Minimizing Energy Consumption with an SDR Based Morphable Radio

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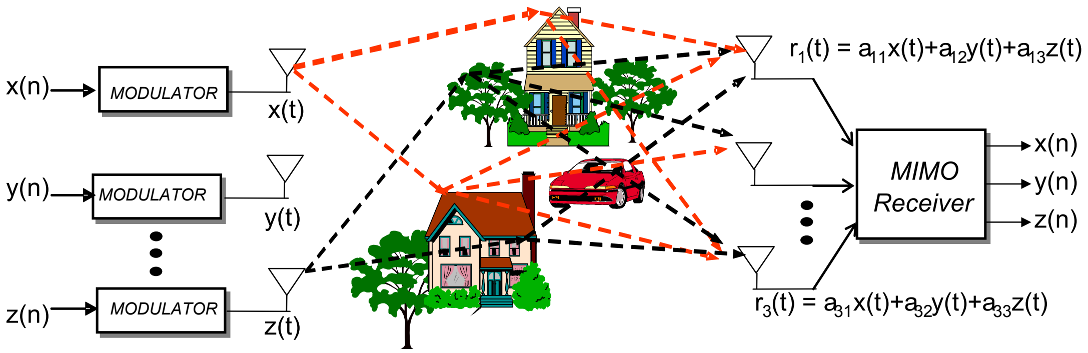
Consider A Versatile Multi Antenna Capable Node

Bandwidth	**0.625, 1.25, 2.5,** 5, 10, 20, **40** MHz	OFDM Constellation size	2, 4, 16, 64-QAM
Antenna configuration	1x1, 1x2, …, 2x4, …. 4x4	Modulation	64/**128**-point OFDM or **OQPSK**
Types of Antenna Proc	- Spatial Multiplexing - CDD TX Diversity - Smart Antenna **- STBC** **- Eigen Beamforming**	Code Coding Rate	Convolutional **Bit-Interleaved Coded Modulation** ½, 2/3, ¾, 5/6
No spatial streams	1, 2, 4	RF bands	2.4, 5.8 GHz, Ka, Ku
Packet Length	1 to **64 KBytes**	Interference Mitigation	Via **Eigen beam-nulling**
Spatial multiplexing decoders	MMSE, **Sphere, ZF, VBLAST**	Interference countermeasure	**Cognitive, sense and avoid**
Packet aggregation	**Up to 16 packets**	Coordinated TX/RX	**STBC**
Mobility support	**Up to 100 mph**	API	**Enhanced Networking API** RF API

- Versatility ⇒ Comms for diverse set of applications
  - Morph into optimum node given:
    - QoS, - Channel Sate, - Interference characteristics
  - Minimize energy utilization per reliably decoded bit

Intro to Multi Input Multi Output (MIMO) Wireless Comms.

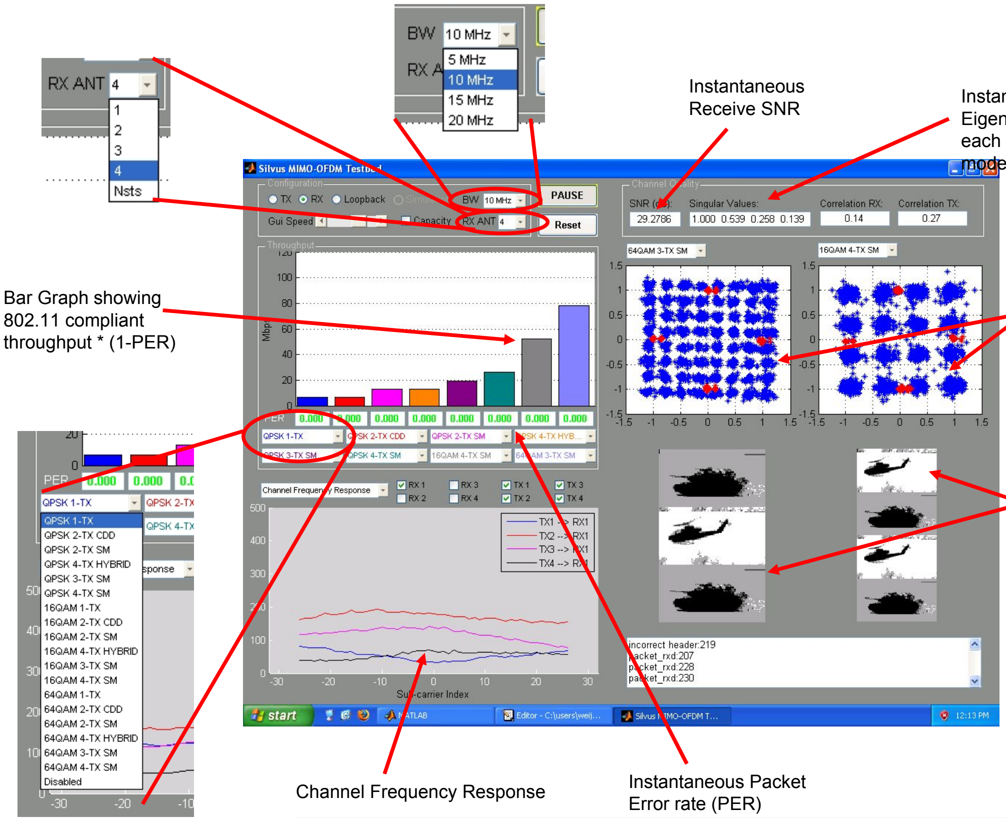


- Different data sent on different transmit antennas
  - All transmissions occur at the same time and in the same frequency band
- The signal from each transmitter is received at **ALL** receive antennas (this is not interference)
- Channel impulse response is a matrix
  - NxM matrix; where N is the number of TX and M is the number of RX antennas; N>M

UCLA Researchers Have Developed one-of-a-kind Morphable 4x4 MIMO SDR*

- 100 Mbps Operation validated in mobile trials at up to 70 mph
- SDR implements a variant of IEEE 802.11n draft standard with provisions for high mobility
- Over 300 PHY modes can be changed on a per-packet basis
- A robust MAC-PHY API allows the implementation of any MAC
- Radio is inclusive of all acquisition, tracking, and estimation algorithms

* MIMO SDR has been developed in collaboration with Silvus Communication Systems



BW 10 MHz

RX ANT 4

SNR (dB): 29.2786

Singular Values: 1.000 0.539 0.258 0.139

Correlation RX: 0.14

Correlation TX: 0.27

PER 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000

```
incorrect header:219
packet_rxd:207
packet_rxd:228
packet_rxd:230
```

Instantaneous Receive SNR

Instantaneous Eigen Value for each Channel Eigen mode

Bar Graph showing 802.11 compliant throughput * (1-PER)

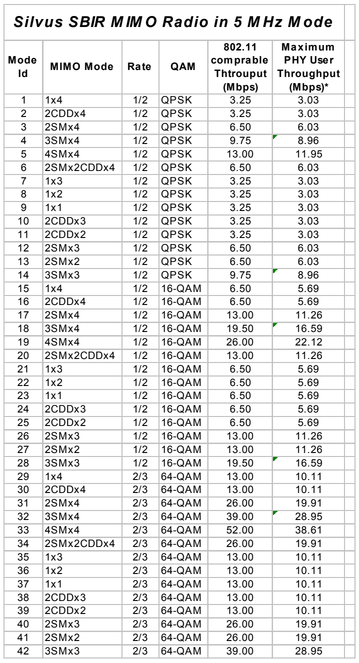
Instantaneous receive constellation

Received Images sent on different TX antennas

Channel Frequency Response

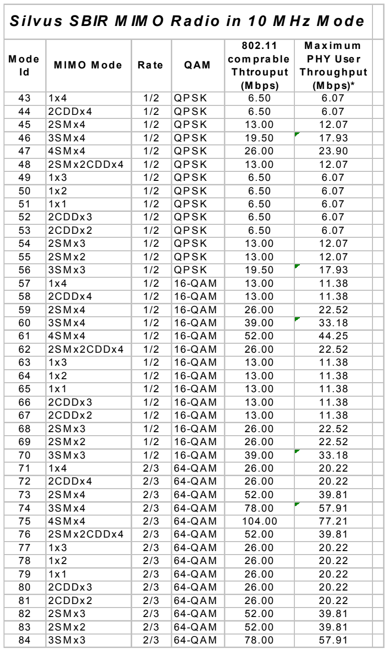
Instantaneous Packet Error rate (PER)

Radio Can Easily Provide 100s of Modes



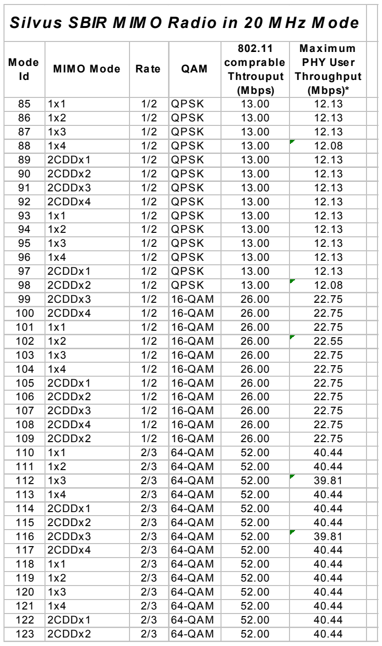
Silvus SBIR MIMO Radio in 5 MHz Mode

Mode Id	MIMO Mode	Rate	QAM	802.11 comprable Thtrouput (Mbps)	Maximum PHY User Throughput (Mbps)*
1	1x4	1/2	QPSK	3.25	3.03
2	2CDDx4	1/2	QPSK	3.25	3.03
3	2SMx4	1/2	QPSK	6.50	6.03
4	3SMx4	1/2	QPSK	9.75	8.96
5	4SMx4	1/2	QPSK	13.00	11.95
6	2SMx2CDDx4	1/2	QPSK	6.50	6.03
7	1x3	1/2	QPSK	3.25	3.03
8	1x2	1/2	QPSK	3.25	3.03
9	1x1	1/2	QPSK	3.25	3.03
10	2CDDx3	1/2	QPSK	3.25	3.03
11	2CDDx2	1/2	QPSK	3.25	3.03
12	2SMx3	1/2	QPSK	6.50	6.03
13	2SMx2	1/2	QPSK	6.50	6.03
14	3SMx3	1/2	QPSK	9.75	8.96
15	1x4	1/2	16-QAM	6.50	5.69
16	2CDDx4	1/2	16-QAM	6.50	5.69
17	2SMx4	1/2	16-QAM	13.00	11.26
18	3SMx4	1/2	16-QAM	19.50	16.59
19	4SMx4	1/2	16-QAM	26.00	22.12
20	2SMx2CDDx4	1/2	16-QAM	13.00	11.26
21	1x3	1/2	16-QAM	6.50	5.69
22	1x2	1/2	16-QAM	6.50	5.69
23	1x1	1/2	16-QAM	6.50	5.69
24	2CDDx3	1/2	16-QAM	6.50	5.69
25	2CDDx2	1/2	16-QAM	6.50	5.69
26	2SMx3	1/2	16-QAM	13.00	11.26
27	2SMx2	1/2	16-QAM	13.00	11.26
28	3SMx3	1/2	16-QAM	19.50	16.59
29	1x4	2/3	64-QAM	13.00	10.11
30	2CDDx4	2/3	64-QAM	13.00	10.11
31	2SMx4	2/3	64-QAM	26.00	19.91
32	3SMx4	2/3	64-QAM	39.00	28.95
33	4SMx4	2/3	64-QAM	52.00	38.61
34	2SMx2CDDx4	2/3	64-QAM	26.00	19.91
35	1x3	2/3	64-QAM	13.00	10.11
36	1x2	2/3	64-QAM	13.00	10.11
37	1x1	2/3	64-QAM	13.00	10.11
38	2CDDx3	2/3	64-QAM	13.00	10.11
39	2CDDx2	2/3	64-QAM	13.00	10.11
40	2SMx3	2/3	64-QAM	26.00	19.91
41	2SMx2	2/3	64-QAM	26.00	19.91
42	3SMx3	2/3	64-QAM	39.00	28.95



Silvus SBIR MIMO Radio in 10 MHz Mode

Mode Id	MIMO Mode	Rate	QAM	802.11 comprable Thtrouput (Mbps)	Maximum PHY User Throughput (Mbps)*
43	1x4	1/2	QPSK	6.50	6.07
44	2CDDx4	1/2	QPSK	6.50	6.07
45	2SMx4	1/2	QPSK	13.00	12.07
46	3SMx4	1/2	QPSK	19.50	17.93
47	4SMx4	1/2	QPSK	26.00	23.90
48	2SMx2CDDx4	1/2	QPSK	13.00	12.07
49	1x3	1/2	QPSK	6.50	6.07
50	1x2	1/2	QPSK	6.50	6.07
51	1x1	1/2	QPSK	6.50	6.07
52	2CDDx3	1/2	QPSK	6.50	6.07
53	2CDDx2	1/2	QPSK	6.50	6.07
54	2SMx3	1/2	QPSK	13.00	12.07
55	2SMx2	1/2	QPSK	13.00	12.07
56	3SMx3	1/2	QPSK	19.50	17.93
57	1x4	1/2	16-QAM	13.00	11.38
58	2CDDx4	1/2	16-QAM	13.00	11.38
59	2SMx4	1/2	16-QAM	26.00	22.52
60	3SMx4	1/2	16-QAM	39.00	33.18
61	4SMx4	1/2	16-QAM	52.00	44.25
62	2SMx2CDDx4	1/2	16-QAM	26.00	22.52
63	1x3	1/2	16-QAM	13.00	11.38
64	1x2	1/2	16-QAM	13.00	11.38
65	1x1	1/2	16-QAM	13.00	11.38
66	2CDDx3	1/2	16-QAM	13.00	11.38
67	2CDDx2	1/2	16-QAM	13.00	11.38
68	2SMx3	1/2	16-QAM	26.00	22.52
69	2SMx2	1/2	16-QAM	26.00	22.52
70	3SMx3	1/2	16-QAM	39.00	33.18
71	1x4	2/3	64-QAM	26.00	20.22
72	2CDDx4	2/3	64-QAM	26.00	20.22
73	2SMx4	2/3	64-QAM	52.00	39.81
74	3SMx4	2/3	64-QAM	78.00	57.91
75	4SMx4	2/3	64-QAM	104.00	77.21
76	2SMx2CDDx4	2/3	64-QAM	52.00	39.81
77	1x3	2/3	64-QAM	26.00	20.22
78	1x2	2/3	64-QAM	26.00	20.22
79	1x1	2/3	64-QAM	26.00	20.22
80	2CDDx3	2/3	64-QAM	26.00	20.22
81	2CDDx2	2/3	64-QAM	26.00	20.22
82	2SMx3	2/3	64-QAM	52.00	39.81
83	2SMx2	2/3	64-QAM	52.00	39.81
84	3SMx3	2/3	64-QAM	78.00	57.91

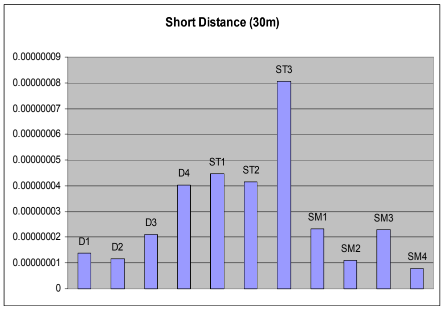


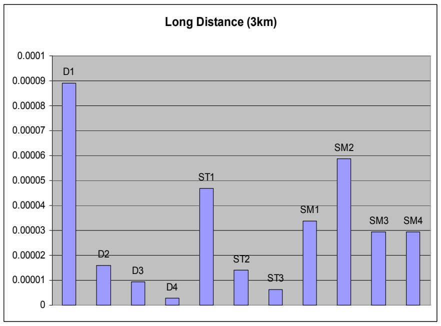
Silvus SBIR MIMO Radio in 20 MHz Mode

Mode Id	MIMO Mode	Rate	QAM	802.11 comprable Thtrouput (Mbps)	Maximum PHY User Throughput (Mbps)*
85	1x1	1/2	QPSK	13.00	12.13
86	1x2	1/2	QPSK	13.00	12.13
87	1x3	1/2	QPSK	13.00	12.13
88	1x4	1/2	QPSK	13.00	12.08
89	2CDDx1	1/2	QPSK	13.00	12.13
90	2CDDx2	1/2	QPSK	13.00	12.13
91	2CDDx3	1/2	QPSK	13.00	12.13
92	2CDDx4	1/2	QPSK	13.00	12.13
93	1x1	1/2	QPSK	13.00	12.13
94	1x2	1/2	QPSK	13.00	12.13
95	1x3	1/2	QPSK	13.00	12.13
96	1x4	1/2	QPSK	13.00	12.13
97	2CDDx1	1/2	QPSK	13.00	12.13
98	2CDDx2	1/2	QPSK	13.00	12.08
99	2CDDx3	1/2	16-QAM	26.00	22.75
100	2CDDx4	1/2	16-QAM	26.00	22.75
101	1x1	1/2	16-QAM	26.00	22.75
102	1x2	1/2	16-QAM	26.00	22.55
103	1x3	1/2	16-QAM	26.00	22.75
104	1x4	1/2	16-QAM	26.00	22.75
105	2CDDx1	1/2	16-QAM	26.00	22.75
106	2CDDx2	1/2	16-QAM	26.00	22.75
107	2CDDx3	1/2	16-QAM	26.00	22.75
108	2CDDx4	1/2	16-QAM	26.00	22.75
109	2CDDx2	1/2	16-QAM	26.00	22.75
110	1x1	2/3	64-QAM	52.00	40.44
111	1x2	2/3	64-QAM	52.00	40.44
112	1x3	2/3	64-QAM	52.00	39.81
113	1x4	2/3	64-QAM	52.00	40.44
114	2CDDx1	2/3	64-QAM	52.00	40.44
115	2CDDx2	2/3	64-QAM	52.00	40.44
116	2CDDx3	2/3	64-QAM	52.00	39.81
117	2CDDx4	2/3	64-QAM	52.00	40.44
118	1x1	2/3	64-QAM	52.00	40.44
119	1x2	2/3	64-QAM	52.00	40.44
120	1x3	2/3	64-QAM	52.00	40.44
121	1x4	2/3	64-QAM	52.00	40.44
122	2CDDx1	2/3	64-QAM	52.00	40.44
123	2CDDx2	2/3	64-QAM	52.00	40.44

Can Multiplicity of Modes Help in Energy Efficiency?

- **An energy efficient mode for scenario 1 may be far from optimum for scenario 2**
- **Consider the transmission of 1 KByte of data from the source to the destination**
  - – Use energy per bit as the metric for comparison
    - Model incorporates baseband processing power, data converter power, RF transceiver biasing power, PA efficiency, TX power
  - – 12 different modes are compared side by side
    - Mode SM4 is optimum for 30 m separation followed by SM2 and D2
    - Mode D4 is optimum for 3 Km separation followed by ST3 and D3
- **But this suggests a departure from conventional techniques used for low power operation !**





Conventional Approach To Wireless Circuit Design

- **Current approach**
  - – PHY designers work in isolation and design for the worst case channel conditions and packet error rates (PER)
    - These result in worst case SINR targets
  - – RF designers start with the worst case SINRs from the PHY designers, and add margin to come up with specs for
    - – Phase noise, linearity, NF, Data Converter precisions, etc.
  - – Result is a system implementation designed for absolute worst case scenarios that seldom occur
- **Short comings of conventional approach**
  - – Power consumption is maintained at the maximum to satisfy the corner cases requiring
    - – High linearity, - low phase noise, - Good IQ matching -etc.
    - Battery power is wasted
  - – Yield is reduced due to stringent requirements placed on transceiver
  - – NRE costs, CAD costs and production costs are all magnified

New Approach To Wireless Circuit Design

- **Paradigm Shift:**
  - PER (packet error rate) is the metric to be guaranteed in a wireless communication system.
  - 99% of the time the transceiver can deliver the desired PER with less than maximum
    - Linearity, phase noise, DAC precision, IQ matching, etc.
- **Potential exists to achieve**
  - 10x improvement in yield
  - 20x reduction in the overall energy consumption
  - 20x reduction in cost
- **What is needed : A morphable radio**
  - Parameter/mode rich PHY
  - RF transceiver blocks with wide range of operating points
  - Optimization protocol that dynamically trades-off the following, so as to deliver on the desired PER with minimal cost (i.e. energy, latency, etc.)
    - PHY mode + PLL phase noise + PA linearity + A/D precision + LNA NF, etc.

Case Study: Convex Optimization of a Mode Rich MIMO PHY Provides 8x Energy Savings

HS Kim, B. Daneshrad, "Link Adaptation for MIMO Wireless Communication Systems," submitted to IEEE Journal of Selected Topics in Signal Processing, special issue on MIMO-Optimized Transmission Systems for Delivering Data and Rich Content.

Problem Definition

- The main objective of the link adaptation is to find the '**optimal mode**' for the wireless link
- The optimal mode **maximizes or minimizes a desired object function** while satisfying given **QoS requirements** and other **system constraints**

- Objectives considered in this work
  - Maximum **Energy Efficiency** (Successful Rx Bits / J / Hz)
  - Maximum **Effective Data Rate** (Successful Rx Bits / sec)
  - **Joint Objective**: Weighted sum of distinct objectives

- QoS Requirements
  - Packet Error Rate (PER) <= PER_0
  - Effective Data Rate (R) >= R_0
  - Delay of the packet <= D_0

	Link Adaptation Example
Objective	Maximize Successful Rx bits/J/Hz
QoS constraints	Effective Data Rate >= 5Mbps PER <= 0.01
System parameters	Packet length (L) = 4000 bits Link distance (d) = 30m

Search Space for Link Adaptation

- MIMO Software Defined Radio (SDR) provides thousands of possible mode combinations
- The broader search space ⇒ Higher gain from link adaptation

Mode Index	Mode	Mapping	Mode Index	Mode	Mapping
M_1	Modulation Scheme	1: OFDM 2: GMSK	M_6	Spectral Efficiency of Modulation	OFDM: BPSK, QPSK, 16QAM, 64QAM GMSK: BT = inf, 0.4, 0.3, 0.2
M_2	Number of Spatial Streams (N_{SS})	1, 2, 3 ,4	M_7	MIMO Detection / FEC Algorithm Pair	1: MMSE / DFE MIMO Detection with Viterbi Decoder 2: Iterative MAP MIMO Detection with MAP FEC Decoder
M_3	Number of Tx Antennas (N_T)	1, 2, 3, 4	M_8	Bandwidth (BW)	0.0195*MHz*, 0.039*MHz*, … 5*MHz*, 10*MHz*
M_4	Number of Rx Antennas (N_R)	1, 2, 3, 4	M_9	Tx Power Level (P_T)	-10dBm, -9.5dBm, -9dBm … 30dBm
M_5	Convolutional Code Coding Rate (C_R)	*1/2, 2/3, 3/4, 5/6*			

Assumed Power Consumption for RF Components

Component	Power Consumption	Parameters
DAC	$P_{DAC}(BW) \approx precision \cdot C_p \cdot 2V_{DD}^2 \cdot BW$ $+\frac{1}{2}V_{DD} \cdot I_o \cdot (2^{precision} - 1) + precision \cdot C_p \cdot f_{cor} \cdot V_{DD}^2$	*precision* = 10, C_p = 1pF V_{DD} = 3V, I_o = 10uA, f_{cor} = 1*MHz*
ADC	$P_{ADC}(BW) \approx$ $\frac{6V_{DD}^2 \cdot L_{\min} \cdot f_{cor}}{10^{-0.1525 \cdot precision + 4.838}} + \frac{6V_{DD}^2 \cdot L_{\min}}{10^{-0.1525 \cdot precision + 4.838}} BW$	*precision* = 10, L_{min} = 0.5um V_{DD} = 3V, f_{cor} = 1*MHz*
Mixer	30mW	
Synthesizer	50mW	
BPF, LPF	2.5mW	
LNA, VGA	LNA: 20mW, VGA: 3mW	
PA	$P_{PA}(P_T) \approx \frac{PAPR}{\gamma} \cdot P_T$	γ : PA efficiency (0.35 for OFDM, 0.75 for GMSK)

Baseband Signal Processing Power Model

- MIMO detection and FEC decoding power consumption is excluded from baseband signal processing power estimation, these are separately incorporated into the power model
- Assume signal processing power is linearly proportional to the bandwidth and the number of antennas
  - The operation clock frequency will be linearly scaled according to the bandwidth in link adaptation system
- Baseband signal processing power estimation of single antenna system is available in [1] and [2]

$$P_{base\_T}(BW) = \begin{cases} 4.09 \cdot 10^{-6} \cdot BW \cdot N_T \ \ (mW) & \text{OFDM} \\ 0.89 \cdot 10^{-6} \cdot BW \cdot N_T \ \ (mW) & \text{GMSK} \end{cases}$$

$$P_{base\_R}(BW) = \begin{cases} 1.62 \cdot 10^{-6} \cdot BW \cdot N_R \ \ (mW) & \text{OFDM} \\ 0.89 \cdot 10^{-6} \cdot BW \cdot N_R \ \ (mW) & \text{GMSK} \end{cases}$$

[1] J. Thomson, B. Baas, E. M. Cooper, J.M. Gilbert, G. Hsieh, P. Husted, et al., “An Integrated 802.11a Baseband and MAC Processor”, *IEEE International Solid-State Circuits Conference*, 2002.

[2] H. Zou, H. J. Kim, S. Kim, B. Daneshrad, R. Wesel, W. Magione-Smith, “Equalized GMSK, Equalized QPSK, and OFDM, a Comparative Study for High-speed Wireless Indoor Data Communications”, *Vehicular Technology Conference*, Vol. 2, May 1999, pp. 1106-1110.

GP Formulation for Maximum Energy Efficiency

- Objective function is NOT concave. However, we can construct a Geometric Programming (GP) form introducing dummy optimization variable (*PSR = 1- PER*)
- GP formulation:
  - Minimize $c_P \cdot P_T \cdot PSR^{-1} + c_{BW} \cdot BW \cdot PSR^{-1} + c_0 \cdot PSR^{-1}$
  - S.T. $PER + PSR \le 1$ $\quad PER_0^{-1} \cdot PER \le 1$ $\quad R_0 \cdot t_{oper} \cdot PSR^{-1} \cdot BW^{-1} \le 1$

$$scale_{PER} \cdot PER^{-1} \cdot P_T^{slope_{PER}} \cdot BW^{-slope_{PER}} = 1$$

- GP can be solved by using general Convex Optimization techniques or a dedicated GP solver
- After obtaining the GP solution of *BW* and P_T in continuous domain, we convert it to a discrete point in the original search space
- Define a subset index vector $\tilde{\mathbf{M}} = [M_1 \ \cdots \ M_7]^T$ which specifies a mode combination with indices from M_1 to M_7 excluding *BW* and P_T.
- To obtain the final solution, all possible $\tilde{\mathbf{M}}$ should be enumerated and GP needs to be solved for each distinct $\tilde{\mathbf{M}}$
- The algorithm complexity of GP solver can be prohibitive for practical real-time systems
- Low complexity GP solving technique will be discussed later

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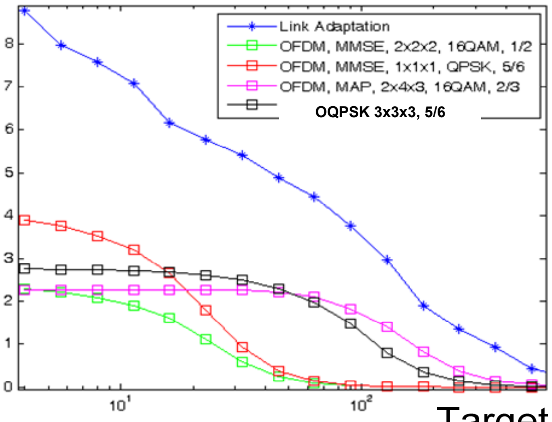
Link Adaptation for Max. Energy Efficiency

- Link Adaptation results in flat fading channel with 8Mbps target data rate, *L* = 1000 bytes
  - Link Adaptation provides significant gain over fixed modes (P_T and *BW* are adaptive)



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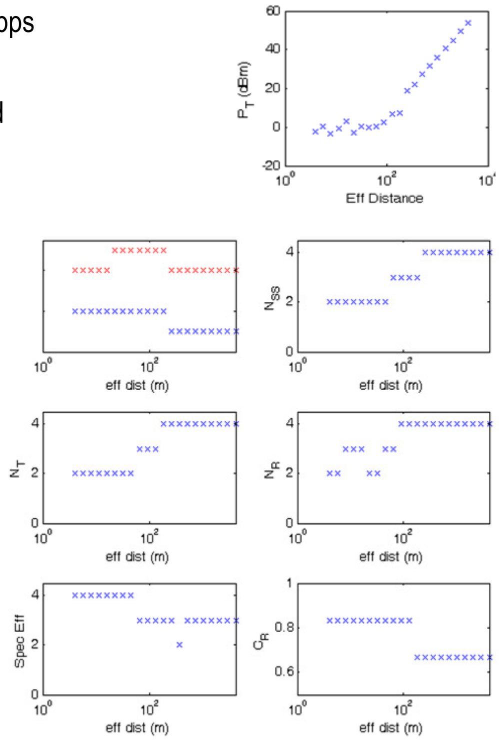


MMS

But This is Only Half the Story

- This study only considers versatilty in baseband
- What about the RF and baseband analog circuits?
  - Can versatility in this domain result in further energy and/or performance savings?
- Consider the possibility of
  - Trading off PLL phase noise for energy
  - Dynamically trading off A/D precision for energy
  - Setting LNA & first stage mixer linearity as a function of out of band interference
- Use PER as the metric of choice for analog systems
  - Look at the entire system (RF/analog + Baseband Algorithm) as a whole and define circuit design success when the desired PER is met
  - Contrast this to meeting desired
    - IQ matching, phase noise, linearity, NF, etc.

Backup

Lessing Luu, Babak Daneshrad, “An Adaptive Weaver Architecture Radio with Spectrum Sensing Capabilieites to Relax RF Component Requirements,” IEEE JSAC April 2007, Vo. 25, No. 3, pp. 538-545.

Case Study: Tunable Weaver Architecture

Tunability delivers a 30 dB gain in IQ mismatch specs as compared to a traditional "worst case design"

Lessing Luu, Babak Daneshrad, "An Adaptive Weaver Architecture Radio with Spectrum Sensing Capabilieites to Relax RF Component Requirements," IEEE JSAC April 2007, Vo. 25, No. 3, pp. 538-545.

A sense and tune approach to reducing IQ matching in Image Reject

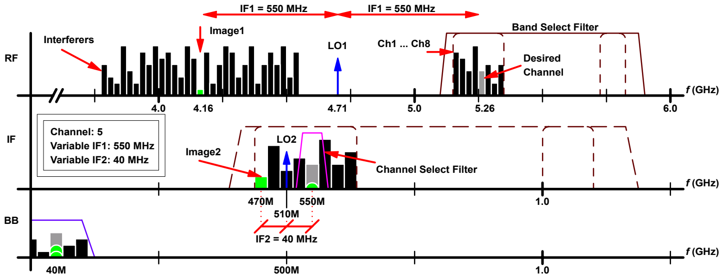
What if …

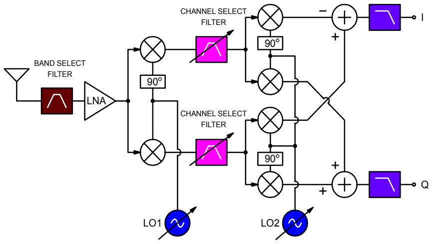
... we could sense where the large image band interferers were?

... we had a radio that was able to adapt and avoid these large interferers?

- Propose the following question:
  - "Would the ability to sense the spectrum and adapt to it relax the Image Rejection requirements all together?"

36 dB Reduction in Image Reject Spec. via Sense-and-Tune Protocol





- For a target packet error rate (PER) of 5%
  - Sense and tune approach reduces image reject (IR) requirement by as much as 36 dB compared to traditional fixed implementations
  - Savings translates into
    - Cost
    - Power efficiency

Data Rates (Mb/s)	IR for Published Weaver (dB)	IR for This Paper (dB)	IR Gain (dB)
6	59	33	26
18	59	33	26
36	60	35	25
48	80	44	36
54	69	41	28

Define New Metric

- Propose to relax Image Rejection.
  - Cannot use Image Rejection as performance metric.
- New metric: SIR Success Rate
  - Is directly related to PER (Packet error rate)
  - Defined as probability (percentage) of achieving a desired SIR.
  - SIR Success Rate = $\frac{\text{\# of satisfied SIR}}{\text{\# of trials}} \times 100$
- Apply metric for different data rates.

Rates (Mb/s)	Sensitivity: no ACI (dBm)	Sensitivity: with ACI (dBm)	SNR (dB)	SIR[a] (dB)
54	-65	-62	24.56	34.56
		...		
6	-82	-79	6.02	16.02