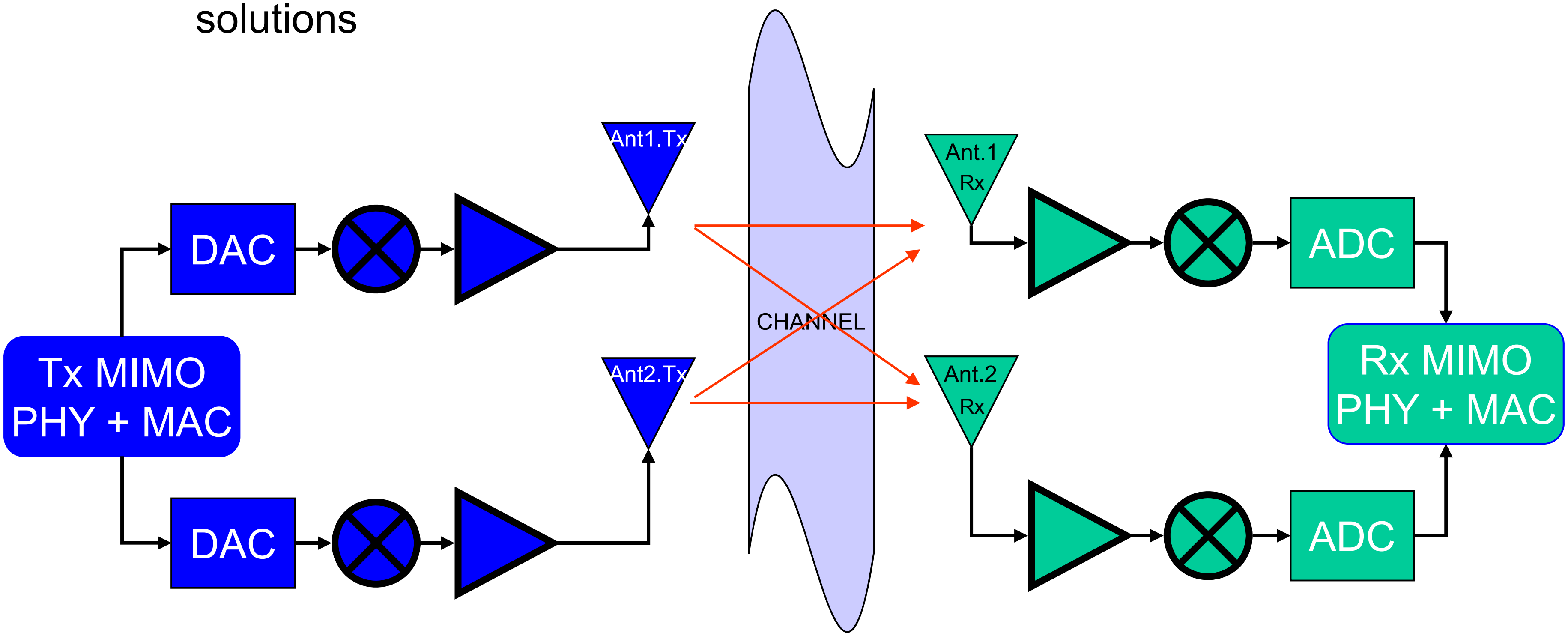
- When the bandwidth of the modulated signal is narrow as compared to the carrier frequency, a variable delay block can be replaced with a programmable phase shifter which is much simpler to implement
  - In this case the MRC system is also referred to as a “phased array”
  - MRC/SWC Phased array can be implemented in the LO path (e.g. ref. [12])
  - MRC/SWC Phased array can be implemented in the signal path (e.g. ref. [13])





MIMO

- A n X m MIMO system can offer a diversity gain of up to n X m
- A multi-antenna system with a full analog path for each antenna allows for maximum system performance and flexibility
  - Phase shifting, combining, beam-forming, etc. can be performed easily at digital baseband
    - On a per subcarrier basis in OFDM systems, for example
  - Allows for “spatial multiplexing”
  - Consumes more power and area than analog-only multi-antenna solutions



MIMO

- Some of this diversity gain (i.e. reliability) can be traded off for "spatial multiplexing" (i.e. a more efficient packing of bits)
  - Spatial multiplexing can allow for an increase in the channel capacity as compared to a SISO system
  - SISO capacity is given by Shannon's famous relation:

$$C_{SISO} = BW \cdot \log_2(1 + SNR)$$

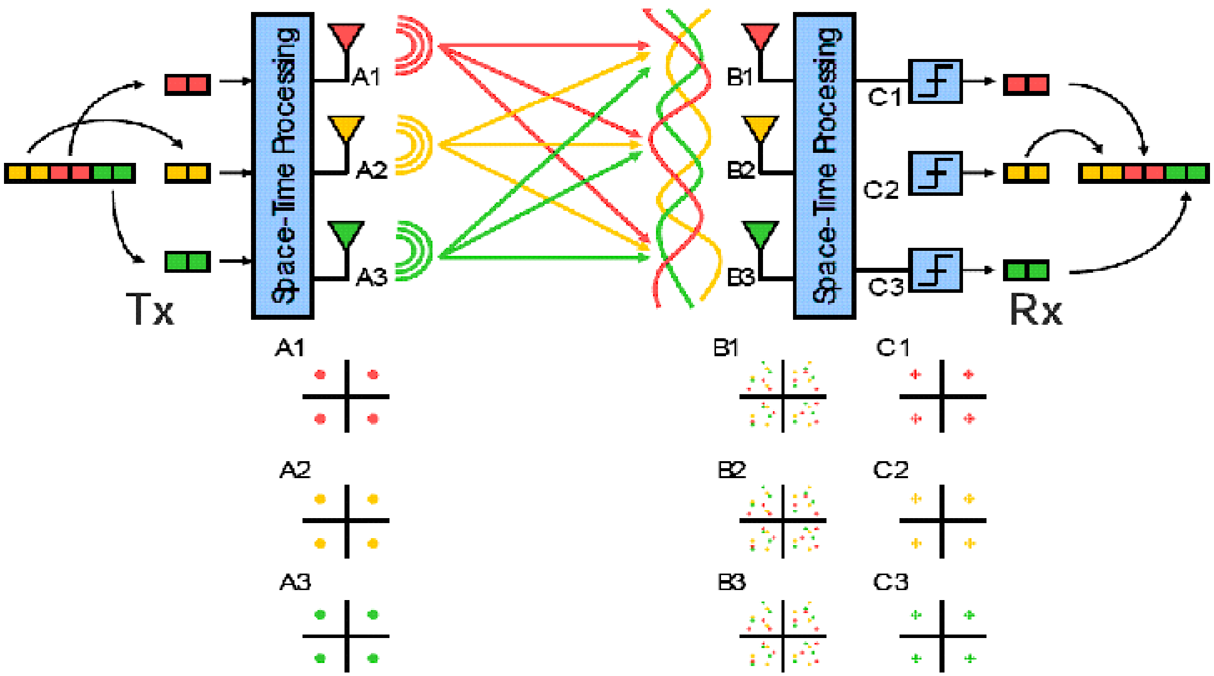
    - Capacity increases linearly with *BW* which is the channel bandwidth and is a very expensive and precious commodity
    - Capacity increases logarithmically with *SNR*. Increasing channel capacity by trying to increase *SNR* is futile.
  - MIMO capacity (in a high SNR environment) is given by

$$C_{MIMO} = \min(n, m) \cdot BW \cdot \log_2(1 + SNR)$$

    - *n* is the number of transmitter antennas and *m* is the number of receiver antennas
    - A huge increase in capacity can be obtained because of spatial multiplexing

Why MIMO OFDM?

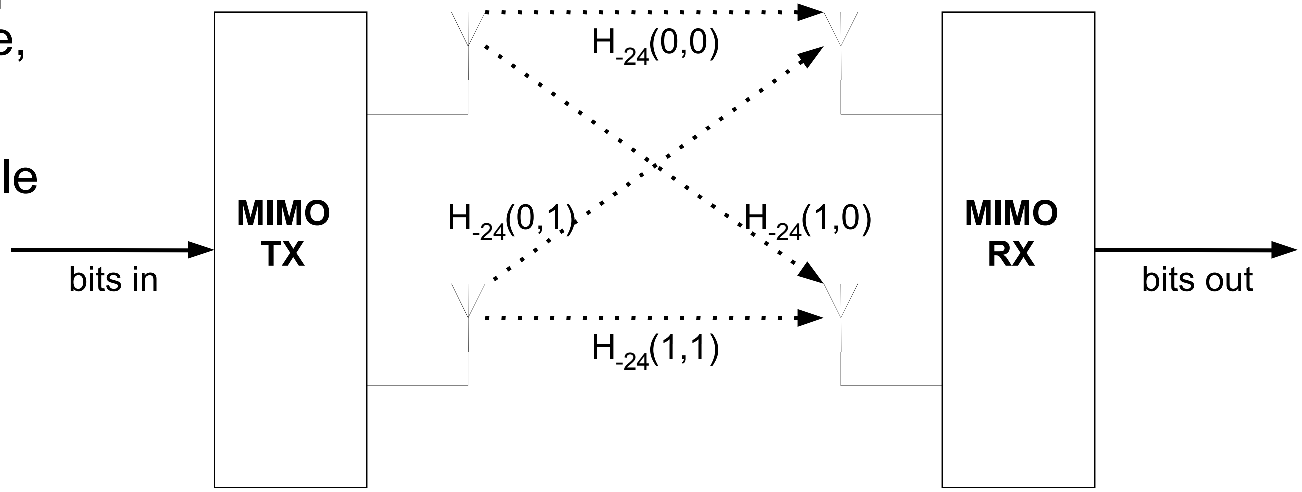
- OFDM has been used for legacy 802.11a/g to enable reasonably high data rates at the presence of multi-path fading present in typical indoor environments.
  - OFDM *combats* the multi-path fading by dividing the wide bandwidth required for high data rate communications to multiple narrow subcarriers such that the modulated bandwidth of each subcarrier is << than 1/(rms delay) of the channel
- Utilizing MIMO OFDM, in general, a "rich scattering" environment can be *used*. The capacity increases with min(M, N), i.e. the minimum of the number of transmitter and receiver antennas.



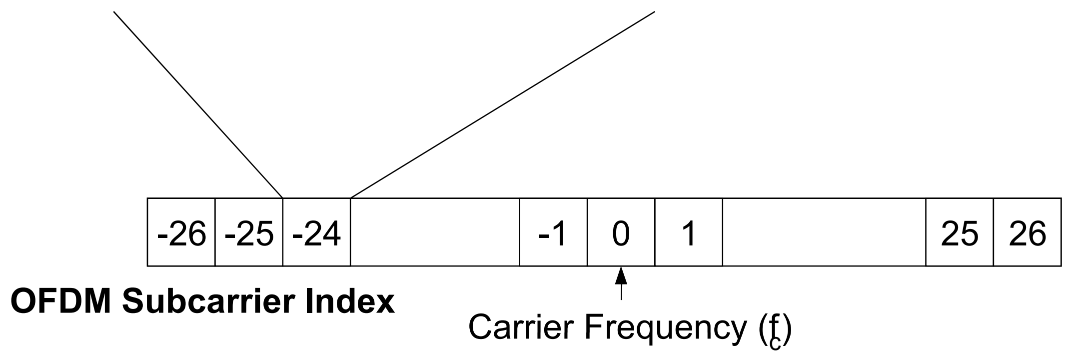
- **Independent data streams are sent on each transmit antenna at the same time and on the same frequency band**
- **Need multiple antennas on both sides**

MIMO-OFDM

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

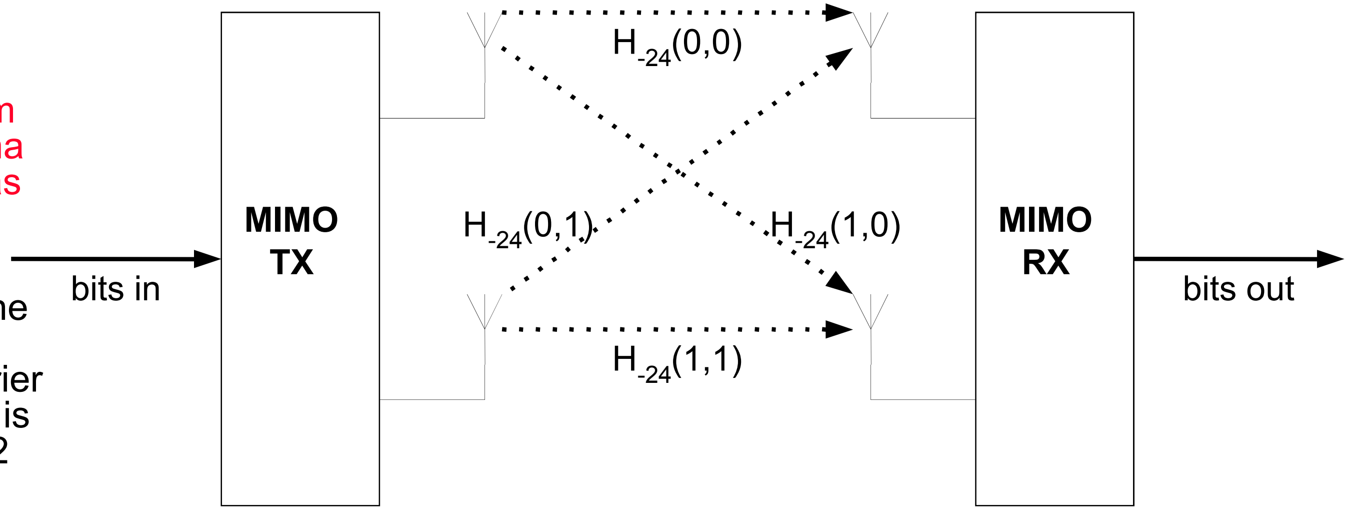


$$\begin{pmatrix} Y_{-24}(0) \\ Y_{-24}(1) \end{pmatrix} = \begin{pmatrix} H_{-24}(0,0) & H_{-24}(0,1) \\ H_{-24}(1,0) & H_{-24}(1,1) \end{pmatrix} \times \begin{pmatrix} X_{-24}(0) \\ X_{-24}(1) \end{pmatrix} + \begin{pmatrix} N_{-24}(0) \\ N_{-24}(1) \end{pmatrix}$$



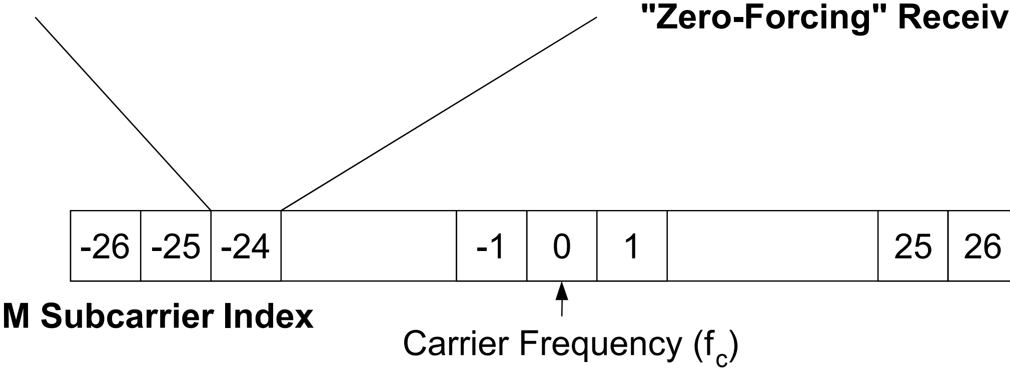
Space Division Multiplexing (SDM)

- 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".



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

"Zero-Forcing" Receiver



OFDM Subcarrier Index

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WLAN Evolution

- .11b
  - 2.4 GHz band
  - Direct sequence spread spectrum (DSSS): 1 and 2 Mbps
  - Complimentary code keying (CCK): 5.5 and 11 Mbps
- .11a
  - 5 GHz band
  - Orthogonal frequency division multiplexing (OFDM)
    - 6,9,12,18,24,36,48,54 Mbps
  - Signal BW = 20 MHz
- .11g
  - 2.4 GHz band
  - .11b + .11a rates: 12 rates
- .11n
  - 2.4 and 5 GHz bands
  - .11g rates + 77 Modulation and coding schemes (MCSs)
  - Top PHY rate of 600 Mbps. Rate increase over .11a/g achieved by:
    - Wider Signal BW of 40 MHz
    - Multiple input multiple output (MIMO)-OFDM: Exploit spatial richness of the channel
    - Higher coding rates

WLAN Evolution

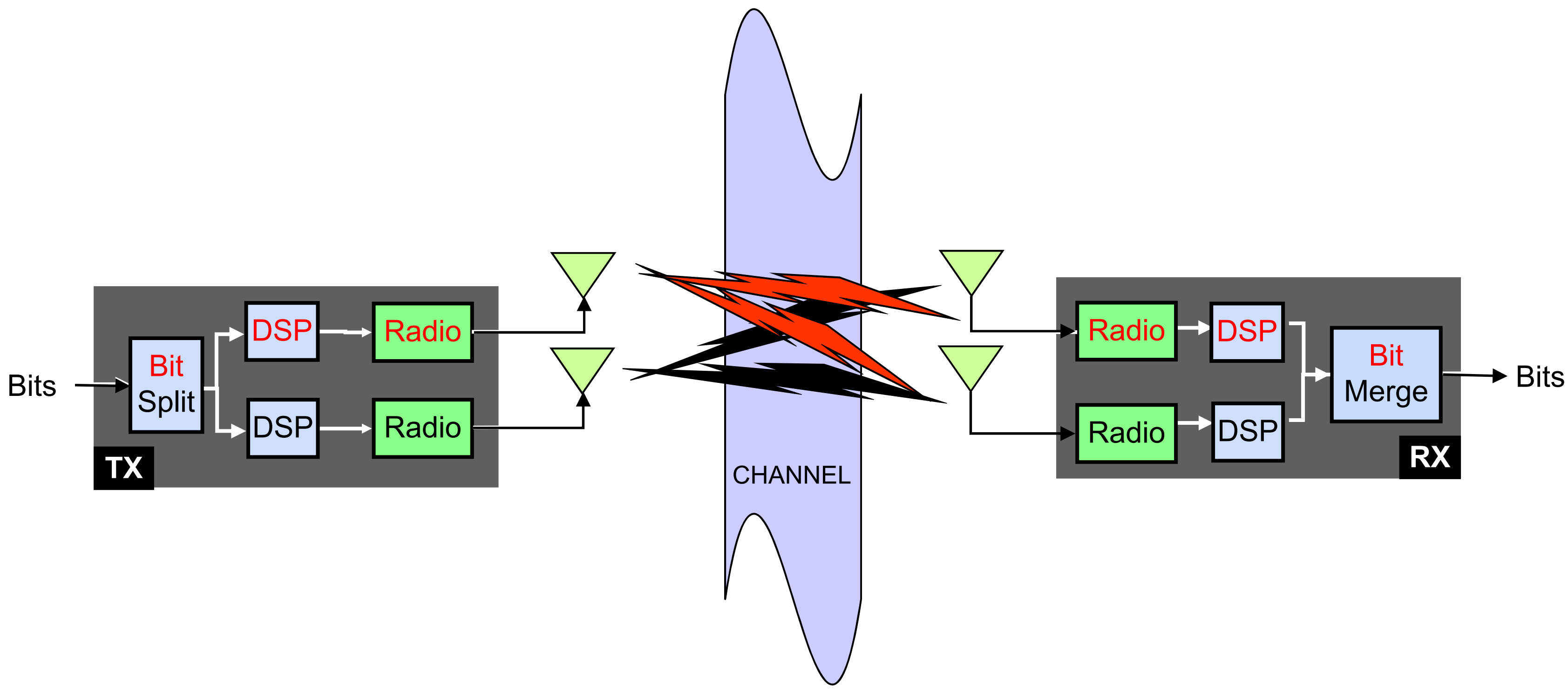
- .11ac
  - 5 GHz band only
  - Backward compatible with 11a/b/g/n
  - Top PHY rate of 6.933Gbps with Nss=8, 160MHz channel, R=5/6, Short GI. Rate increase over .11n achieved by:
    - Wider Signal BW of 80 and 160MHz with channel bonding
    - 256-QAM modulation

What was added in .11n PHY & MAC?

- Spatial Division Multiplexing (SDM) through MIMO-OFDM
- Bandwidth Expansion
- Higher Rate Binary Convolutional Code (BCC)
- New Frame Formats
- Reduced Interframe Spacing (RIFS)
- Short Guard Interval (GI)
- Space-Time Block Code (STBC)
- Transmit Beam Forming (TxBF)
- Low Density Parity Check Code (LDPC)
- New Modulation and Coding Schemes (MCSs)
- Aggregation Techniques

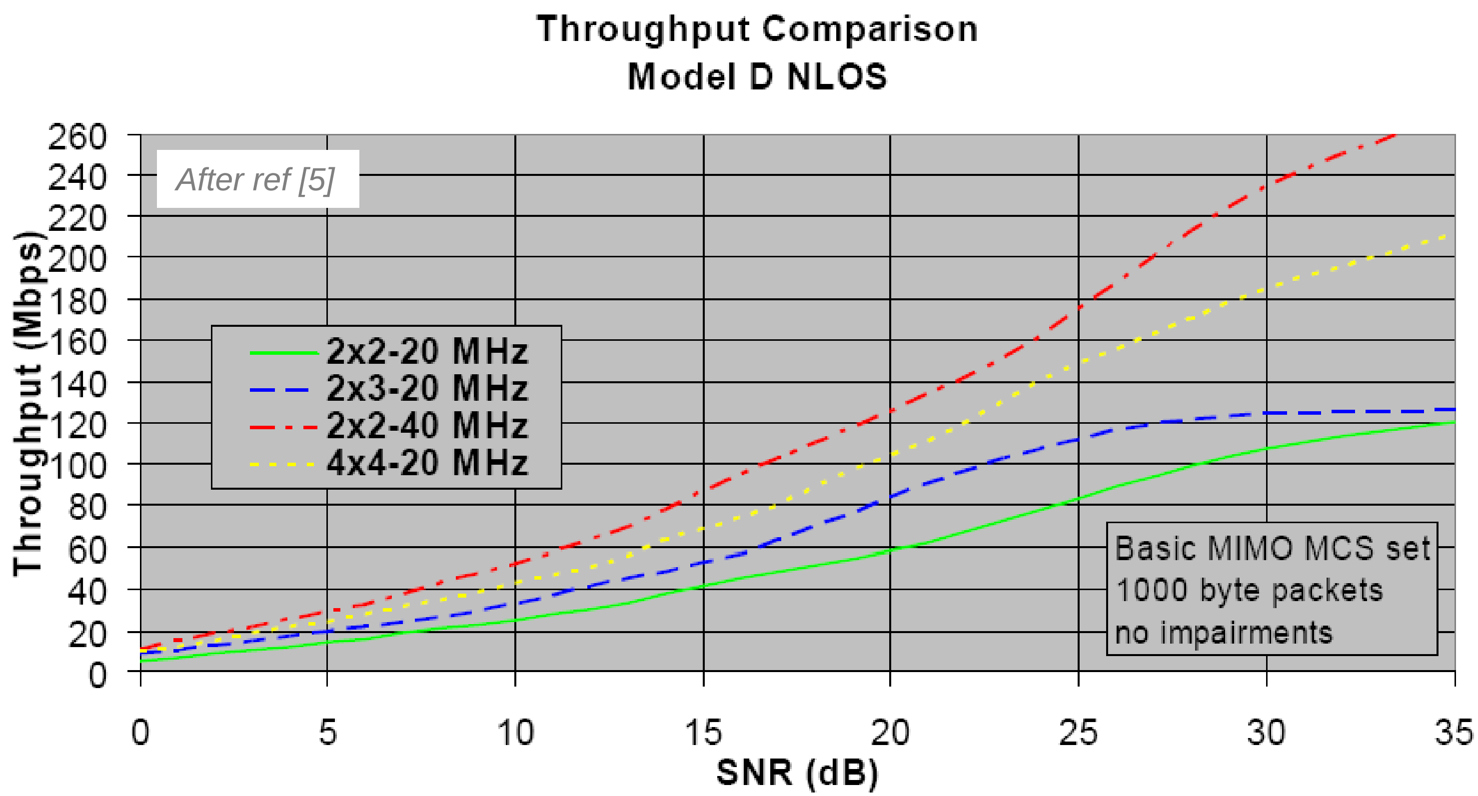
Impact of SDM on Radio: Area and power consumption

- A MIMO SDM system requires multiple Rx/Tx chains and AFEs
  - Compact design becomes much more important
  - Low power design becomes much more important
- To increase robustness, even more Rx or Tx chains may be desired



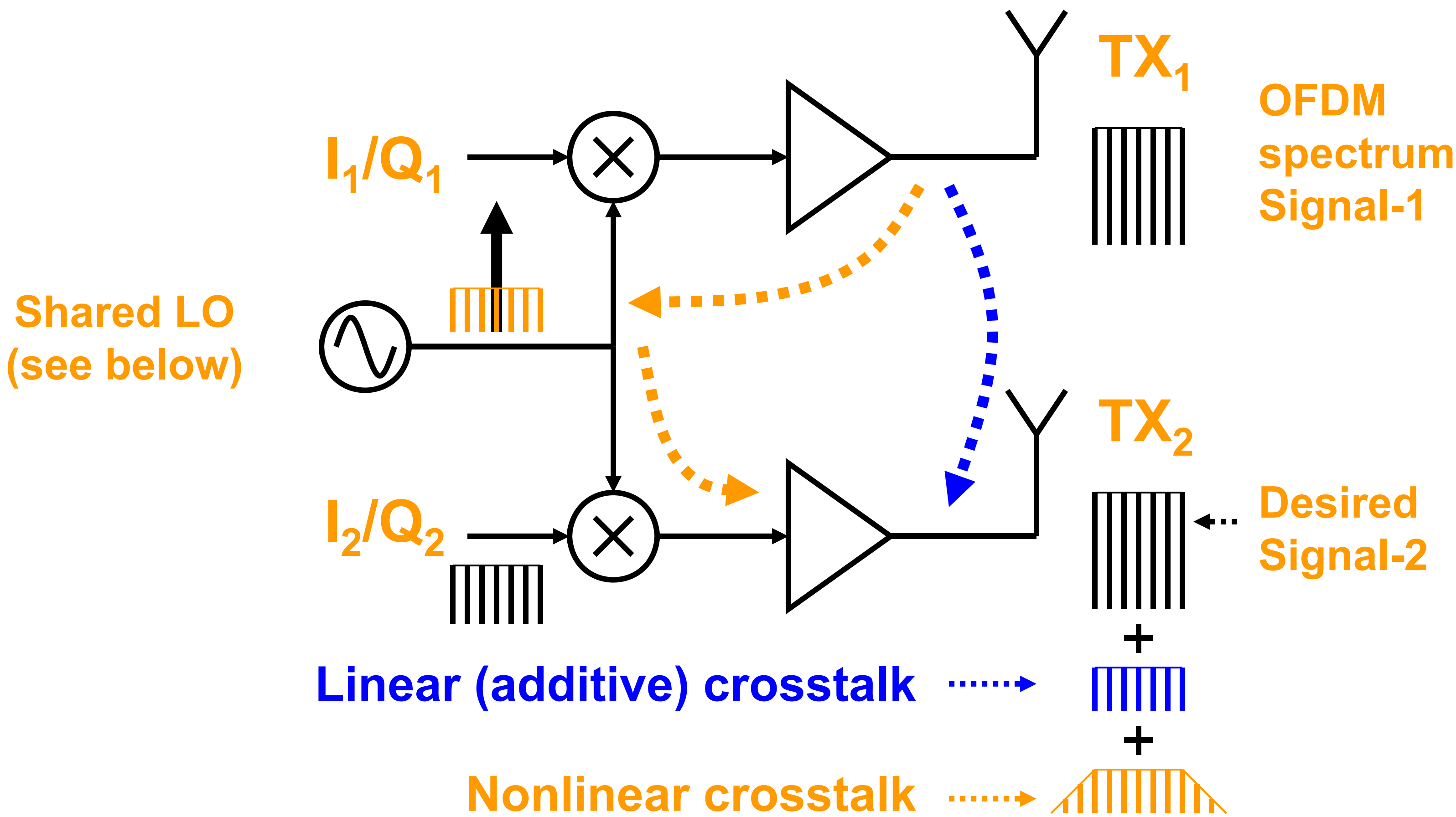
Impact of SDM on Radio: SNR and EVM requirements

- As compared to non SDM systems (SNR ~ 22dB for legacy a/g), a higher SNR is required to obtain the highest data rates promised by MIMO SDM systems (SNR ~ 30dB)



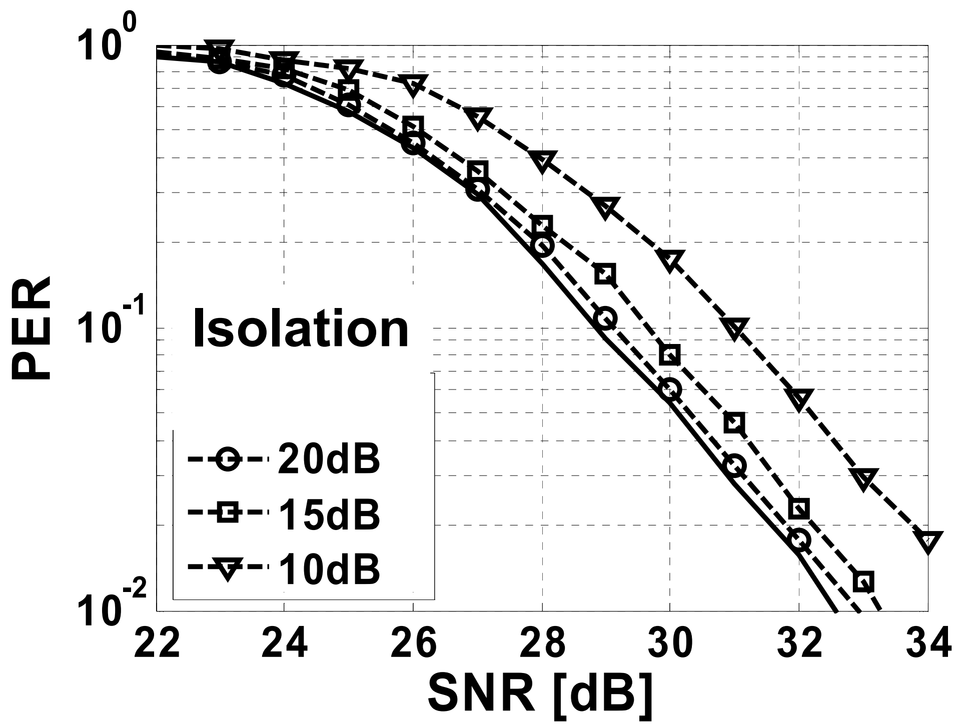
Impact of SDM on Radio Design: Crosstalk

- Linear (additive) and Nonlinear (multiplicative) crosstalk have very different impacts on MIMO system performance



Figs. & Discussions of crosstalk largely after ref. [6]

Impact of SDM on Radio Design: Crosstalk



- MIMO processing is inherently trying to cancel additive crosstalk (channel + radio)
- 20dB isolation is adequate
- Apply usual isolation tricks in design/layout

Impact of SDM on Radio Design: Other Requirements

- Tx or Rx chains are *not* required to have absolute phase matching
  - Any mismatch or variations of Rx or Tx chains is tracked as part of the overall MIMO channel
  - Channel is "learned" on the receiver DSP-side based on the received preamble
- Frequency and phase of the multiple spatially multiplexed streams is tracked jointly
  - A single common reference source (crystal) should be used for all streams
  - All else being the same, and *assuming* that the phase noise from the multiple streams are correlated, the phase noise requirements for an SDM system are no more stringent than for a SISO system. In reality a better PN is highly desirable, however, since:
    - In reality, the correlation factor is not exactly 1
    - Because of other reasons, such as higher coding rate required in 11n
    - …

One Good Design Choice: Shared LO

- ❑ Avoids duplication of synthesizer/VCO power dissipation
  - ➢ Better area and power consumption
- ❑ Provides two estimates of *same* phase noise-- Better phase noise tracking
  - ➢ Better effective EVM
- ❑ Avoids pulling between multiple VCOs
  - ➢ Reduced nonlinear cross-talk
- ❑ If not possible to use same PLL, at least share the same reference crystal oscillator

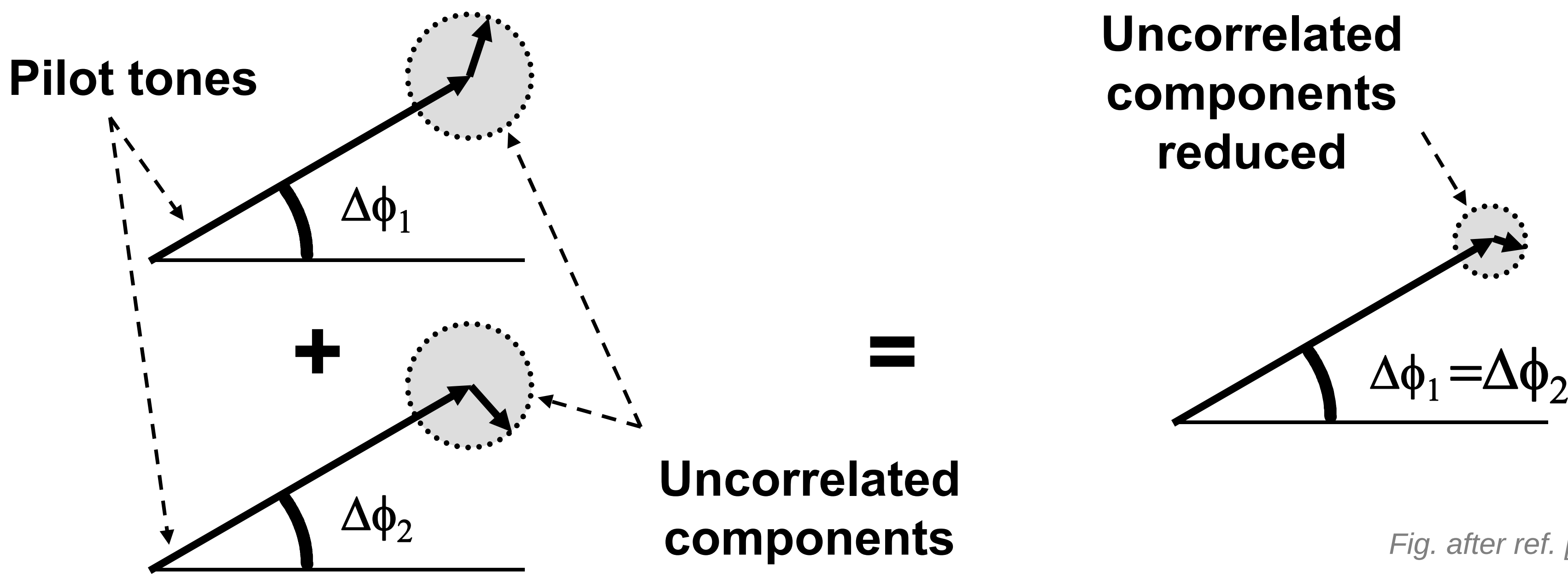
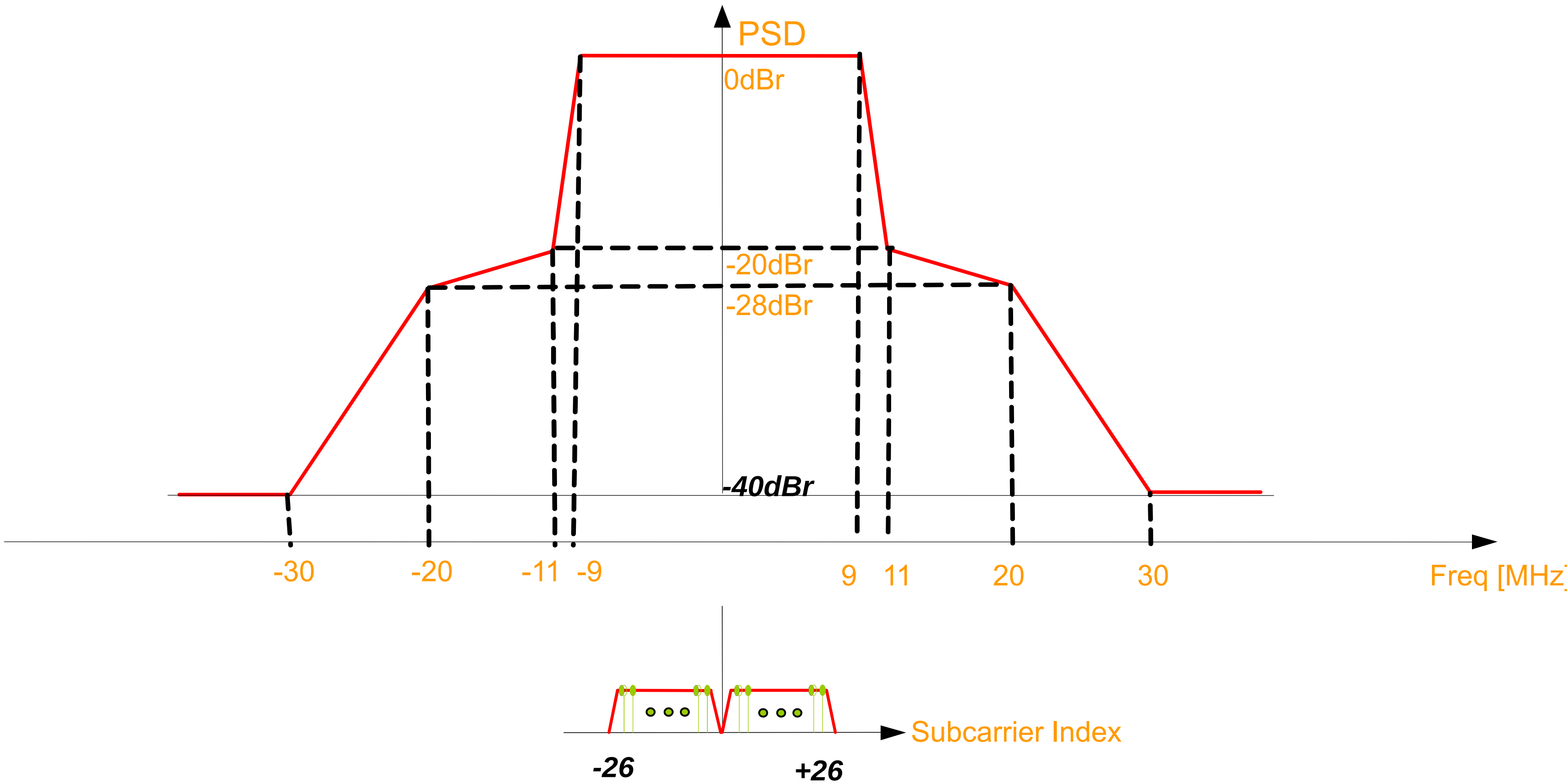


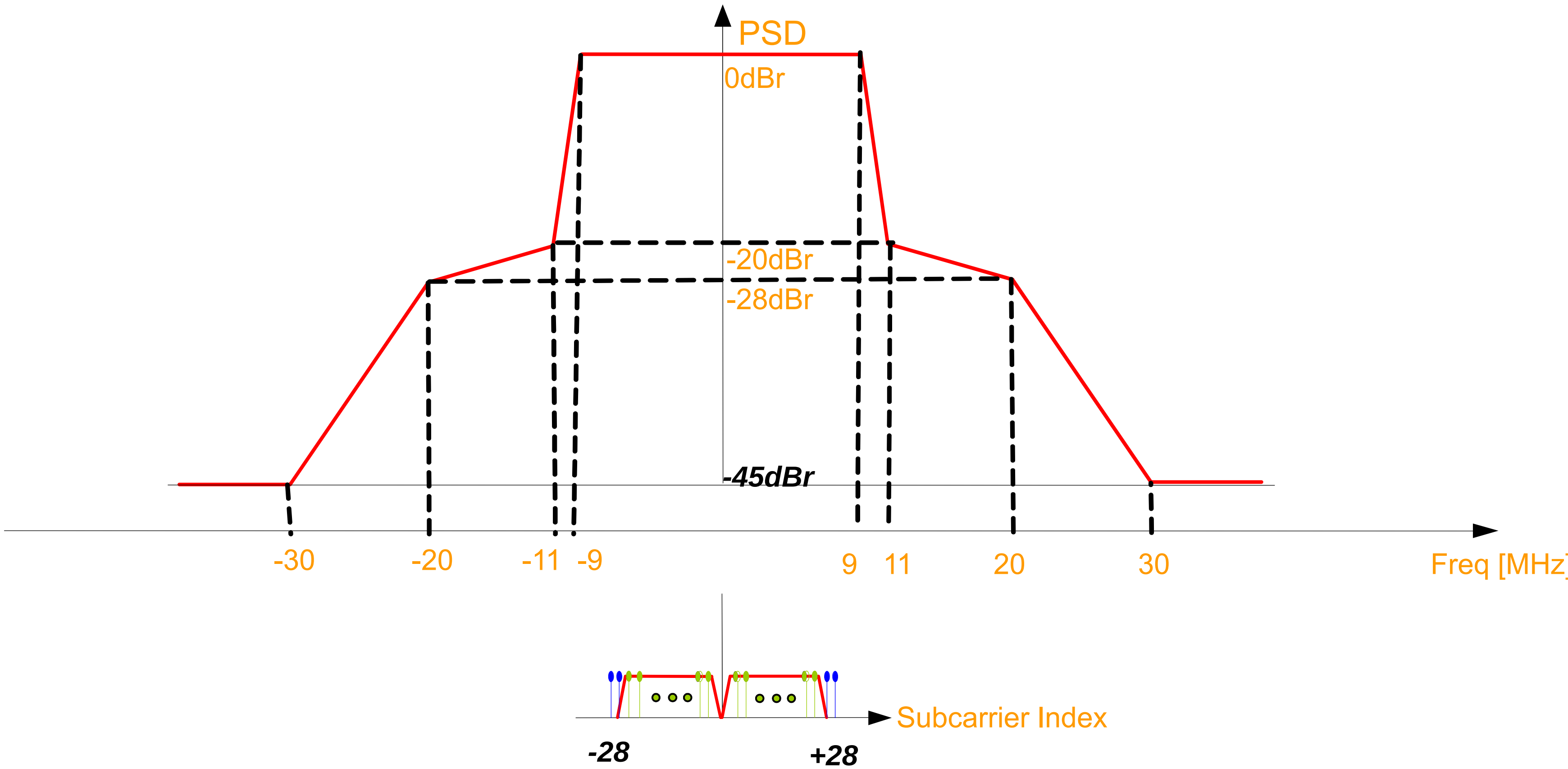
Fig. after ref. [6]

Bandwidth Extension & Spectral Mask: (legacy A/G)



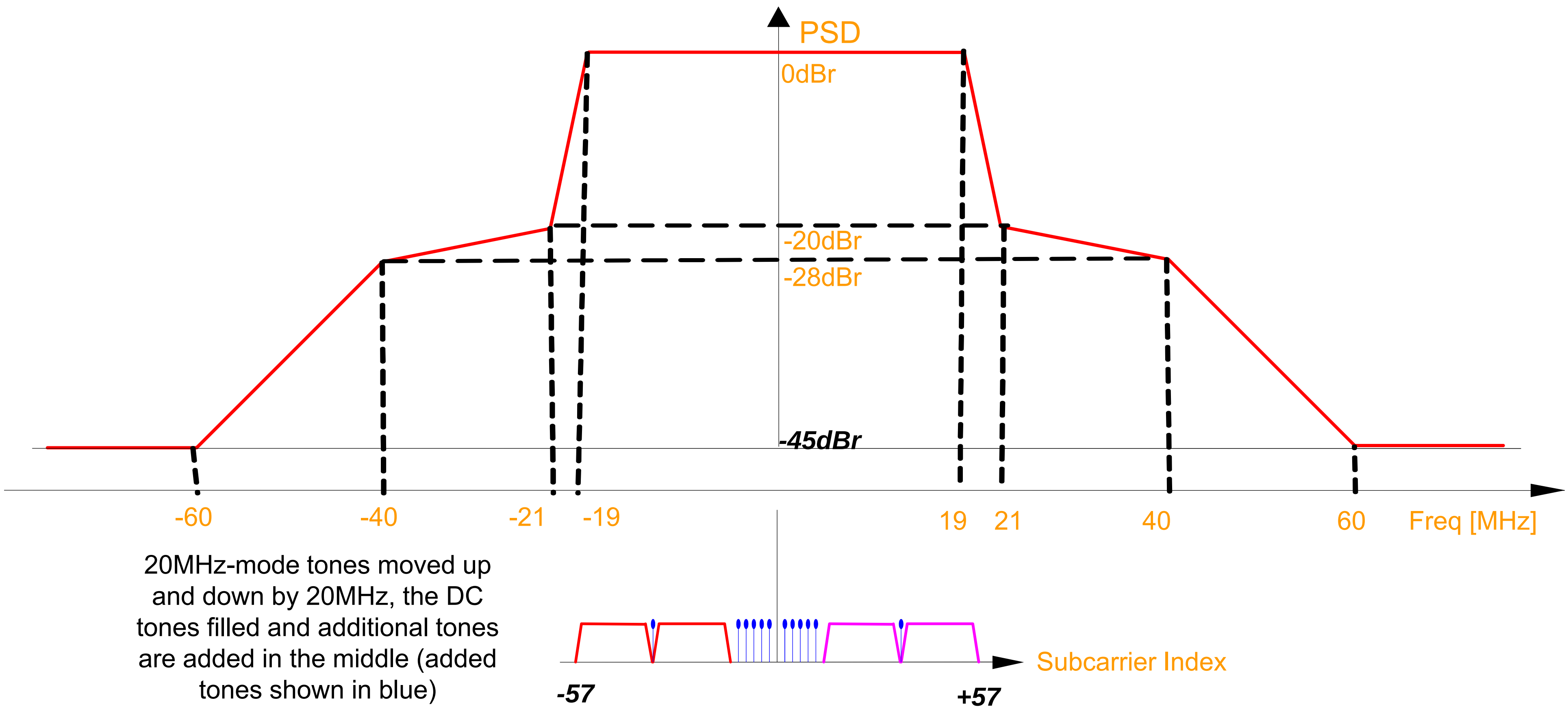
- For legacy A/G, the spectral mask floor is set to -40dBr.
- For legacy A/G, there are a total of 52 subcarriers (# -26 through #26 with #0 excluded)

Bandwidth Extension & Spectral Mask: 802.11n 20MHz Mode



- ❑ 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 (# -28 through #28 with #0 excluded)
  - ➢ 8% increase in PHY rate relative to legacy A/G

Bandwidth Extension & Spectral Mask: 802.11n 40MHz Mode



- ❑ 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 (# -57 through # +57 with #0 excluded)
  - ➢ Use of 108 data subcarriers increases PHY rate by 2.25x relative to legacy A/G

Bandwidth Extension & Spectral Mask
Implications on Radio (20MHz mode)

- Additional subcarriers in 20MHz mode has:
  - No impact on Rx or Tx RF sections
  - No impact on PLL
  - On baseband Rx and Tx sections:
    - Flatter frequency response across the desired passband
      - Less amplitude ripple
      - Less group delay variation
    - Sharper filter roll-off for same ACRR and ALCR
- Lower spectral mask floor (-45dBr) requires:
  - More linear transmitter
  - Lower noise transmitter
  - Lower noise VCO and LOGEN chain

Bandwidth Extension & Spectral Mask
Implications on Radio (40MHz mode)

- Wide-band 40MHz mode has:
  - No or minimal impact on Rx or Tx RF sections
  - Phase noise of PLL needs to be considered up to +/-20MHz
    - Particularly for fractional-N implementations
  - On baseband Rx and Tx sections:
    - High speed baseband blocks required
      - e.g. opamps with >1GHz GBW product necessary for opamp-RC style filters and VGAs
    - Wide-band and flat frequency response across the desired passband
      - Low amplitude ripple
      - Low group delay variation
    - Sharper filter roll-off for reasonable ACRR and ALCR
  - Higher speed ADCs and DACs needed

Bandwidth Extension & Spectral Mask
Implications on Radio (40MHz mode)

- Low spectral mask floor (-45dBr) requires:
  - Linear and wide-band transmitter
    - Implications and complications with respect to digital predistortion
  - Low noise transmitter
  - Low noise VCO and LOGEN chain

Higher Rate Binary Convolutional Codes
Implications on Radio

- Legacy code rates of 1/2, 2/3, and ¾ are carried over.
  - With the addition of the 4 subcarriers in the 20MHz mode, a data rate of 58.5Mbps is achieved with a BCC rate of ¾.
- A mandatory code rate of 5/6 has been added for MCS7
  - An additional increase of 11% in data rate
- A higher coding rate reduces the redundancy and therefore robustness of the code
  - A better EVM is required on Tx side
  - A worse sensitivity is achievable on the Rx side (with all else being the same)

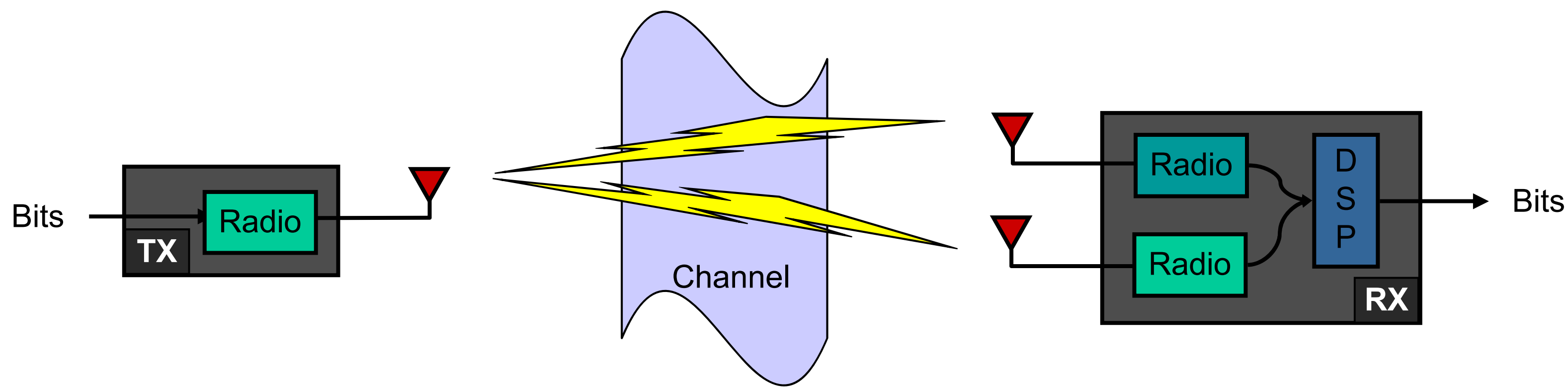
Index	Modulation	Code Rate	Data Rate (Mbps)
0	BPSK	½	6.5
1	QPSK	½	13
2	QPSK	¾	19.5
3	16-QAM	½	26
4	16-QAM	¾	39
5	64-QAM	2/3	52
6	64-QAM	¾	58.5
7	64-QAM	5/6	65

Space Time Block Codes

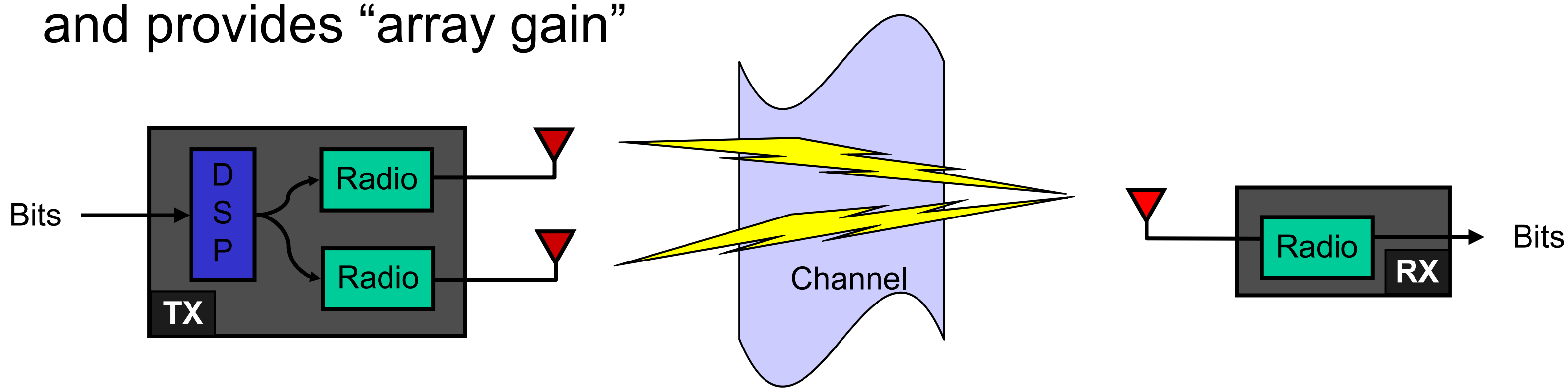
- Space Time Block Code (STBC)
  - Increases rate at range for scenarios with more transmit chains than receive chains
  - Useful especially for transmitting to single antenna devices
  - Does not require closed-loop operations
  - Same data sent in different timeslots and on different antennas
  - If channel paths to the RX are statistically independent, then probability of simultaneous fading becomes very small
  - STBC is an optional mode of 802.11n
- Requirements on radio:
  - If sent to a single antenna receiver, no particular requirement on the receiver
  - If combined with SDM, the requirements are the same as outlined in SDM discussion

Beamforming / MRC

- Uses multiple transmit and/or receive radios to form coherent signals
- Receive beamforming / combining boosts reception of signals



- Phased array transmit beamforming to focus energy to each receiver and provides “array gain”



Rx MRC

- MRC is performed on a *per subcarrier* basis to help reduce multipath deep nulls
  - Note difference with analog MRC
- The system will pick the higher SNR of *each subcarrier* between the multiple MRC channels

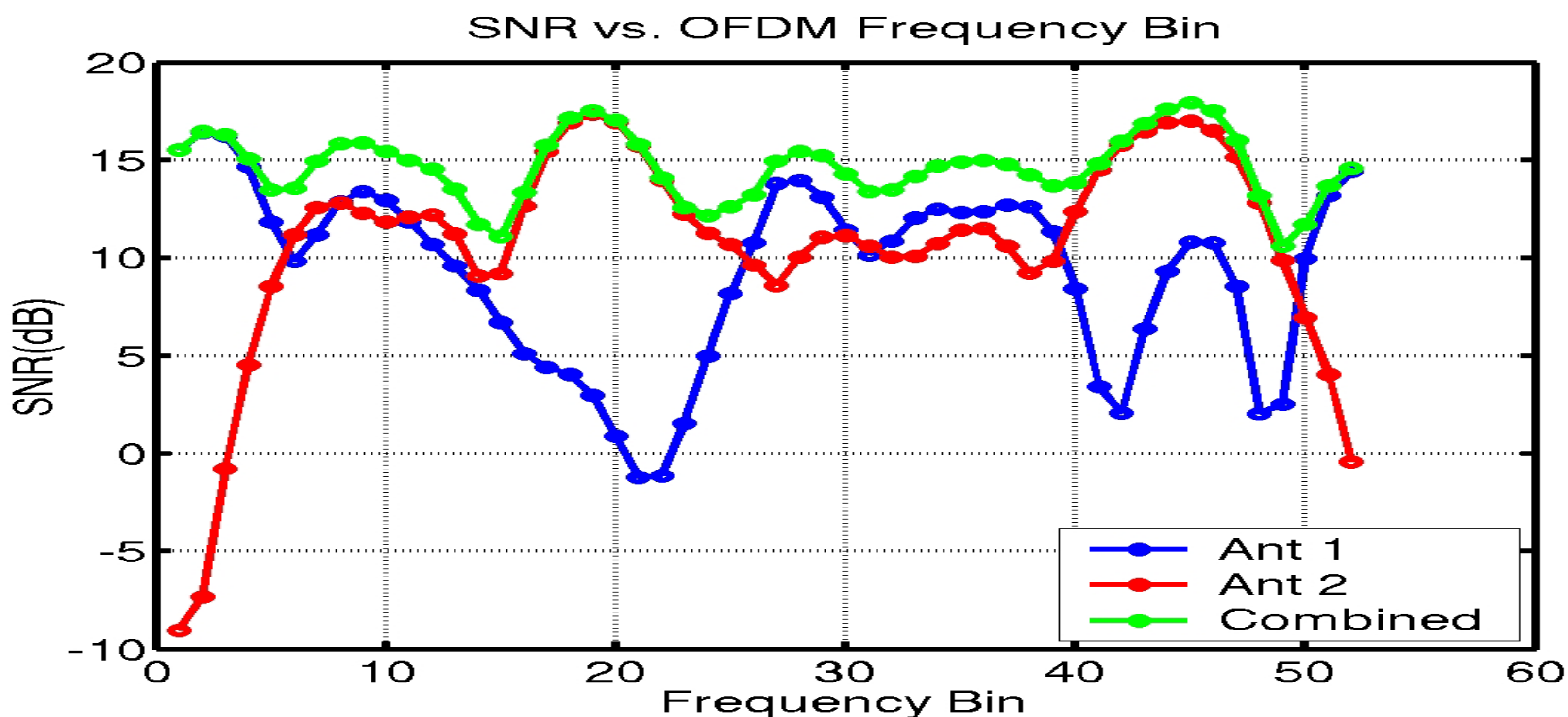


Fig. after ref. [7]

MRC

- In order to maximize benefits of beamforming, the radio must preserve high SNR on all subcarriers
  - In particular the SNR of the inner tones which are subject to DC and low frequency effects must be preserved
    - For example HPFs utilized for DC cancellation can adversely impact the SNR of the inner tones for all beamformed channels, with no recovery of those subcarriers possible

Transmit Beamforming

- TX beamforming implies channel knowledge at the TX
  - Direction of the beam is dependent on the relative phase of the signals at the Tx antennas
  - Requires some form of feedback loop
    - Explicit feedback: the receiver estimates the channel state information (CSI) and sends back to transmitter through a special message
    - Implicit feedback: The transmitter *estimates* the channel based on the packets received from the intended receiver and the assumption of channel reciprocity
  - The required beamforming phase accuracy is dependent on the width of the beam
  - The width of the beam is dependent on the number of transmit antennas

LDPC

- Optional Low Density Parity Check (LDPC) code provides higher performance than BCC code
- 12 different codes based on same code structure
  - Same code rates as BCC code
    - ½ , 2/3, ¾, 5/6
  - Three block lengths
    - 648, 1296, 1944
- The higher performance of LDPC codes as compared to BCC codes would ideally somewhat relieve the requirements on the radio Rx and Tx EVM
  - They are optional and we cant bank on them!

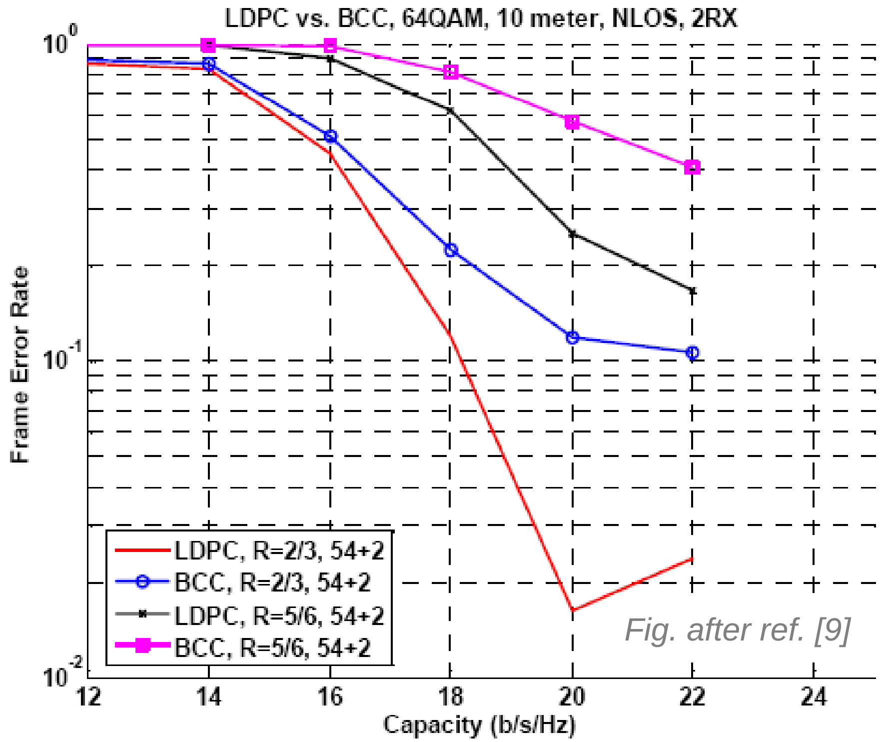


Fig. after ref. [9]

Modulation Coding Schemes & Implications on Radio

- The modulation coding schemes (MCS) allow for the various mandatory and optional modes of 802.11n. These include:
  - Use of multiple streams
  - Use of different modulation types
  - Use of different binary convolutional codes
  - Use of the different bandwidths (20MHz and 40MHz)
  - Use of robust duplicate mechanism in 40MHz mode
  - Use of asymmetric MCSs for transmit beam forming and STBC
  - …
- The implications on radio implementation has been individually discussed under each heading

Modulation and Coding Scheme (MCS)

default OFDM guard interval

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

Modulation and Coding Scheme (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
16	3	BPSK	½	2	2	52	108	156	324	19.50	40.50	21.67	45.00
17	3	QPSK	½	2	2	52	108	312	648	39.00	81.00	43.33	90.00
18	3	QPSK	¾	2	2	52	108	312	648	58.50	121.50	65.00	135.00
19	3	16-QAM	½	2	2	52	108	624	1296	78.00	162.00	86.67	180.00
20	3	16-QAM	¾	2	2	52	108	624	1296	117.00	243.00	130.00	270.00
21	3	64-QAM	⅔	2	2	52	108	936	1944	156.00	324.00	173.33	360.00
22	3	64-QAM	¾	2	2	52	108	936	1944	175.50	364.50	195.00	405.00
23	3	64-QAM	5/6	2	2	52	108	936	1944	195.00	405.00	216.67	450.00
24	4	BPSK	½	2	2	52	108	208	432	26.00	54.00	28.89	60.00
25	4	QPSK	½	2	2	52	108	416	864	52.00	108.00	57.78	120.00
26	4	QPSK	¾	2	2	52	108	416	864	78.00	162.00	86.67	180.00
27	4	16-QAM	½	2	2	52	108	832	1728	104.00	216.00	115.56	240.00
28	4	16-QAM	¾	2	2	52	108	832	1728	156.00	324.00	173.33	360.00
29	4	64-QAM	⅔	2	2	52	108	1248	2592	208.00	432.00	231.11	480.00
30	4	64-QAM	¾	2	2	52	108	1248	2592	234.00	486.00	260.00	540.00
31	4	64-QAM	5/6	2	2	52	108	1248	2592	260.00	540.00	288.89	600.00
32	1	BPSK	½	1	1		48		48		6		6.67

Further MCS entries (33-76) are defined to support unequal modulation for tx beamforming using SVD.

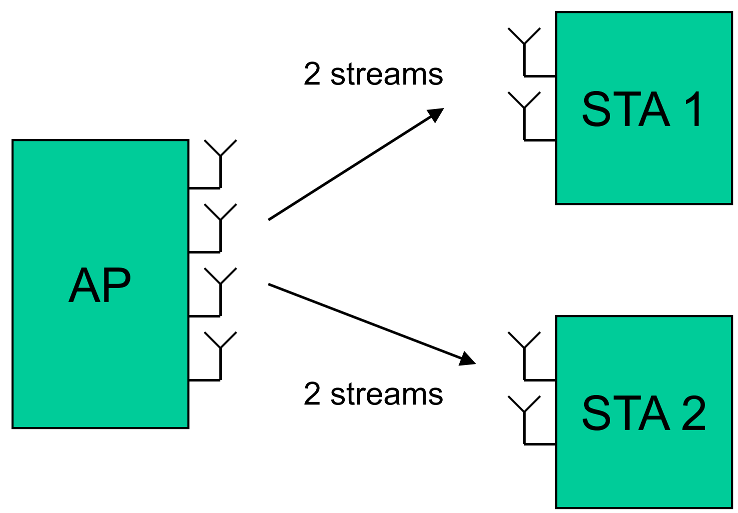
TGac Maximum PHY Data Rate Examples

- In TGac significantly higher PHY rates can be achieved
  - Maximum Nss is set to 8
  - Maximum constellation is 256-QAM
  - Maximum channel bandwidth is 160MHz (contiguous or non-contiguous)
- With a code rate of 5/6 and a short GI

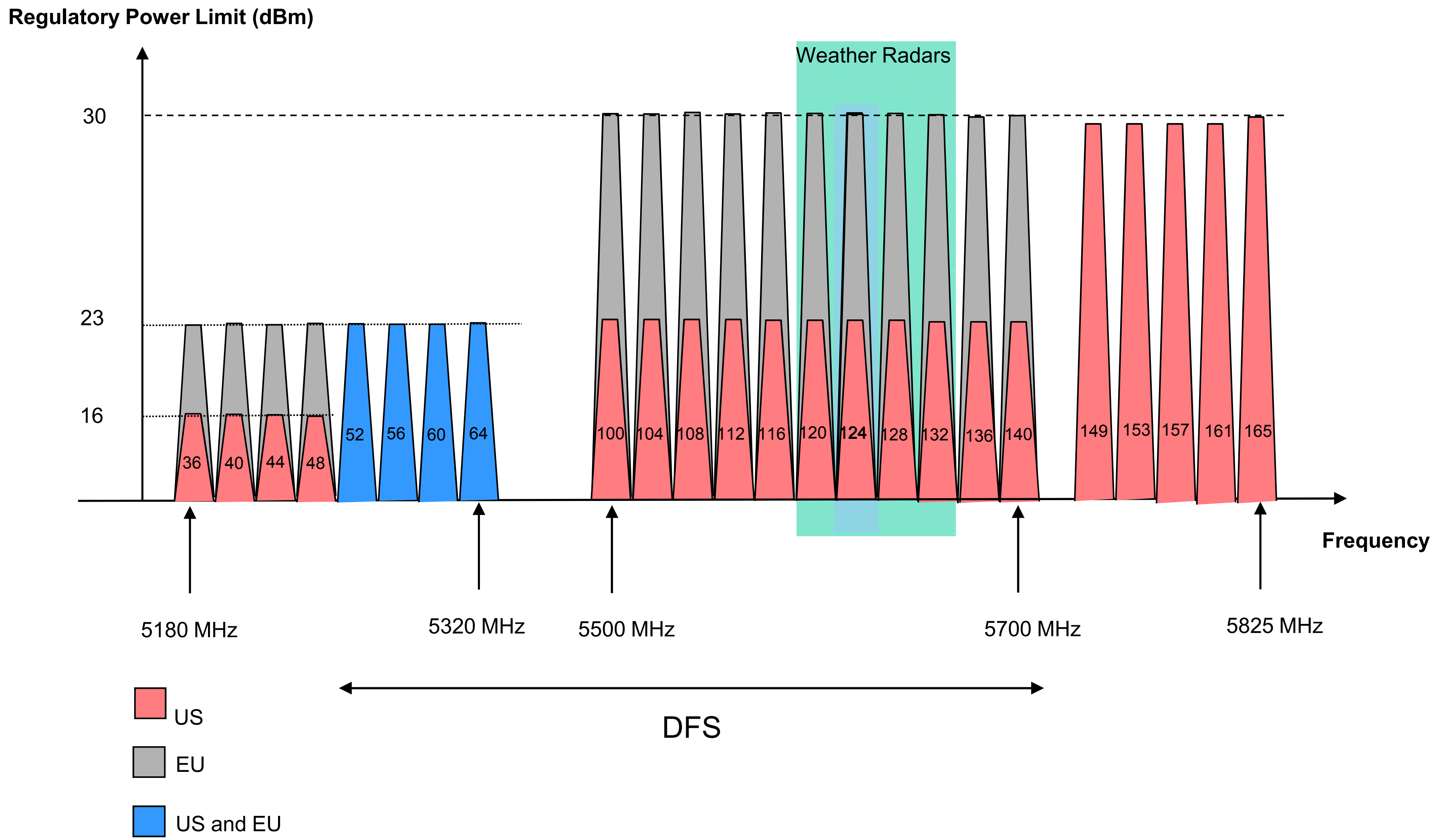
	BW = 80 MHz	BW = 160 MHz*
Nss = 1	433 Mbps	867 Mbps
Nss = 2	867 Mbps	1.7 Gbps
Nss = 4	1.7 Gbps	3.5 Gbps
Nss = 8	3.5 Gbps	6.9 Gbps

MU-MIMO Highlights

- Significant gain in aggregation possible (no maximum PHY rate increase)
  - OFDMA or Pre-coding used to achieve orthogonality amongst users



5 GHz Channelization (US and EU)



Outline

- Introduction, Market Overview & Market Trends
- Communication System Performance in a Multipath Channel:
  - The problem with multipath
  - Mitigation methods for multipath
  - Taking advantage of multipath
- WLAN Evolution & 802.11
  - Additions in 802.11n PHY and impacts on radio
  - 802.11n Sensitivity and EVM requirements
  - Some optional modes of 802.11n and 802.11ac
  - A brief introduction to 802.11ac
- Some 802.11 Radio Requirements
  - Impacts of some radio impairments on system performance
- Examples of Circuit Techniques and Architectures Used in 802.11n Radios
- Evolution of Radios: SISO to MIMO
- Real World Performance & Multi-Vendor Interoperability
- Conclusion

802.11n Sensitivity Requirements

- 802.11n sensitivity requirements:
  - At the levels stated below, PER < 10% at 4096 byte packets is required
  - Power levels are average levels on *each* Rx antenna

Table 20-22—Receiver minimum input level sensitivity

Modulation	Rate (R)	Adjacent channel rejection (dB)	Nonadjacent channel rejection (dB)	Minimum sensitivity (20 MHz channel spacing) (dBm)	Minimum sensitivity (40 MHz channel spacing) (dBm)
BPSK	1/2	16	32	–82	–79
QPSK	1/2	13	29	–79	–76
QPSK	3/4	11	27	–77	–74
16-QAM	1/2	8	24	–74	–71
16-QAM	3/4	4	20	–70	–67
64-QAM	2/3	0	16	–66	–63
64-QAM	3/4	–1	15	–65	–62
64-QAM	5/6	–2	14	–64	–61

802.11n EVM Requirements

- EVM requirements are stated below
  - Stated in RMS
  - Averaged over subcarriers, OFDM frames and spatial streams
  - Requires to 20MHz and 40MHz channels
  - Linear cross-talk between the spatial streams are corrected for
    - Be aware of this fact when measuring EVM of a MIMO transmitter with a single-channel VSA

Table n76—Allowed relative constellation error versus constellation size and code rate

Modulation	Code Rate	Relative constellation error (dB)
BPSK	1/2	-5
QPSK	1/2	-10
QPSK	3/4	-13
16-QAM	1/2	-16
16-QAM	3/4	-19
64-QAM	2/3	-22
64-QAM	3/4	-25
64-QAM	5/6	-28

Practical Advantages of a Better EVM

- Although the 11n standard requires an Tx EVM specification of only -28dB at the highest rate, a better radio EVM can provide many advantages:
  - Improved sensitivity level for an AWGN channel at the receiver
  - More EVM budget for the PA
  - Even more aggregation and longer packets due to lower probability of error
  - Possibility of higher order proprietary modulation schemes for higher data rates

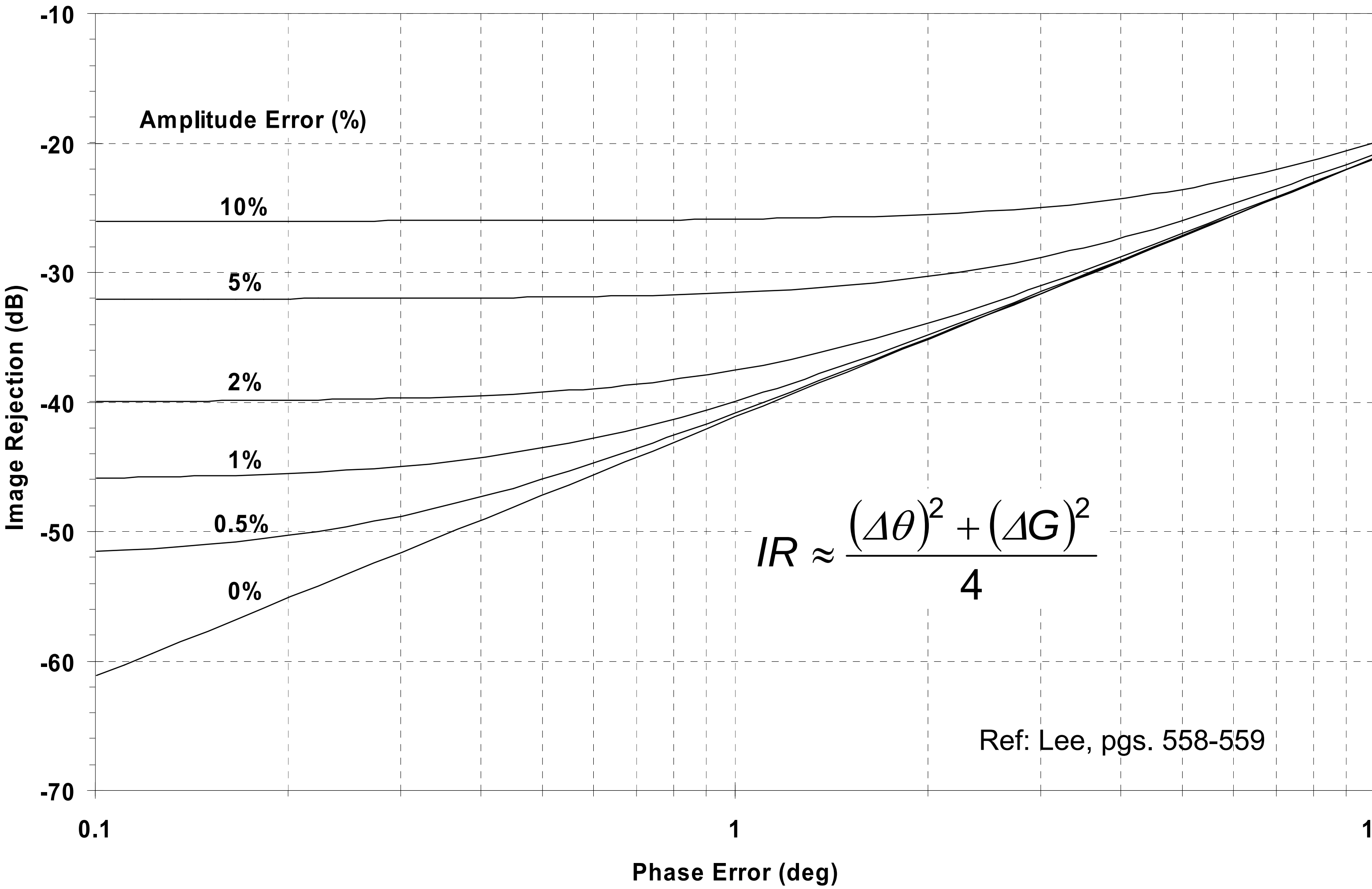
- As a tradeoff, a better overall EVM (radio Tx + PA) requires:
  - A better transmitter (PN, IQ balance, linearity, etc.)
  - More back off on the PA transmit power
    - Efficiency impact
    - Range impact

What are the Special Requirements of 802.11n radios?

- Some of the specific requirements (on isolation of the chains, for example) have already been discussed. Beyond that, in general,
  - A “better” radio (transmitter, receiver and PLL) are required for satisfying the 802.11n requirements
  - Not all radio characteristics *have to* be better for an 802.11n radio
    - For example, a better NF is *not* required to meet the bare minimum standard requirements on sensitivity
    - But from an customer point of view, a better performance than the legacy products is *expected*
  - In particular, to meet the better EVM requirements radio impairments have to be reduced. In particular,
    - Better PN is required
    - Better quadrature balance is required
  - As an example, impact of quadrature imbalance on image rejection and the subsequent impact of image rejection on EVM is shown in the next two slides

Impact of Quadrature Imbalance on Image Rejection

- Quadrature gain and phase errors:



$$IR \approx \frac{(\Delta\theta)^2 + (\Delta G)^2}{4}$$

Impact of Image Rejection on EVM

How to Improve Radio Performance to satisfy 802.11n/ac

- General circuit performance improvement techniques should be utilized
  - Variety of techniques available depending on the block. A couple of examples:
    - Retiming the VCO dividers with the VCO output helps reduce the contribution of the dividers to the PLL noise
    - Utilizing linearization techniques on the transmitter (and receiver) allows for a smaller contribution of nonlinearities to the EVM
- Attention to details
  - For example, how do the following factors contribute to the PLL noise?
    - Supply utilized for various PLL blocks
    - Bias currents utilized for various PLL blocks
    - The LO generation and distribution blocks
    - Are the varactor models accurate?
    - Are all factors contributing to the loaded tank *Q* of the VCO taken into account?
- Calibrate, calibrate, calibrate!!

Calibration Techniques

- As much as calibrations were *"nice to have"* for legacy 802.11 systems, they are significantly more important for 802.11n and even more so for 11ac
- Chip level and system level auto-calibration is required for overcoming difficulties of integrated radio design, increasing chip and system yield and improving performance.
- Some examples:
    - VCO tuning
    - Tx and Rx IQ Calibration
    - R-Calibration on bandgap blocks
    - RC time constant calibration
    - Integrated power detector
    - Integrated temperature sensor
    - Transmit LO feedthrough cancellation
    - AFC
    - Process sensing
    - TSSI

TGac: A Few Additonal Challenges

- Radio
  - 256-QAM requires higher EVM (< -32dB) requirements
  - Ability to bond two dis-contiguous 80Mhz channels into one logical 160MHz channel
  - Ability to handle larger signal BWs up to 160Mhz on both transmit and receive chains

- Mixed-signal
  - Need 4x higher sampling ADC/DACs from current generation 11n

- PHY
  - ML (or AML) for handling 256-QAM rates
  - VHT preamble processing
  - Synchronization challenges and demod accuracy to support 256-QAM
  - Multi-user MIMO

- RTL and MAC
  - Higher (4x) clocking and ability to handle much higher TPUTs

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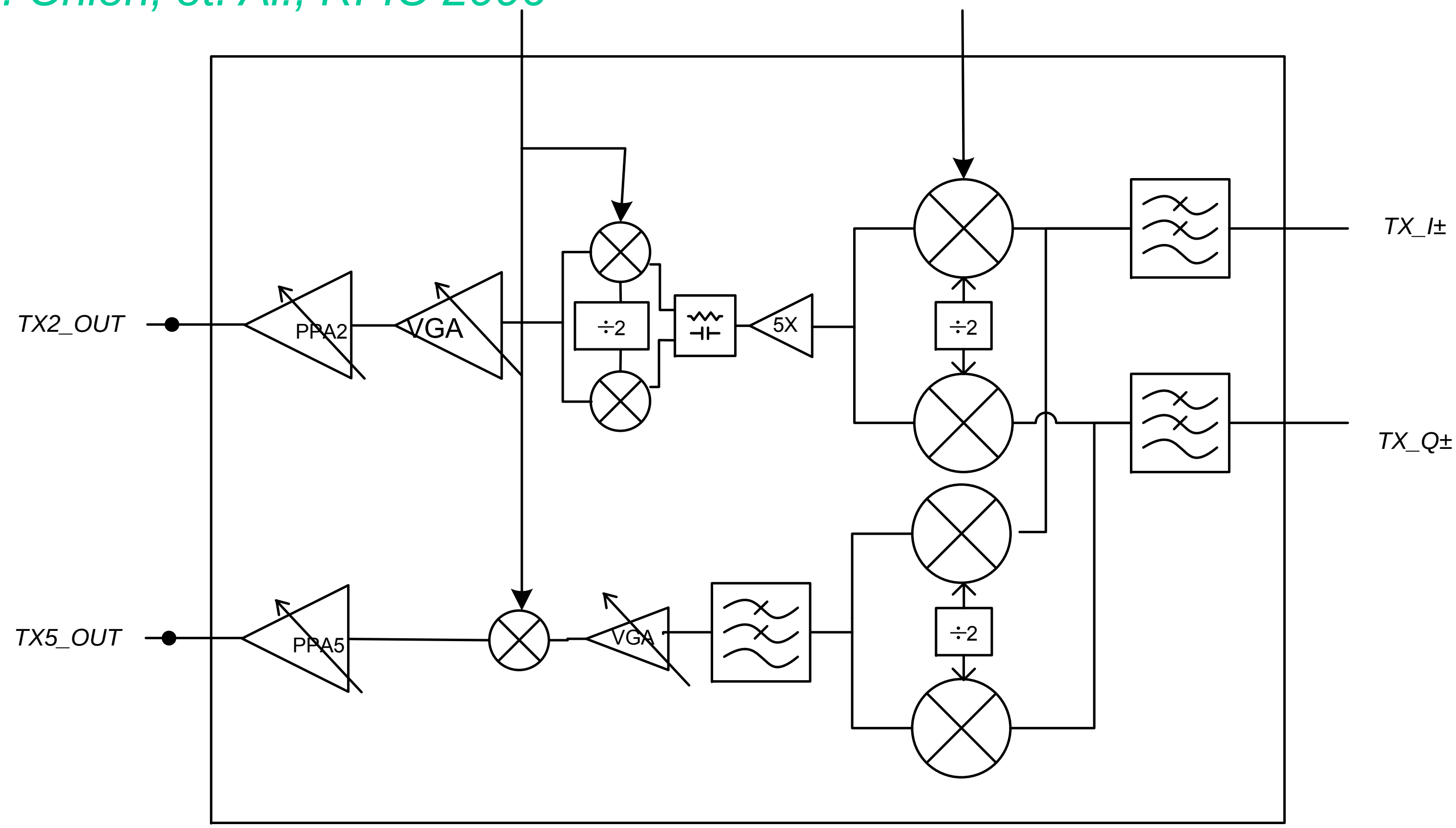
TX Architecture

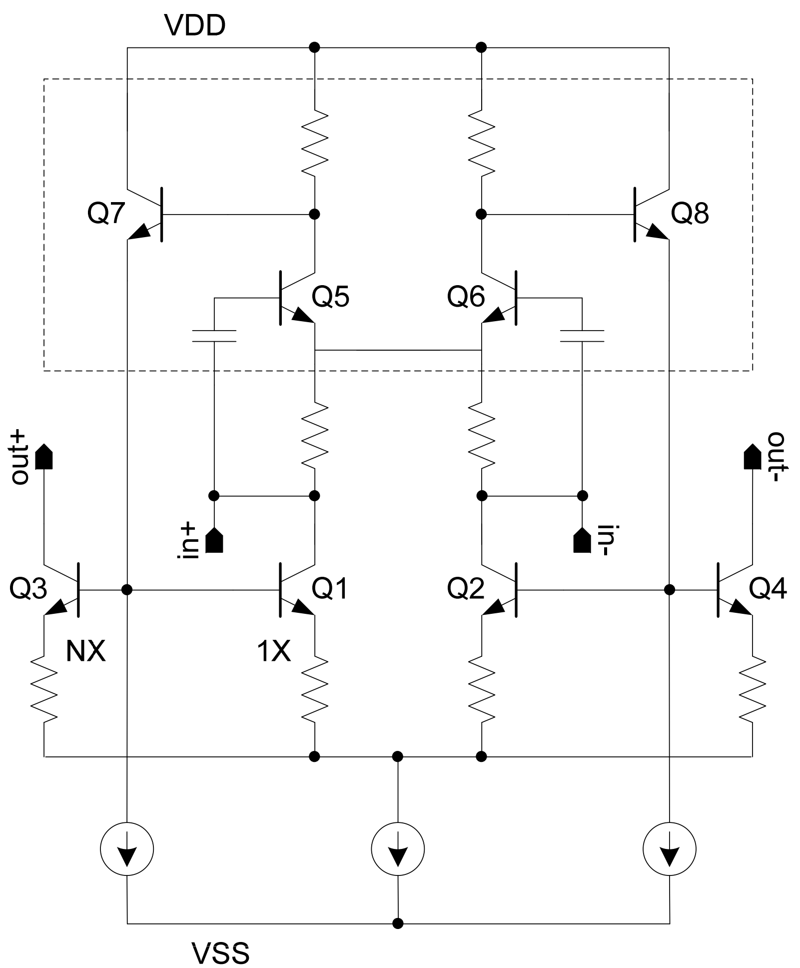
Ref. G. Chien, et. Al., RFIC 2006



- **Used in a 2x3 multi-band SiGe super-heterodyne implementation**
- **Sideband rejection TX architecture to suppress the lower-sideband mixing component for 2.4GHz operation**
- **0.5dB/step VGA used to compensate for gain variation**
- **Fully-Differential signal path with on-chip balun at TX outputs**

IF Current Amplifier

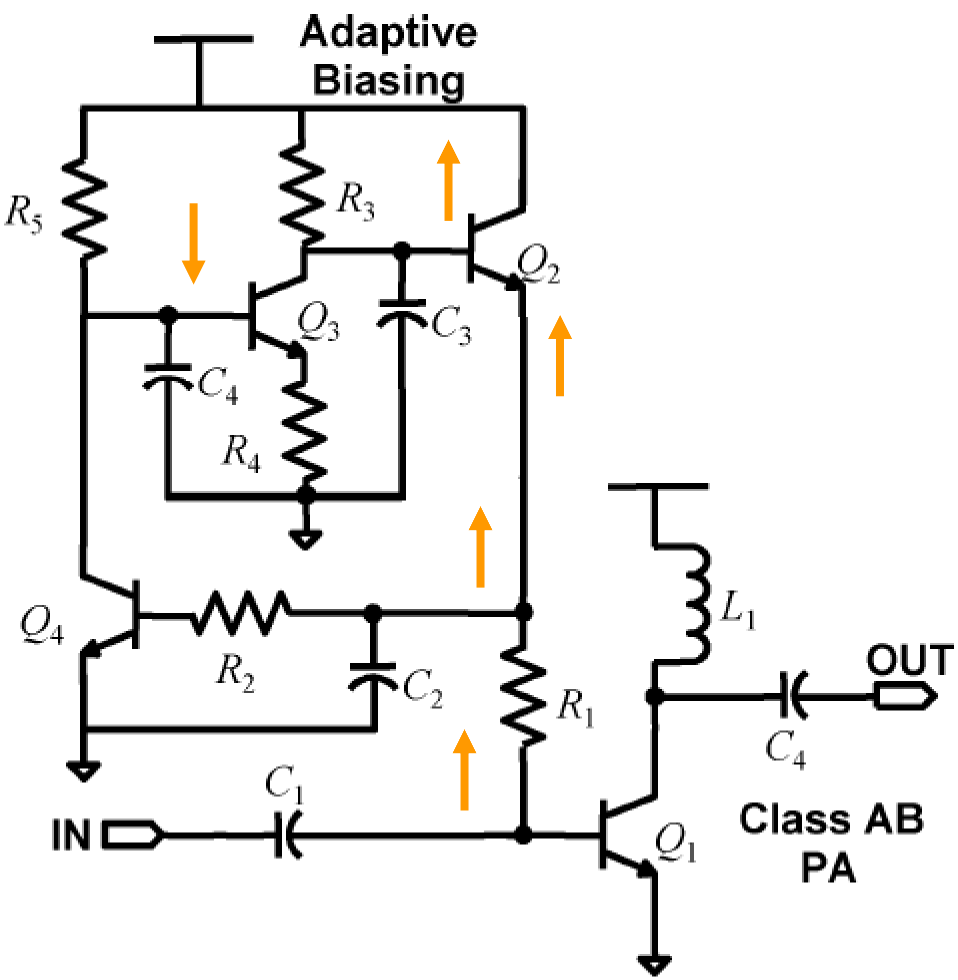
Ref. G. Chien, et. Al., RFIC 2006



- **IF Current Amplifier bases on a (Nx) current multiplier (Q1/2, Q3/4)**
- **An auxiliary amplifier (Q5/Q6) is used to enhance HF beta performance**
- **No additional current is used for the aux. amp.**

Adaptively Biased PA

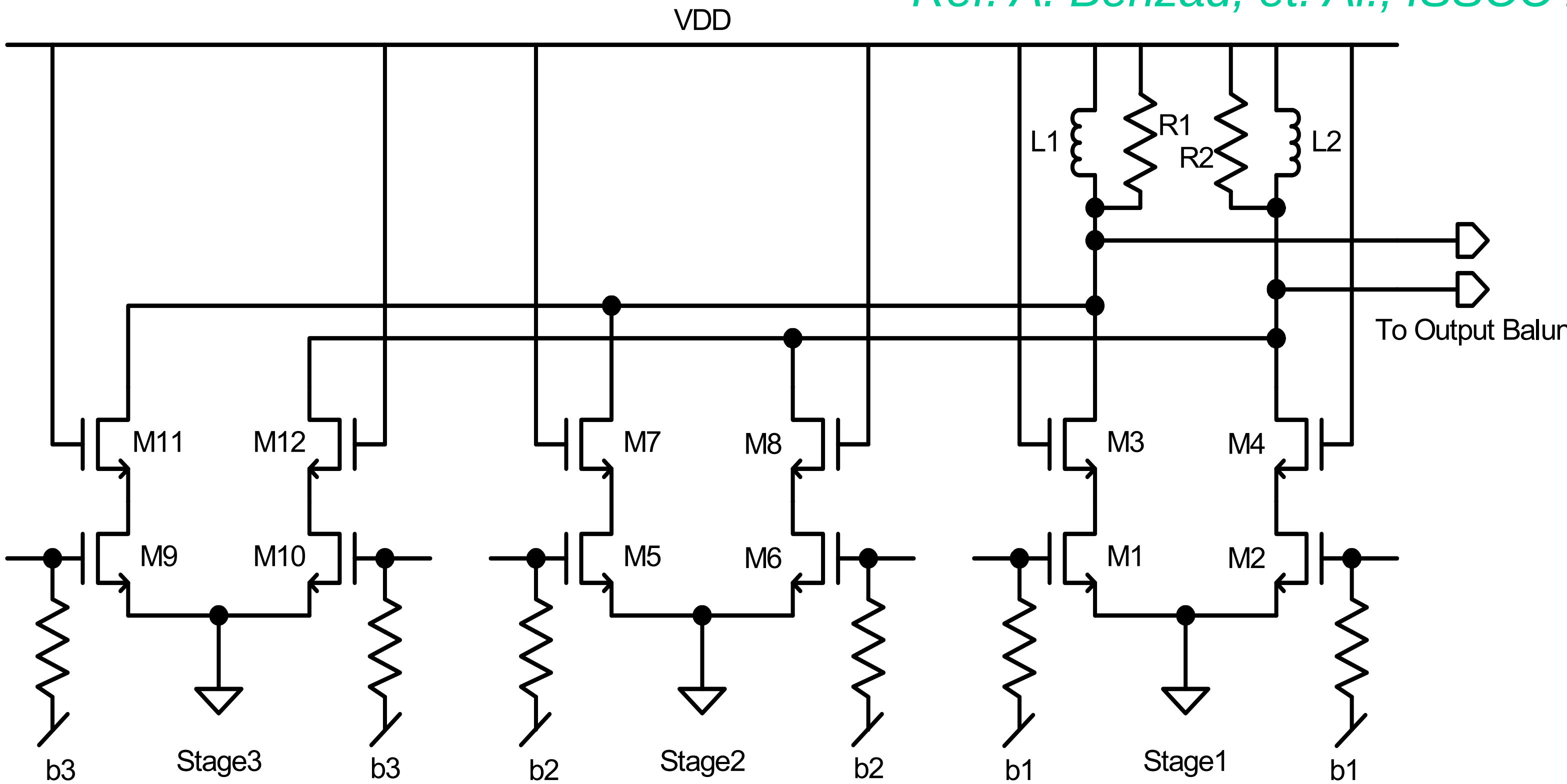
Ref. D. Rahn, et. Al., JSSC Aug. 2005



- **Used in a 2x2 multi-band SiGe super-heterodyne implementation**
- **Adaptive biasing used to reduce power consumption and increase PAE**
- **Main PA device is Q1**
- **Adaptive bias applied through R1 and generated using Q2, Q3 and Q4**
- **Allows for lower quiescent power consumption and higher linearity for large input signals**
- **Achieves 11/13.5 dBm with 4% EVM for 2.4/5GHz band**

PA driver Transconductance Linearization

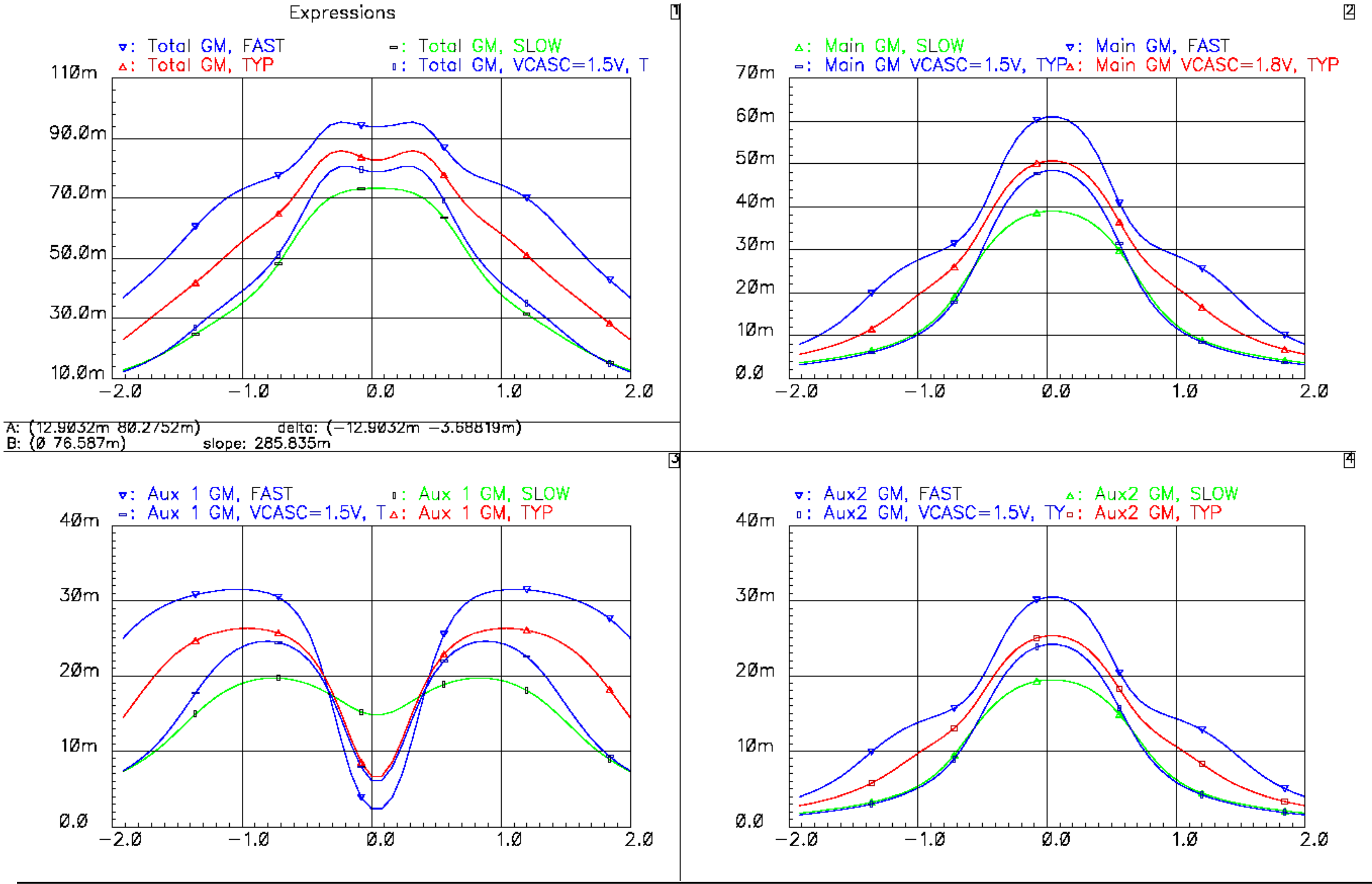
Ref. A. Behzad, et. Al., ISSCC 2007



- **Used in a 2x2 multi-band CMOS direct-conversion implementation**
- **Offset bias voltages b1, b2, b3 allow for the linearization of the transconductance**
  - **Lower quiescent power consumption**
  - **Higher linearity under large input signals**

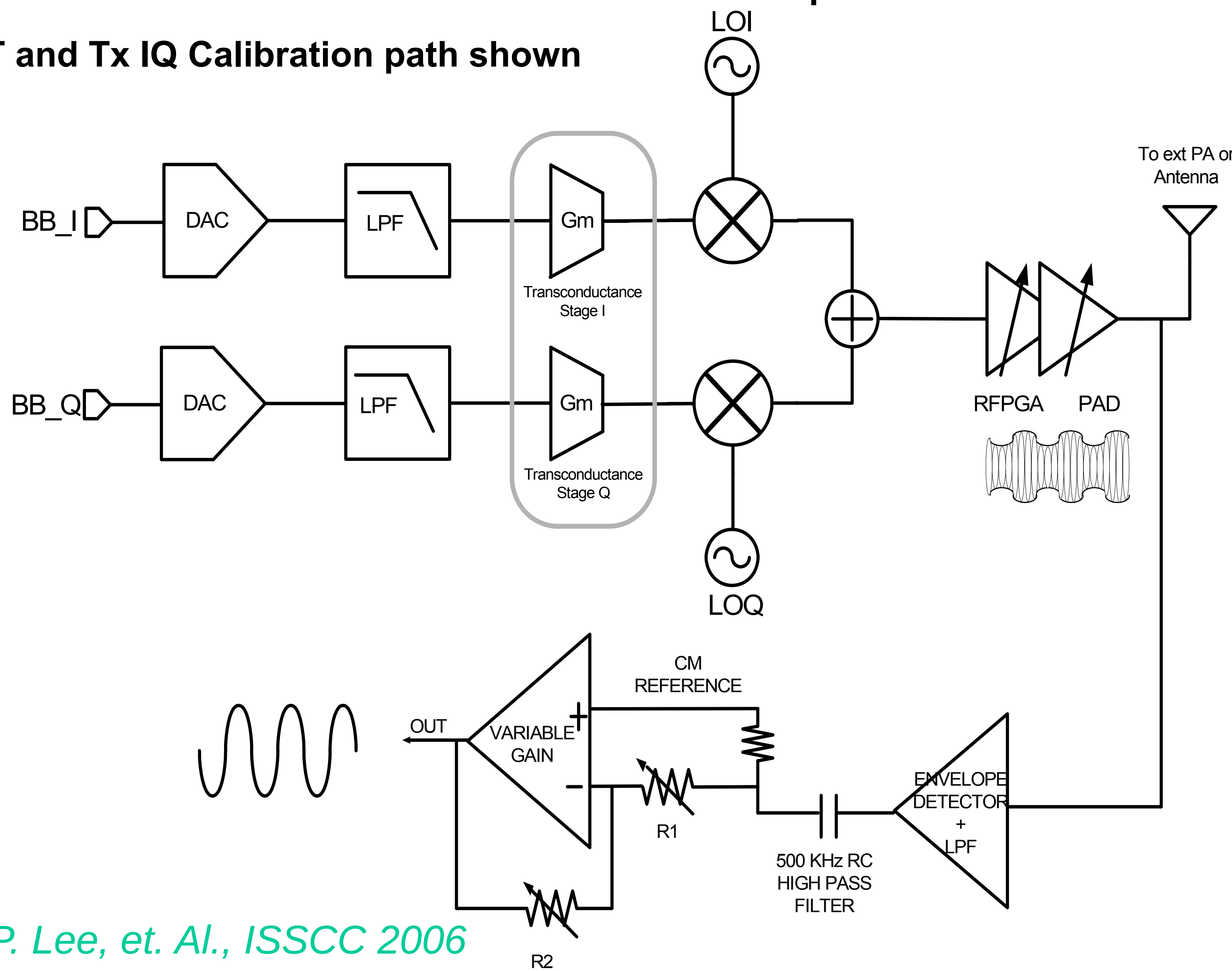
PA Driver Transconductance Linearization

- **Simulated each stage Gm and effective total Gm under various process corners**



Transmitter Architecture & Tx Calibration Path

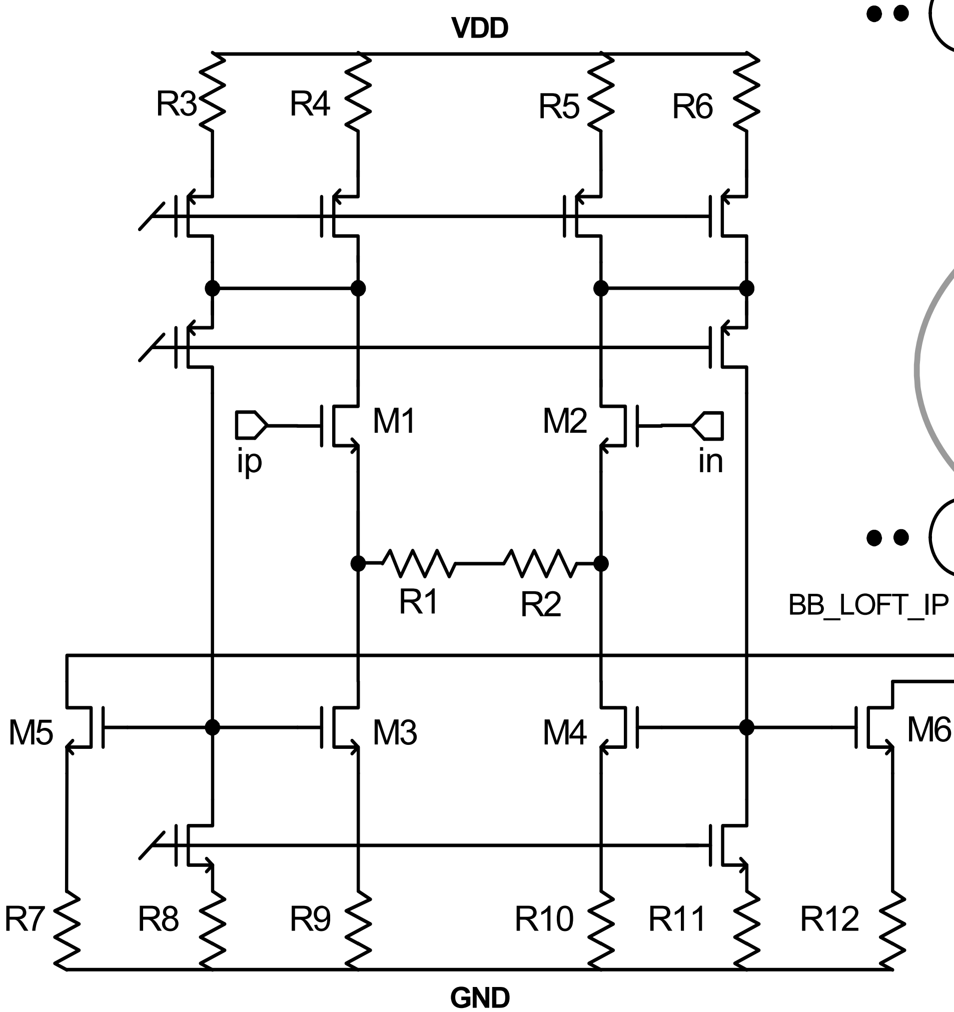
- Used in a 2x2 multi-band CMOS direct-conversion implementation
- LOFT and Tx IQ Calibration path shown

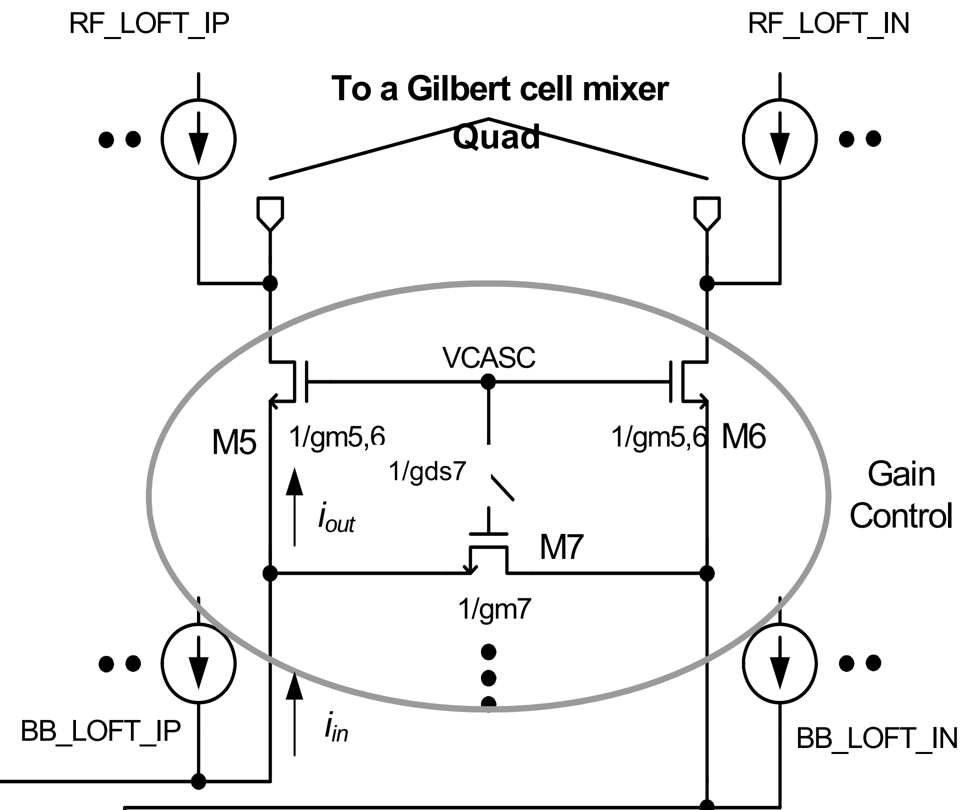


Ref. C. P. Lee, et. Al., ISSCC 2006

Tx Mixer Variable-Gain Transconductor Stage

- **Highly linear mixer Gm**
- **Offset based LOFT scales with gain control**



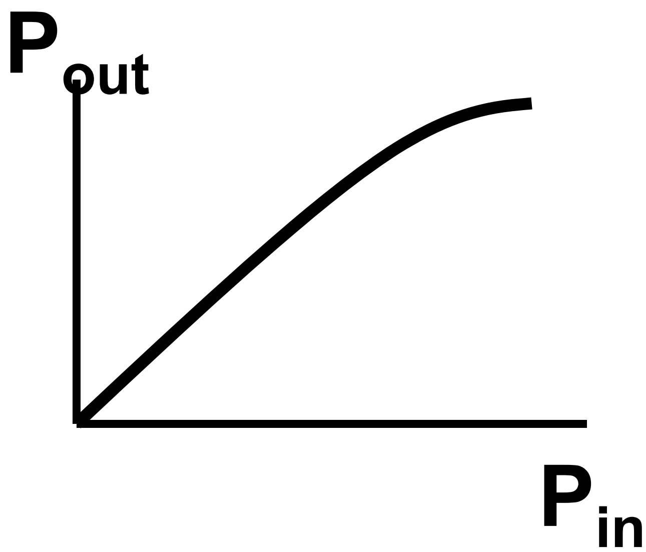


- **Mechanisms for cancelling offset based and coupling based LOFT**

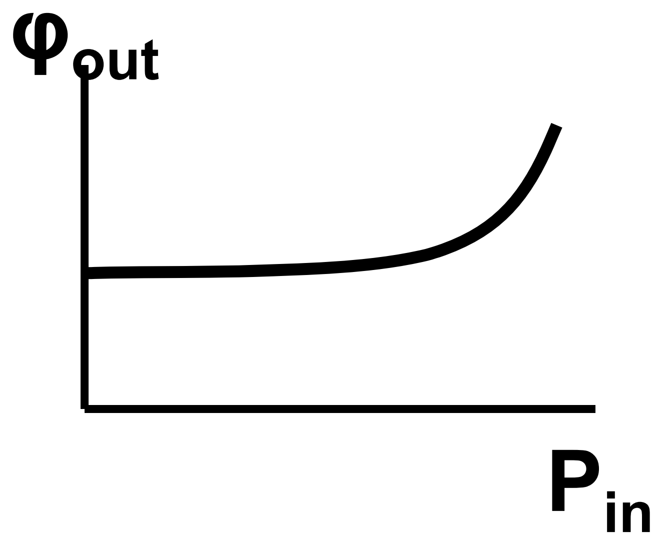
Ref. C. P. Lee, et. Al., ISSCC 2006

PA Nonlinearity

- High order modulations are quite sensitive to phase nonlinearities, in addition to amplitude nonlinearities



AM-AM

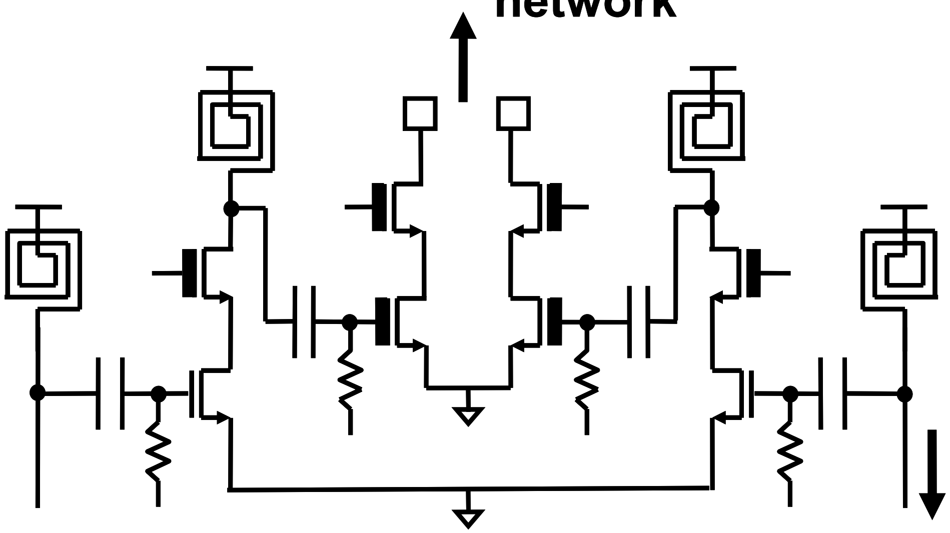


AM-PM

- 3 different schemes of Tx/PA linearization will be presented in the next several slides

Power Amplifier

Ref. Y. Palaskas, et. Al., ISSCC 2006

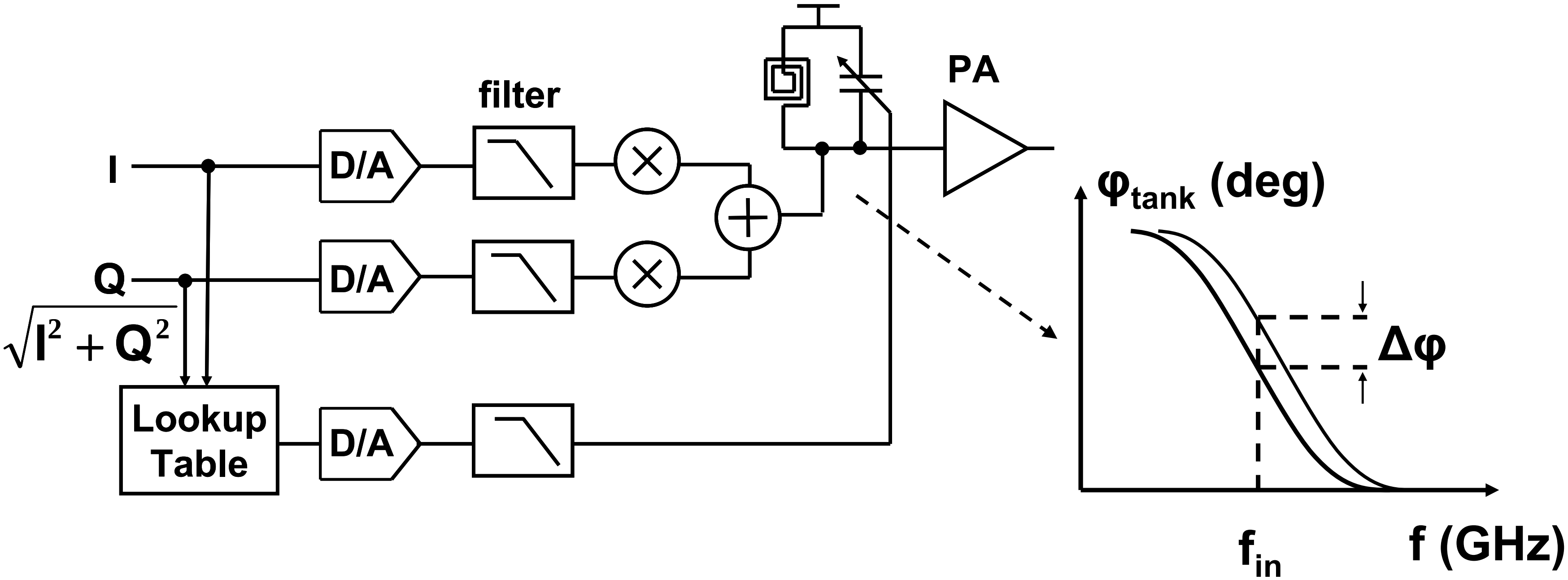


- Class-AB
- Thick gate devices for good efficiency and reliability
- P_{1dB}≈20dBm, P_{AVG} ≈12dBm (54Mb/s, EVM=-25dB)

- Apply linearization to increase P_{AVG} and efficiency

Digitally-Assisted AMPM Linearization

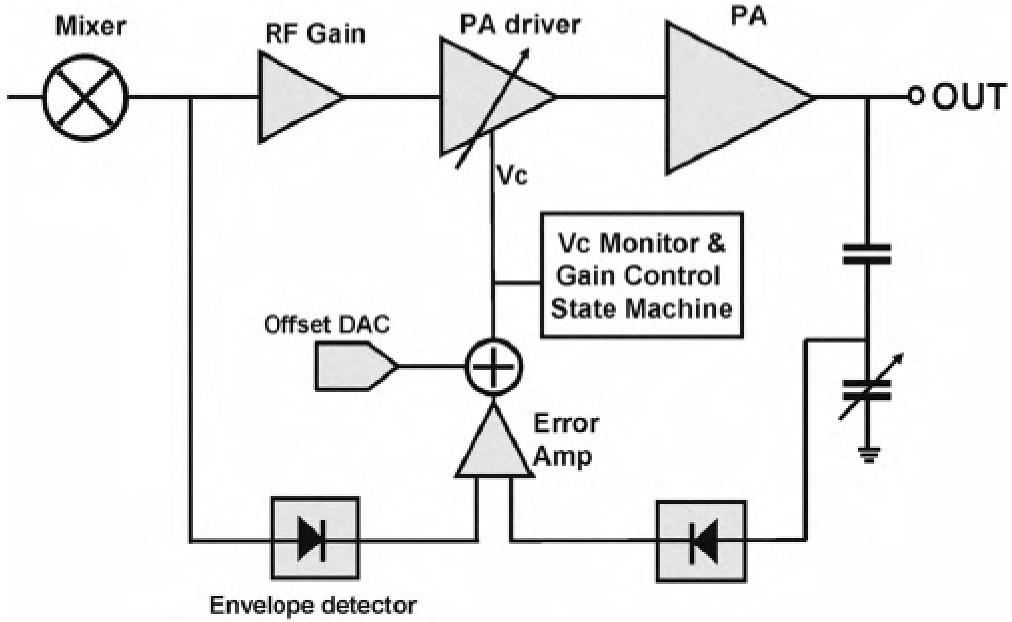
Ref. Y. Palaskas, et. Al., ISSCC 2006



- **5GHz implementation**
- **Varactor introduces phase shift to cancel signal-dependent phase shift of PA**
- **Varactor controlled by amplitude of digital IQ data**
- **P_{AVG} = 16dBm @ EVM=-25dB (w/o linearazation 12dBm)**
- **2.8x efficiency improvement**

AMAM Analog PA Linearization Loop

M. Terrovitis, et. Al., ESSCIRC 2009



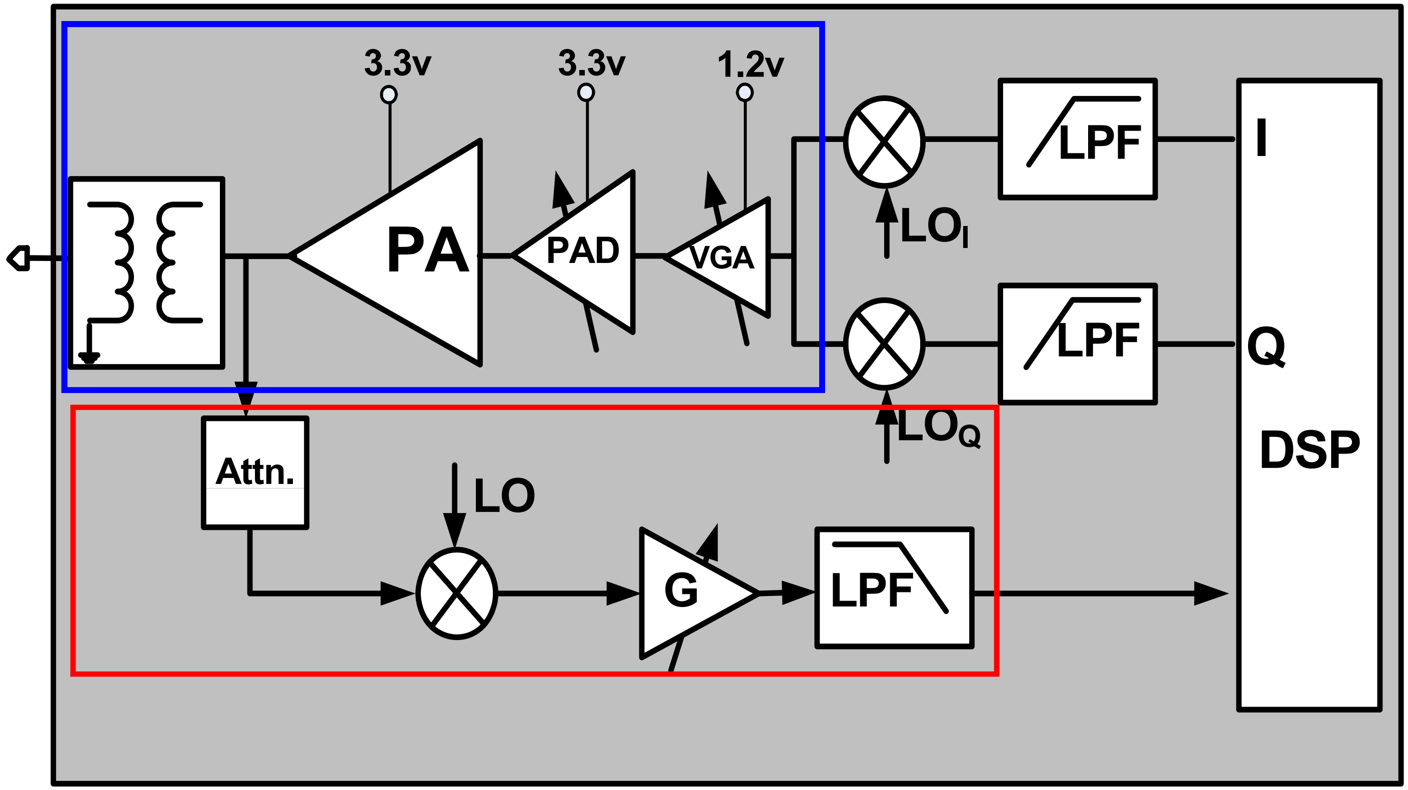
- 2.4GHz implementation
- Achieves 13.6dBm -28dB EVM without linearization and 18.4dBm with at the chip output
  - TR switch is also integrated but balun is external

Analog + Digital Tx Linearization

Top-Level Block Diagram:

3-stage PA with On-chip balun

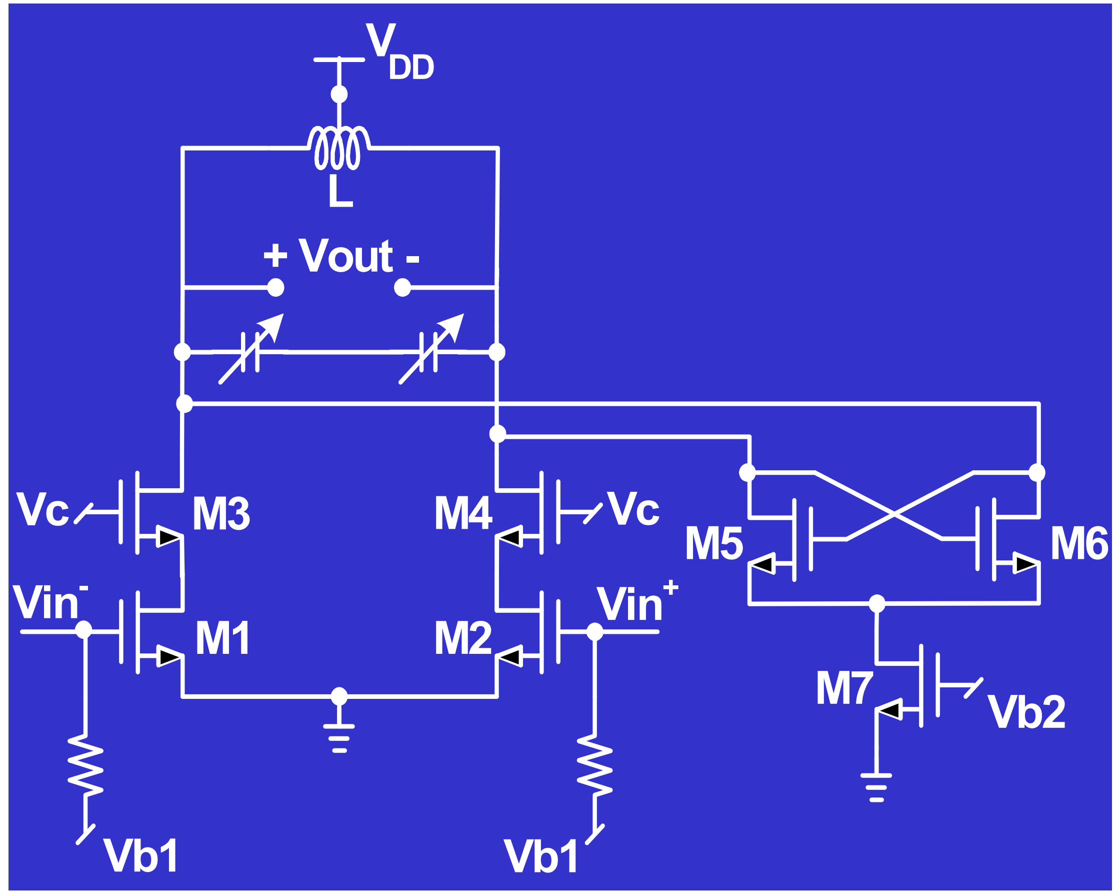
Feedback path used for PA pre-distortion



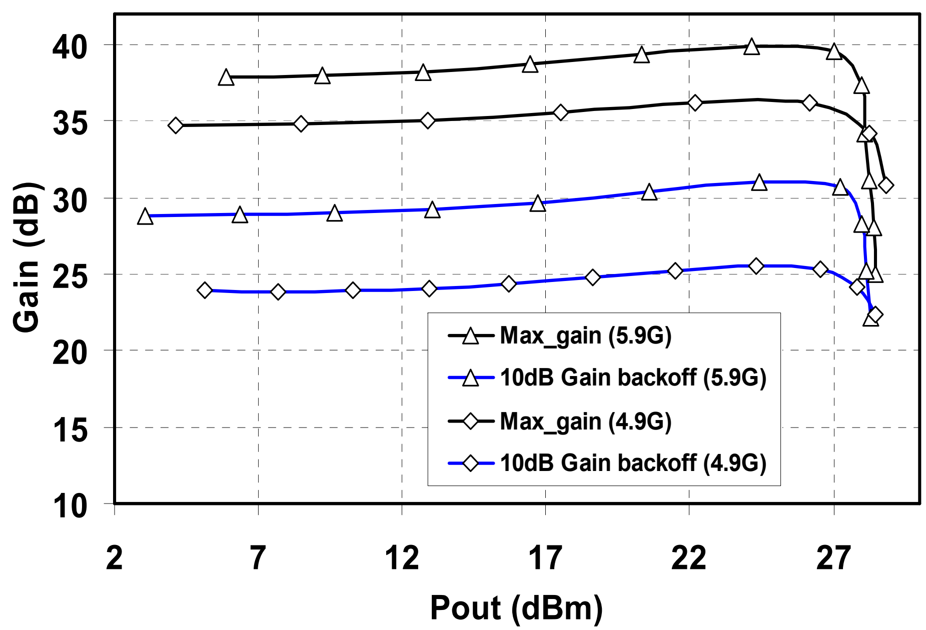
Ref. A. Afsahi, et. Al., RFIC 2009

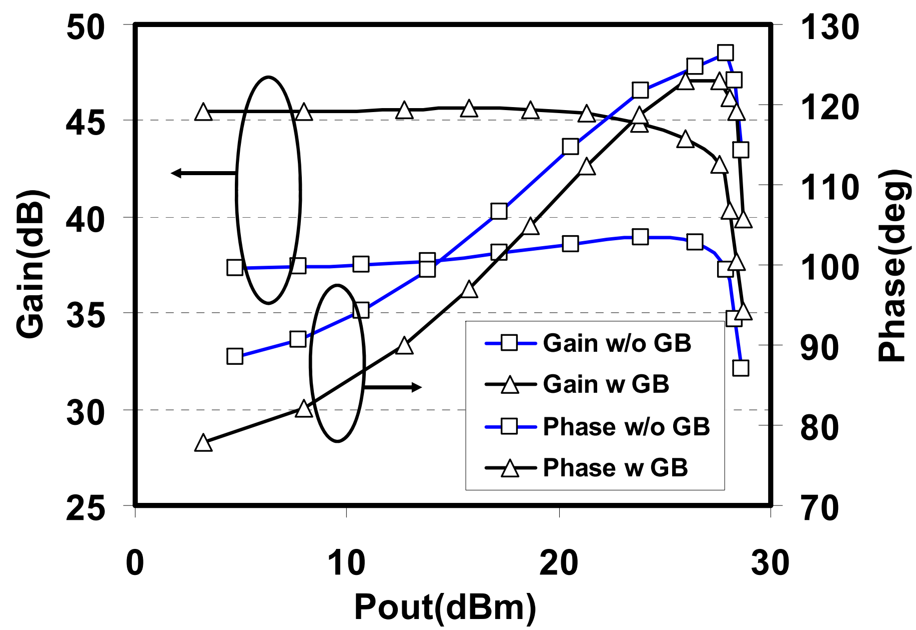
VGA and PAD Circuit Implementation

- Multiple-branching for gain control
- Utilizing gain boost
- Thick-gate device for cascode in PAD



Simulated Gain Control and Gain Boost



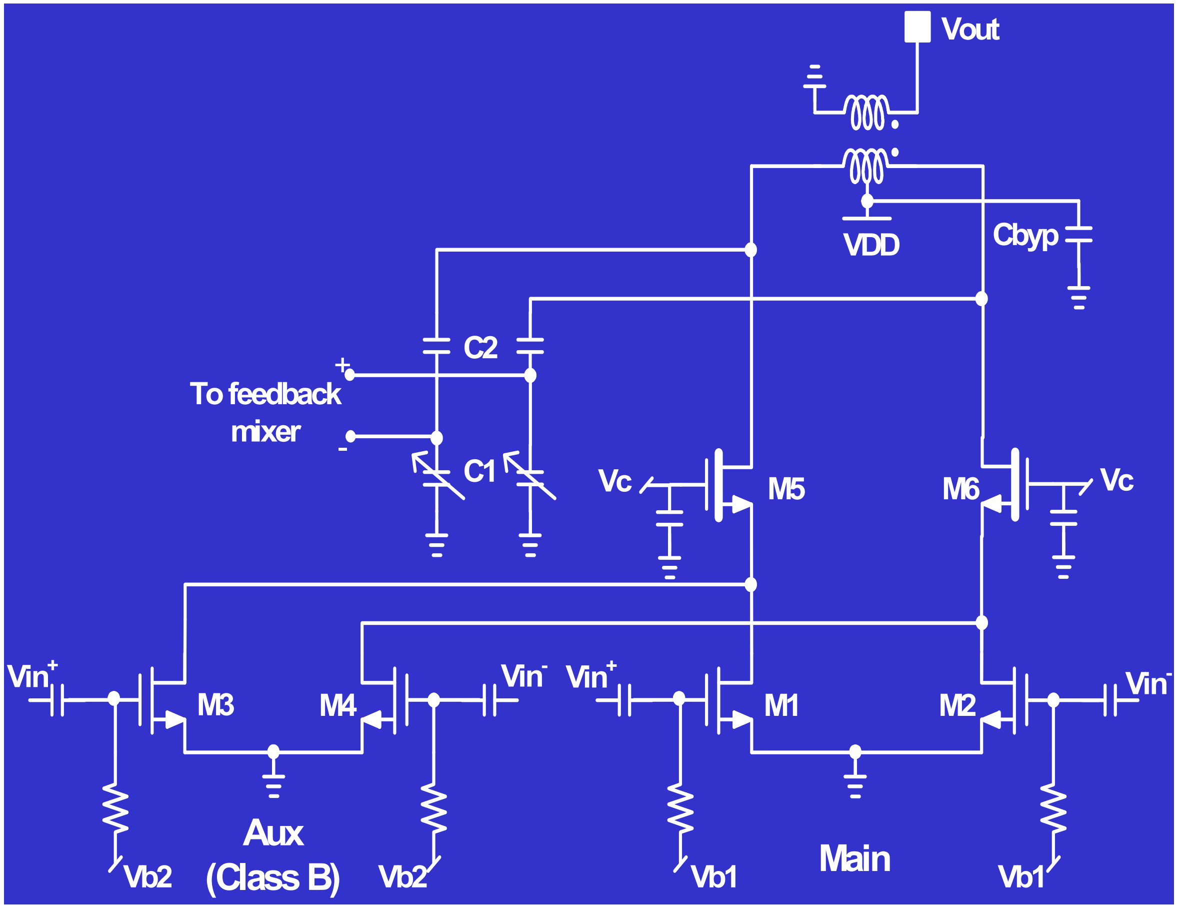


Gain vs. Pout for two different gain codes

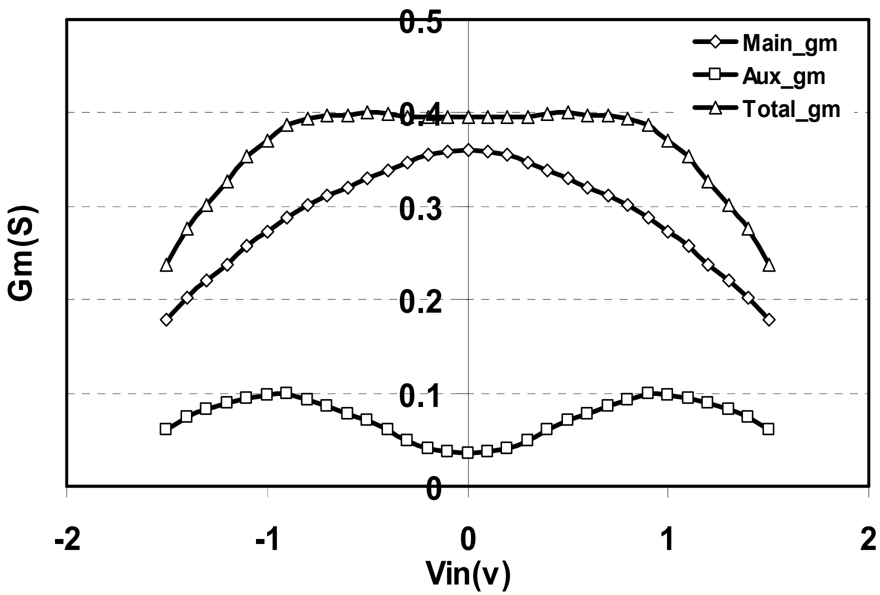
5.5GHz AM/AM and AM/PM with and without gain boost

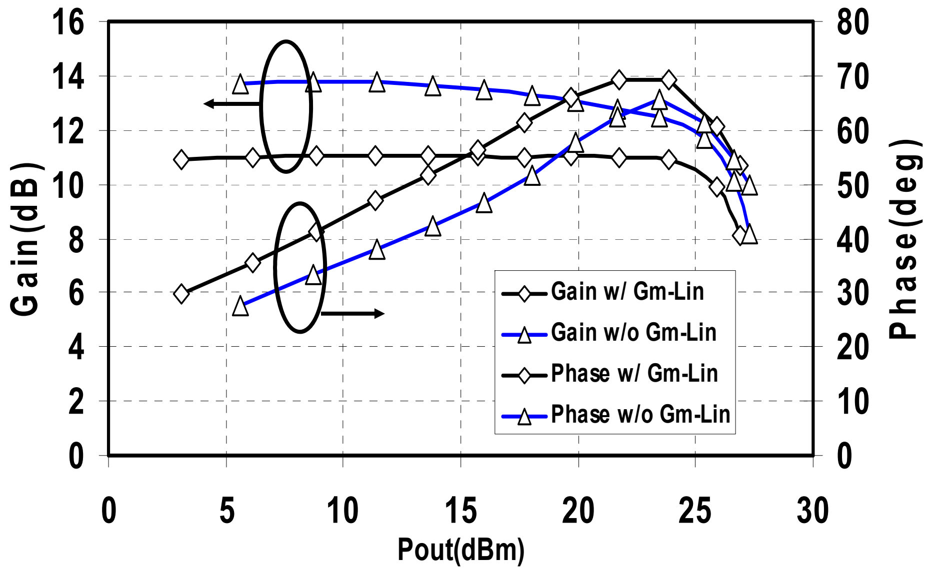
PA Circuit Implementation

- Utilizing gm-linearization technique
- Thick-gate device for cascode
- On-chip balun
- Capacitor divider for feedback path



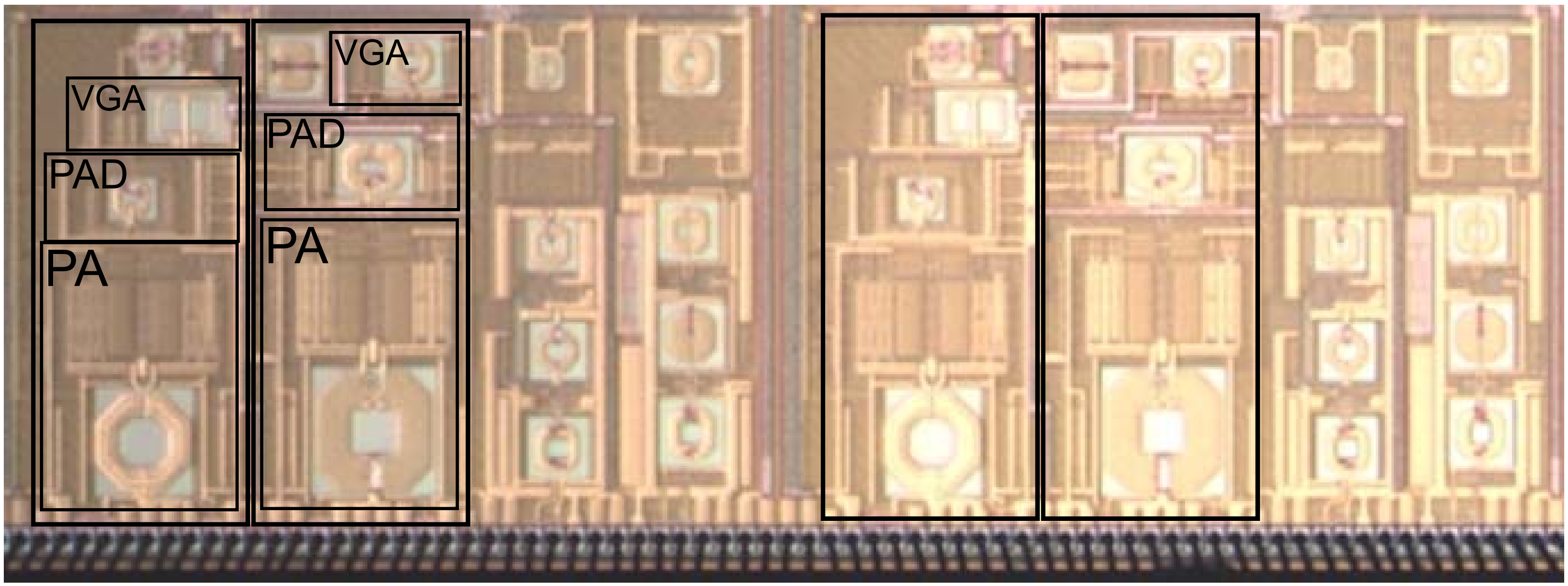
Gm Linearization





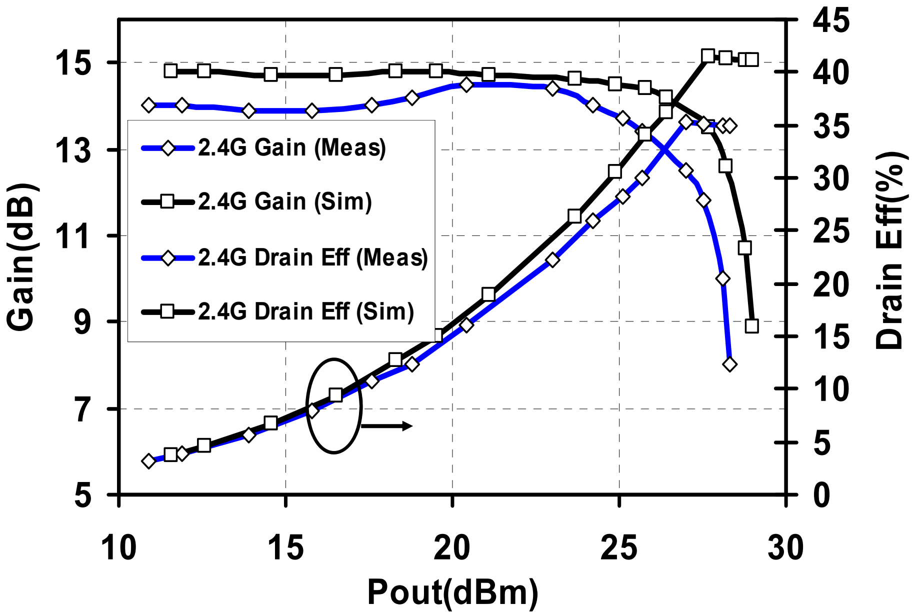
- P1dB is improved from 21.7dBm to 26.6dBm by using Gm-linearization
- Lower gain due to class-B operation of Aux section

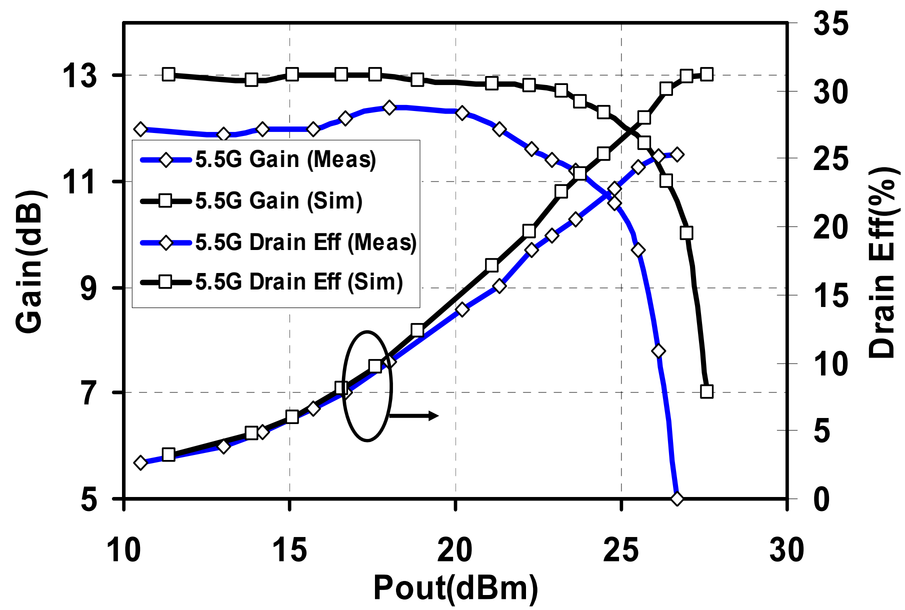
Die Photo



	VGA	PAD	PA
2.4GHz	0.074mm^2	0.132mm^2	0.31mm^2
5GHz	0.085mm^2	0.092mm^2	0.27mm^2

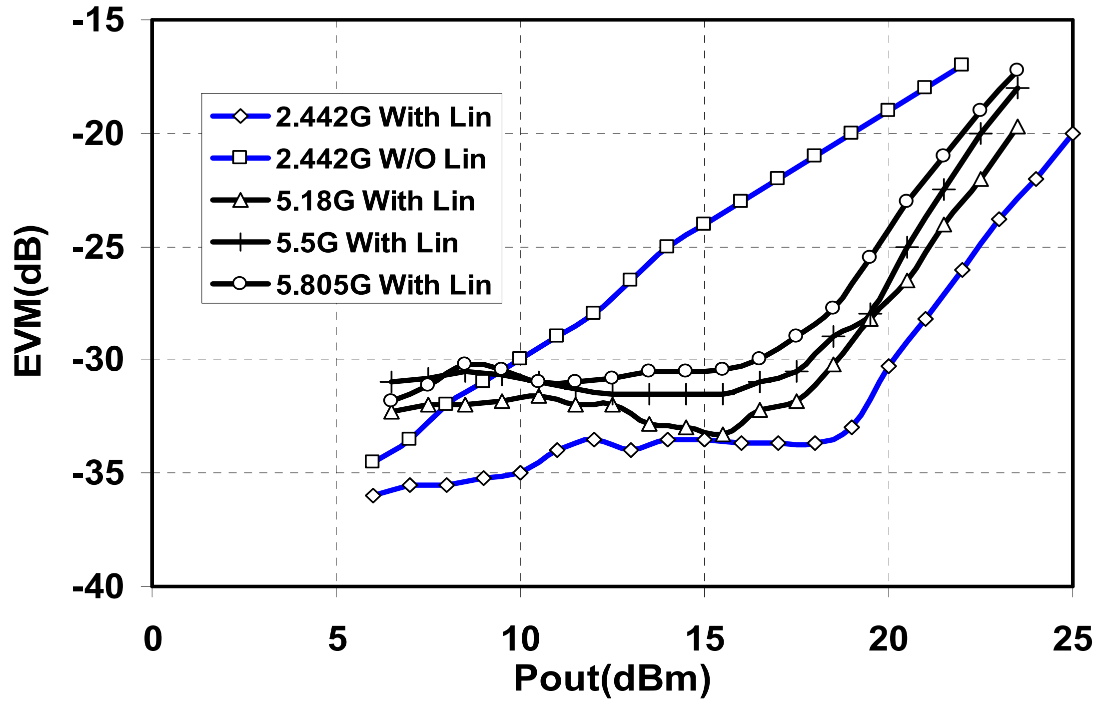
Gain and Drain Efficiency





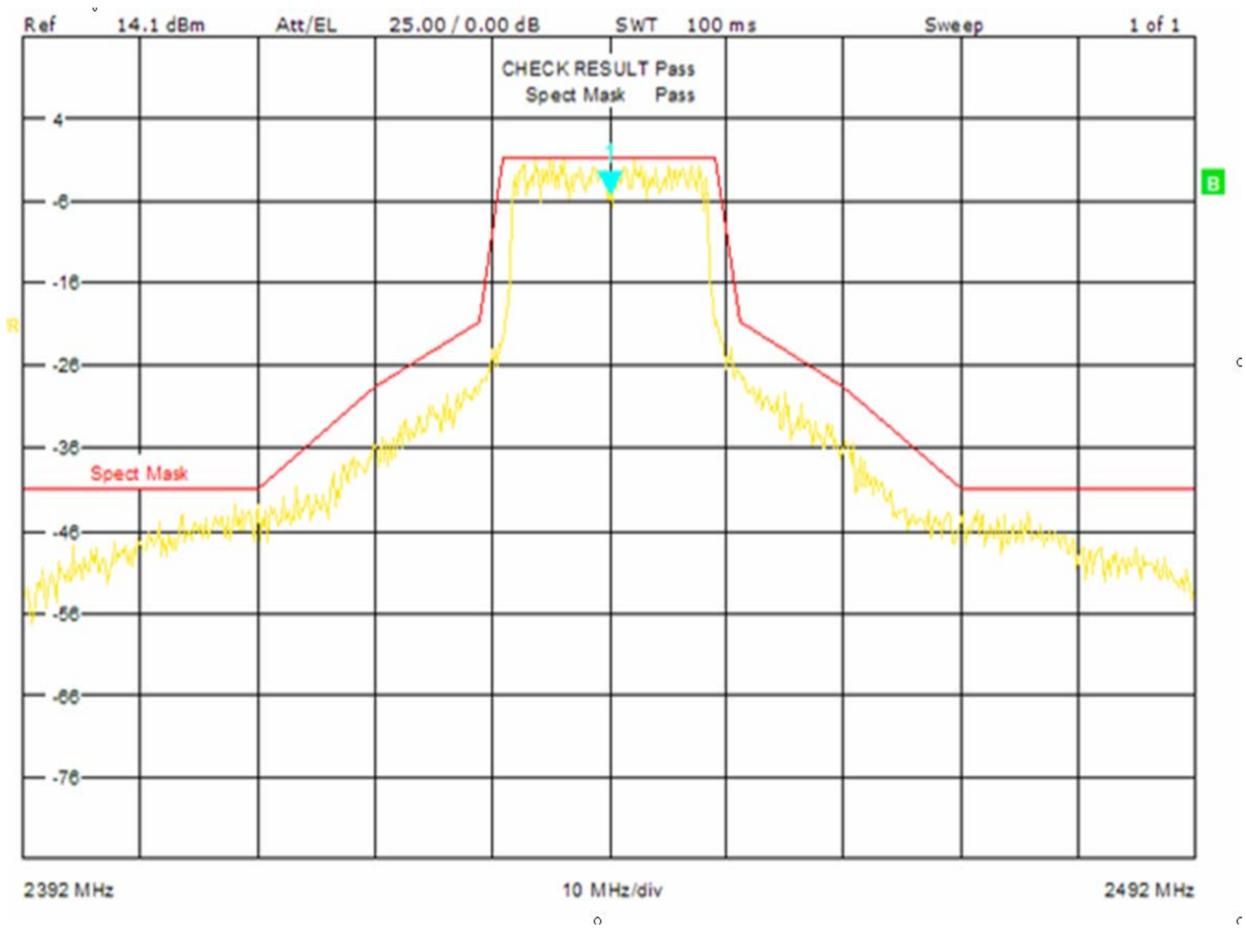
	PA gain	Psat	Peak Drain Eff
2.4G	14dB	28.3dBm	35.30%
5.5G	12dB	26.7dBm	25.30%

EVM vs. Pout



	2442MHz	5180MHz	5500MHz	5805MHz
Pout @ -25dB EVM	22.4dBm	21.1dBm	20.5dBm	19.7dBm
Pout @ -28dB EVM	21.1dBm	19.7dBm	19.5dBm	18.3dBm

Spectral Mask



- 22dBm Po at 2.442GHz

Comparison with published Dual-Band WLAN PAs

	ref[a]	ref[b]	A Afsahi [RFIC 2009]
Psat (2.4G)	25dBm		28.3dBm
Psat(5.5G)	23.5dbm		26.7dBm
Power/Eff @ -28dB EVM (2.4G)	15.5dBm/19%	17.5dBm/16%	21.1dBm/18%
Power/Eff @ -28dB EVM (5.5G)	14.5dBm/12%	17dBm/12.5%	19.5dBm/12.5%
Max CW Eff (2.4G)	50%		35.3%
Max CW Eff (5.5G)	30%		25.3%
Linearization	DPD	No	DPD & Offset-Gm
On chip balun	No	N/A	Yes
Supply	3.3v	3.3v	3.3v
Technology	90nm CMOS	SiGe HBT	65nm CMOS

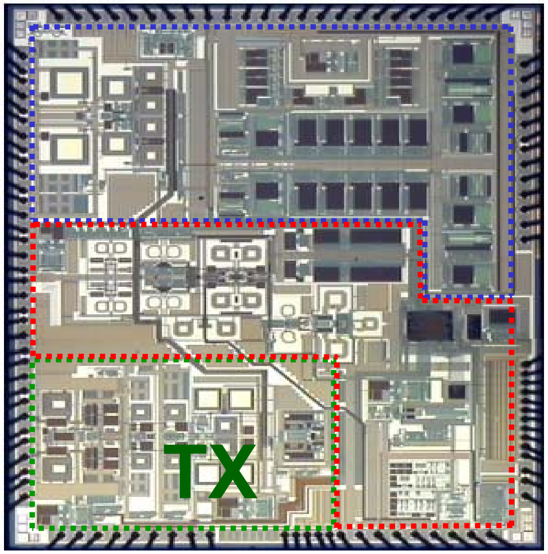
• Ref. [a]: O. Degani et al., “A 1x2 MIMO Multi-Band CMOS Tranceiver with an Integrated Front-End in 90nm CMOS for 802.11a/g/n WLAN Application” ISSCC 2008.

• Ref. [b] H.H. Liao et al., “A Fully Integrated 2x2 Power Amplifier for Dual Band MIMO 802.11n WLAN Applications using SiGe HBT Technology”, RFIC 2008

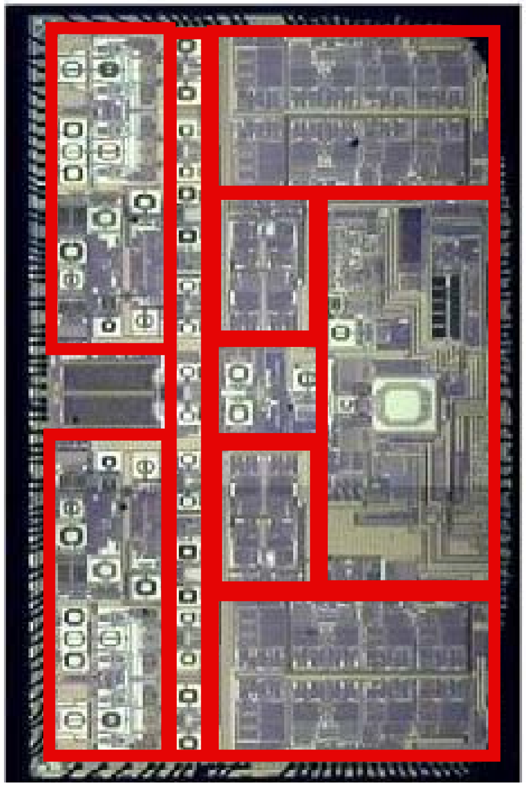
Outline

- ❑ Introduction, Market Overview & Market Trends
- ❑ Communication System Performance in a Multipath Channel:
  - ➢ The problem with multipath
  - ➢ Mitigation methods for multipath
  - ➢ Taking advantage of multipath
- ❑ WLAN Evolution & 802.11
  - ➢ Additions in 802.11n PHY and impacts on radio
  - ➢ 802.11n Sensitivity and EVM requirements
  - ➢ Some optional modes of 802.11n and 802.11ac
  - ➢ A brief introduction to 802.11ac
- ❑ Some 802.11 Radio Requirements
  - ➢ Impacts of some radio impairments on system performance
- ❑ Examples of Circuit Techniques and Architectures Used in 802.11n Radios
- ❑ Evolution of Radios: SISO to MIMO and Single Function to Multi-Function
- ❑ Real World Performance
- ❑ Conclusion

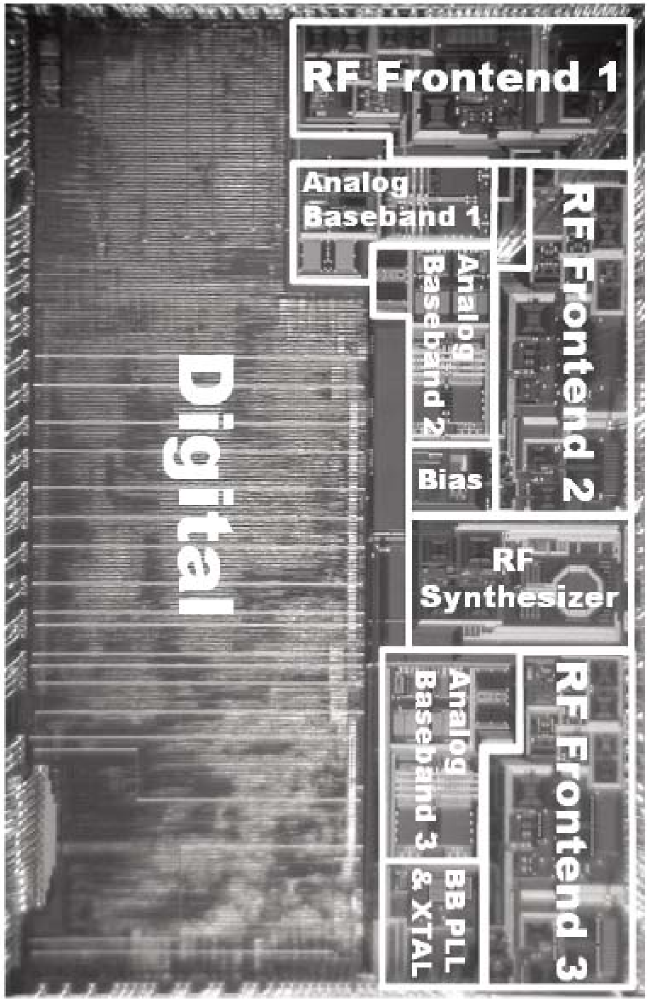
Evolution of Radios: SISO to MIMO



802.11a radio
(ISSCC 2003)



2x2 802.11a/b/g/n radio
(ISSCC 2007)

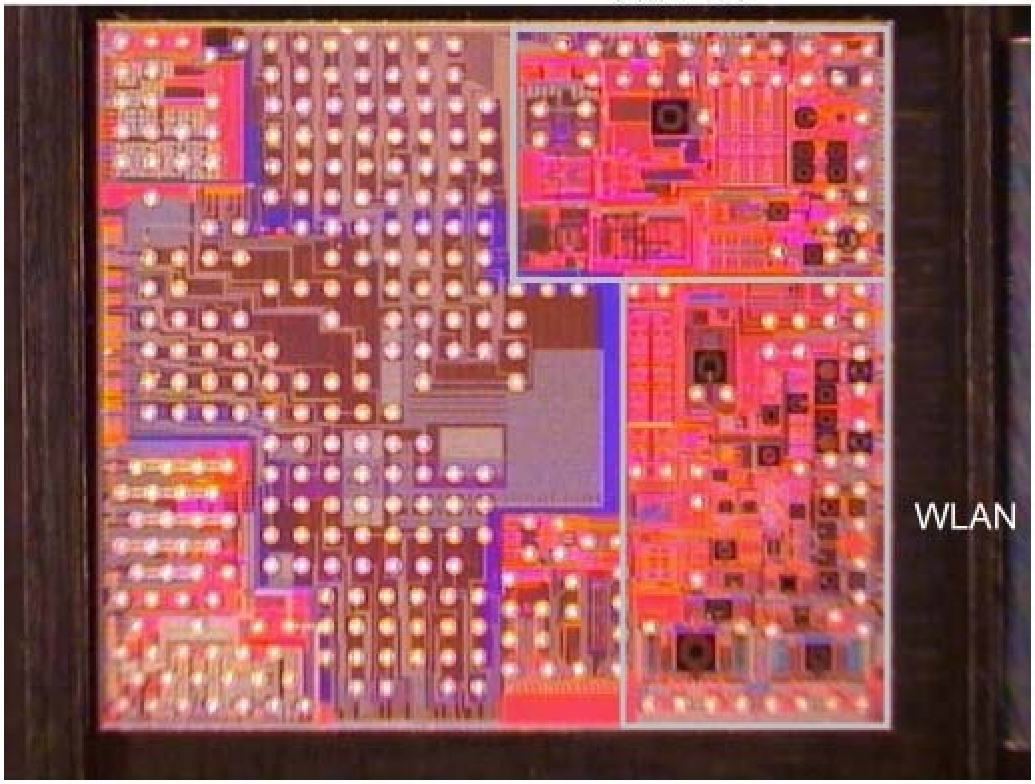


3x3 802.11a/b/g/n SoC
(ISSCC 2011)

Evolution of Radios: SISO to MIMO-An Example

	802.11a	2x2 802.11n	3x3 802.11n
Author/Conf	Behzad, ISSCC 2003	Behzad, ISSCC 2007	A-Alibeik ISSCC 2011
Radio/SoC	Radio-only	Radio-only	SoC
Process	0.18um CMOS	0.18um CMOS	65nm CMOS
Area (mmsq)	11.7	18	10.4 (radio)
In-band PN (5GHz; dBc/Hz)	~ -100	~ -108	~ -102
Tx EVM Floor (5GHz; dB)	~ -34	~ -40	~ -36
Rx NF (dB)	4	4	4
Chariot Throughput	24	> 200	> 300

Evolution of Radios: Multi-Function Radios

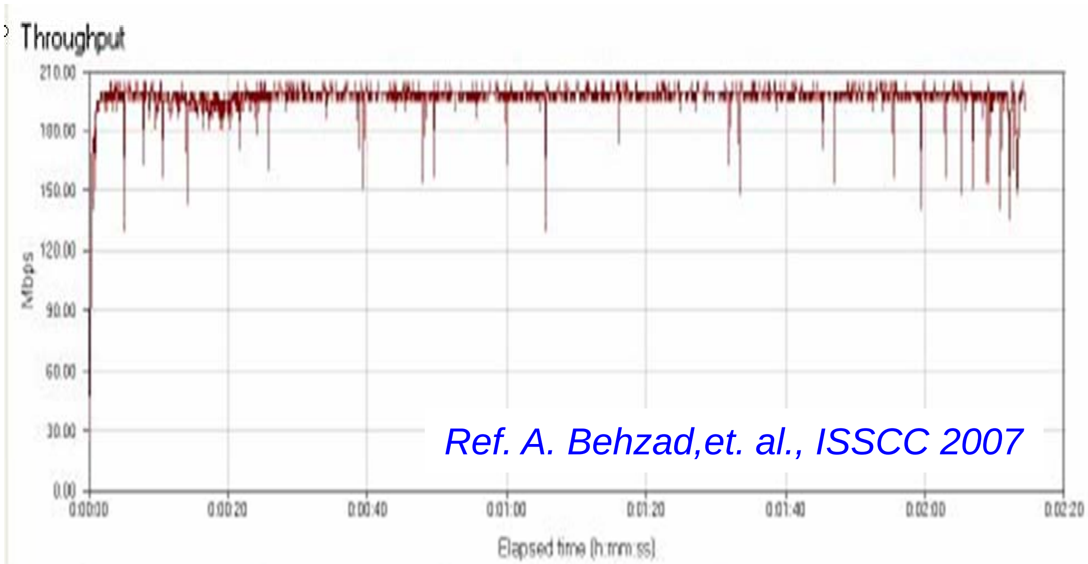


802.11a/b/g/ssn + FM/BT SoC
(ISSCC 2010)

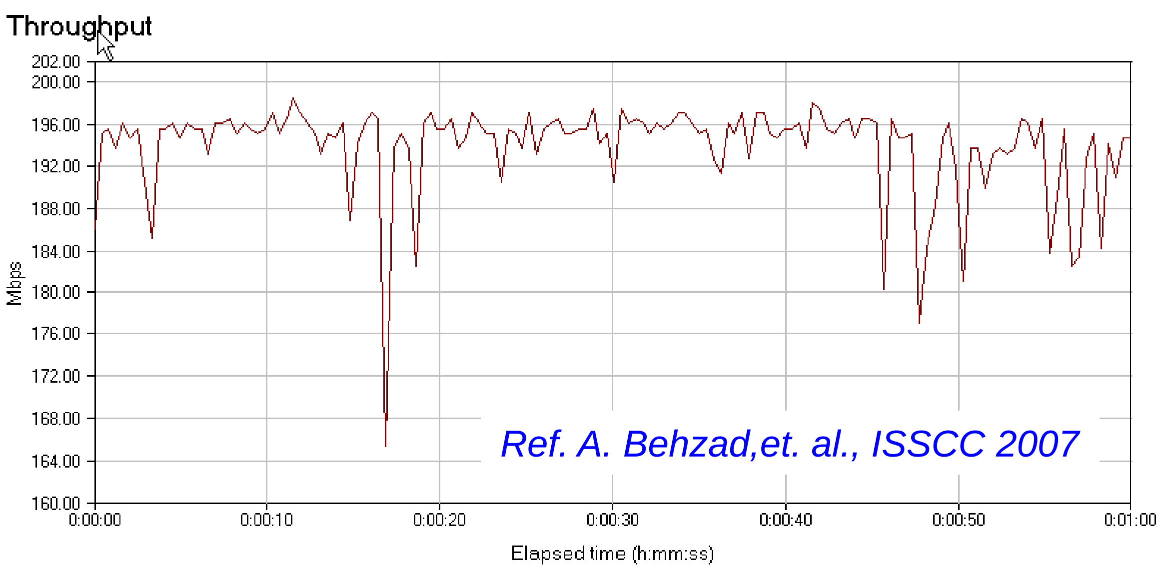
Real-World Performance/Throughput

- Chariot throughput test is a very high level test and can be limited by *many* factors
  - Radio performance
  - Digital PHY performance
  - MAC performance
  - Processor performance
  - Network switch performance
  - …
- Many setups to measure throughput/performance
  - Cable-connected AWGN channel or controlled channel emulator setup
    - Results are for the most part repeatable and easily comparable to other similar measurements
    - Direct comparisons of subcomponents still not possible due to the high-level nature of the Chariot test. Comparisons of the *overall* systems, however is quite valid
  - Over-the-air measurements (rate vs. range over the air)
    - Requires the different solutions to be tested in the *exact* same setup for fair comparisons to be made
    - However, general conclusions can still be made and very high level comparisons may still be possible

Real-World Performance/Throughput

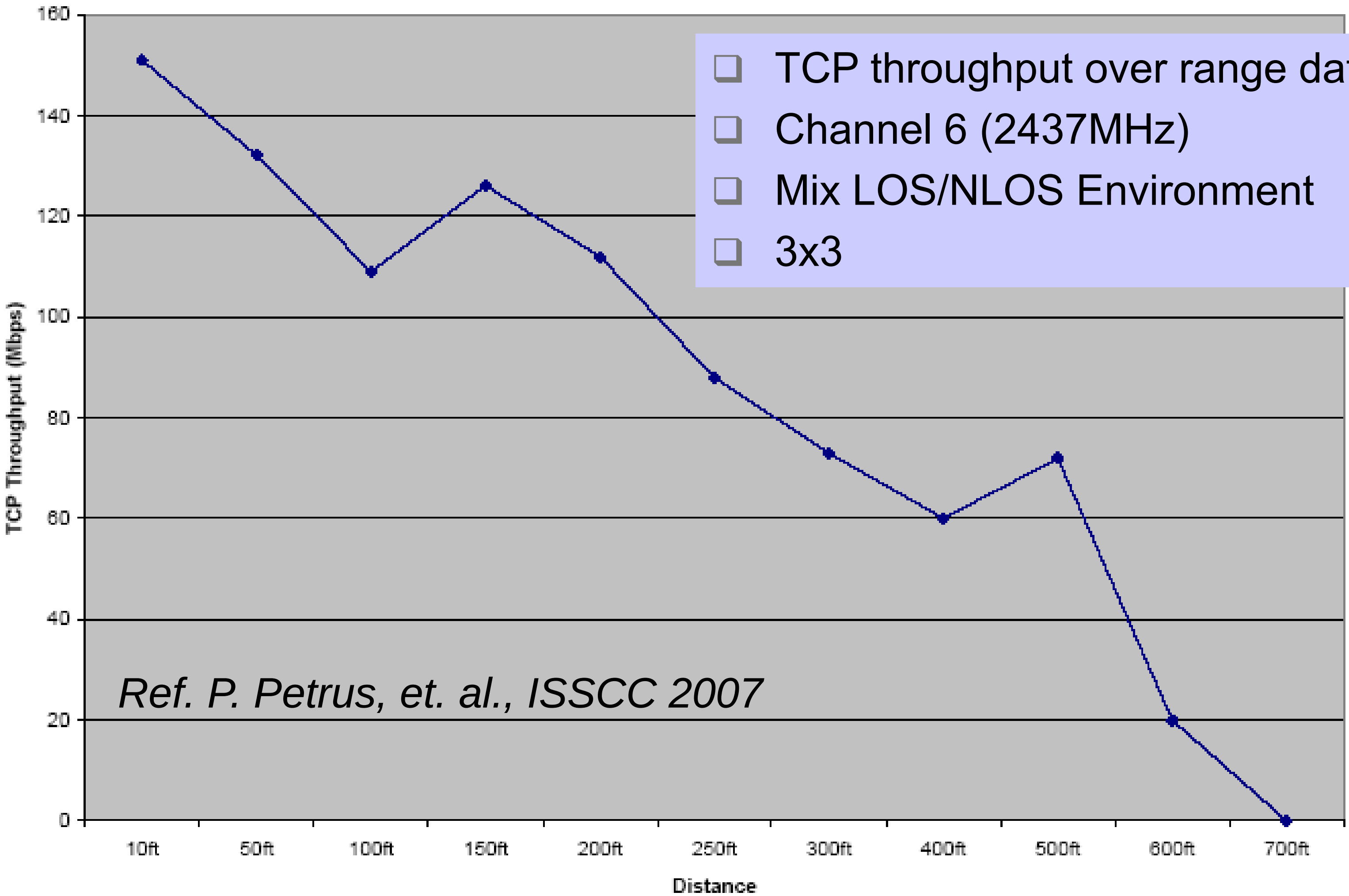


- Cable test
- 2x2 system
- Throughput > 200Mbps
- PHY Rate = 270Mbps
- 2.442GHz channel



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

Real-World Performance/Throughput



- TCP throughput over range data
- Channel 6 (2437MHz)
- Mix LOS/NLOS Environment
- 3x3

Ref. P. Petrus, et. al., ISSCC 2007

Conclusions

- MIMO OFDM systems are a relatively new topic of interest and we have briefly touched on various aspects of this very rich topic and in particular the requirements for the radio
- Integrated radios, especially CMOS ones, have come a *very* long ways in a very short period of time
  - Improvements in performance
  - Reductions in size
  - Higher degrees of integration
  - Higher yields
  - Multi-function capability and co-existence

→ Radios will have to become even cheaper and even better with more improvements in co-existence by utilizing innovative systems and circuits techniques as well as taking further advantage of the power of DSP for self-calibration in order to accommodate the complex needs of future communication standards

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Rohit Gaikwad
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Vinko Erceg
Michael Hurlston

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Talk Abstract

- **An Introduction to 802.11a/b/g/n/ac Radio Design : From Systems to Transistors**
  - A short lecture on the evolution of the 802.11 standard with an emphasis on the radio design will be presented. After a brief discussion of the market trends, the performance of the 802.11's OFDM-based modulations as well as multi-in multi-out (MIMO) design in an multi-path environment will be outlined. The general evolution of the 802.11 PHY from *b* to *a* to *g* to *n* to *ac* is presented and the impact of these PHYs on the radio design is discussed. Further, the impacts of various radio impairments (noise, quadrature inaccuracy, nonlinearity, etc.) on the performance of the various PHYs will also be presented. Some specific examples of circuit techniques and architectures used in various 802.11n radios will be discussed. The evolution of 802.11 radio performance metrics throughout the past several years will be outlined. The lecture will wrap up with some real-world throughput measurement results and a brief discussion of the future trends of radio design.

Author Bio

- Arya Behzad obtained his BSEE and MSEE from ASU and UC Berkeley in 1991 and 1994 respectively. After working for UTC, Microunity and Maxim, he joined Broadcom in 1988 where he is currently a Senior Director of Engineering working on radios and SoCs for current and future generation wireless products. He was designated as a Broadcom Distinguished Engineer in 2007 and as a Broadcom Fellow in 2009 for the design and productization contributions to CMOS RF transceivers and power amplifiers. He has published numerous papers and is an inventor on well over 100 issued patents in the areas of precision analog circuits, gigabit Ethernet, set-top boxes and wireless networking. He has taught courses and presented technical seminars at various conferences and at several universities. He is a retired member of the ISSCC Wireless Technical Committee as well as a retired Guest and Associate Editor of the JSSC. He has authored the book, "Wireless LAN Radios", IEEE Press/Wiley. He is an IEEE Distinguished Lecturer as well as an IEEE Fellow.