HOW DO MIMO RADIOS WORK?

Adaptability of Modern 802.11 and LTE Technology

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Wireless technology has come a long way since mobile phones first emerged in the 1970s. Early radios were all analog. Modern radios include digital signal processing (DSP) in the baseband layer – a technology that changes everything about radios and enables vast improvements in throughput and range.

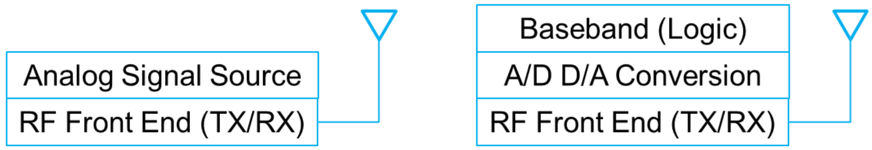

Figure 1: *Block diagram of traditional analog radio (left) vs. modern radio with a baseband layer (right); Baseband logic can make the radio adaptable to time-variable wireless channel conditions*

The baseband layer in modern IEEE 802.11 and LTE radios adapts radio operation to a variety of channel conditions, optimizing throughput, packet error rate (PER) and range. The adaptation algorithms are complex as they have many degrees of freedom, as summarized in Table 1.

Table 1: *Wireless adaptation techniques typically supported by baseband logic*

Adaptation	Variables
Modulation	BPSK, QPSK, 16-QAM, 65-QAM, 256-QAM[1]
Signaling	CCK, DSSS, OFDM[2]
Coding rate	1/2, 3/4, 5/6
# spatial streams	1 to 8
Channel width	Wi-Fi: 20/40/80/160 MHz; LTE: up to 20 MHz
Guard Interval (GI)[3]	Wi-Fi: 400/800 ns; LTE: 5.2 usec
MIMO mode	Spatial Multiplexing (SM), TX diversity, RX diversity

New generation Multiple Input Multiple Output (MIMO) 802.11n/ac radios have more complex adaptation algorithms than legacy Single Input Single Output (SISO) 802.11a/b/g devices. While SISO devices only vary modulation, 802.11n/ac radios work with a more complex Modulation Coding Scheme (MCS). An MCS includes the following variables: modulation, coding rate, GI, channel width and the number of spatial streams.

The technique of transmitting multiple spatial streams in the same frequency channel is called Spatial Multiplexing (SM). SM only works under favorable channel conditions and in wireless channels with low

[1] BPSK = binary phase shift keying; QPSK = quadrature phase shift keying; QAM = quadrature amplitude modulation
[2] CCK = complimentary code keying; DSSS = direct sequence spread spectrum, OFDM = orthogonal frequency division multiplexing
[3] Guard Interval (GI), aka Cyclic Prefix (CP), is the field at the start of each OFDM symbol that allows multipath to settle prior to having the receiver decode the symbol. GI has to be longer for environments where multipath takes longer to settle (e.g. longer GI for outdoors vs. shorter GI for indoors). SGI for 802.11n is 400 ns vs. legacy GI of 800 ns.

MIMO correlation. Low correlation means that each stream can be transmitted in such a way as not to interfere too much with other streams, for example via a directed beam or distinct antenna polarization.

Figure 2 presents an example of data rate adaptation of an 802.11g link. The link consists of a transmitting (TX) device and a receiving device (RX) with a programmable RF attenuator between the TX and RX controlling the path loss of the link vs. time.

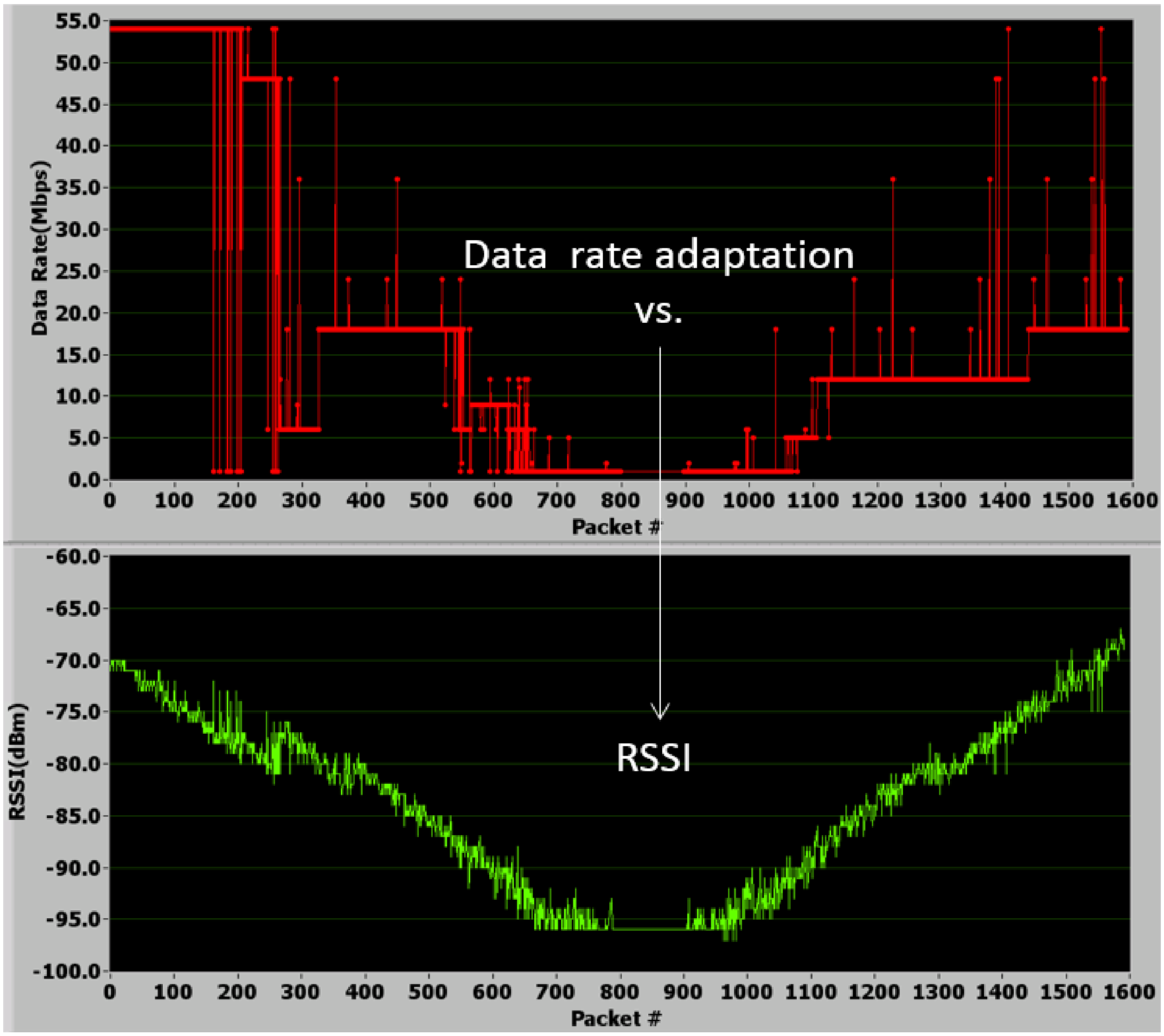

Figure 2: *Example of 802.11g data rate adaptation. Data rate vs. RSSI is plotted vs. packet # while path loss between the TX and RX radios is first increased and then decreased. This link under test never recovers its maximum data rate of 54 Mbps even after the RX signal is restored to full power*.

Initially under favorable conditions the 802.11g link starts operating, as expected, at its maximum data rate of 54 Mbps. As path loss increases and receive signal strength indicator (RSSI) slopes down, the TX device adapts data rate downward. The TX device sets data rate based on Packet Error Rate (PER) that it measures by counting acknowledgements (ACKs) from the RX station.

The interesting thing is that after RSSI reaches the bottom of the dynamic range and then signal power is gradually restored back to its maximum level, the link never regains its maximum data rate. Why not?

Adaptation logic is typically 'stateful', meaning that the previous states of the adaptation state machine impact the decisions of the adaptation logic. If we were to power cycle the DUTs, the data rate would go back to its maximum setting of 54 Mbps.

The behavior of adaptation algorithms is easily observable under controlled conditions, for example inside octoBox™ RF chamber [1], but very difficult to observe in the real-world (e.g. when testing in a house).

Table 1 shows all the possible data rates of 802.11 a/b/g/n radios vs. the channel width, number of spatial streams and GI settings. The Mbps figures in Table 1 have been computed based on the IEEE 802.11 standard [2] in a spreadsheet created by octoScope [4].

Table 1: *Data rates in Mbps of 802.11 a/b/g/n radios*

	20 MHz Channel				40 MHz Channel			
Streams	1	2	3	4	1	2	3	4
802.11b 2.4 GHz	1, 2, 5.5, 11							
802.11a 5 GHz	6, 9, 12, 18, 24, 36, 48, 54							
802.11g 2.4 GHz	1, 2, 6, 9, 12, 18, 24, 36, 48, 54							
802.11n 2.4 and 5 GHz	6.5, 13, 19.5, 26, 39, 52, 58.5, 65	13, 26, 39, 52, 78, 104, 117, 130	19.5, 39, 58.5, 78, 117, 156, 175.5, 195	26, 52, 78, 104, 156, 208, 234, 260	13.5, 27, 40.5, 54, 81, 108, 121.5, 135	27, 54, 81, 108, 162, 216, 243, 270	40.5, 81, 121.5, 162, 243, 324, 364.5, 405	54, 108, 162, 216, 324, 432, 486, 540
802.11n, SGI[4] enabled 2.4 and 5 GHz	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	14.4, 28.9, 43.3, 57.8, 86.7, 115.6, 130, 144.4	21.7, 43.3, 65, 86.7, 130, 173.3, 195, 216.7	28.9, 57.8, 86.7, 115.6, 173.3, 231.1, 260, 288.9	15, 30, 45, 60, 90, 120, 135, 150	30, 60, 90, 120, 180, 240, 270, 300	45, 90, 135, 180, 270, 360, 405, 450	60, 120, 180, 240, 360, 480, 540, **600**

As shown in Table 1, 802.11n radios can reach a maximum theoretical data rate of 600 Mbps using a 40 MHz wide channel, short GI (SGI) and 4 spatial streams.

[4] SGI = short guard interval.

The new Very High Throughput (VHT) 802.11ac technology can theoretically achieve 6.9 Gbps by using higher order MIMO (up to 8x8) and wider channels (up to 160 MHz). The 802.11ac data rates in Table 2 have been computed based on the IEEE 802.11ac standard [3] in a spreadsheet created by octoScope [4].

Table 2: *Data rates in Mbps of 802.11ac radios in 20, 40, 80 and 160 (80+80) MHz channels*

	20 MHz Channel							
Streams	1	2	3	4	5	6	7	8
800 ns GI	6.5	13.0	19.5	26.0	32.5	39.0	45.5	52.0
	13.0	26.0	39.0	52.0	65.0	78.0	91.0	104.0
	19.5	39.0	58.5	78.0	97.5	117.0	136.5	156.0
	26.0	52.0	78.0	104.0	130.0	156.0	182.0	208.0
	39.0	78.0	117.0	156.0	195.0	234.0	273.0	312.0
	52.0	104.0	156.0	208.0	260.0	312.0	364.0	416.0
	58.5	117.0	175.5	234.0	292.5	351.0	409.5	468.0
	65.0	130.0	195.0	260.0	325.0	390.0	455.0	520.0
	78.0	156.0	234.0	312.0	390.0	468.0	546.0	624.0
			260.0			520.0		
400 ns GI	7.2	14.4	21.7	28.9	36.1	43.3	50.6	57.8
	14.4	28.9	43.3	57.8	72.2	86.7	101.1	115.6
	21.7	43.3	65.0	86.7	108.3	130.0	151.7	173.3
	28.9	57.8	86.7	115.6	144.4	173.3	202.2	231.1
	43.3	86.7	130.0	173.3	216.7	260.0	303.3	346.7
	57.8	115.6	173.3	231.1	288.9	346.7	404.4	462.2
	65.0	130.0	195.0	260.0	325.0	390.0	455.0	520.0
	72.2	144.4	216.7	288.9	361.1	433.3	505.6	577.8
	86.7	173.3	260.0	346.7	433.3	520.0	606.7	693.3
			288.9			577.8		

	40 MHz Channel							
Streams	1	2	3	4	5	6	7	8
800 ns GI	13.5	27.0	40.5	54.0	67.5	81.0	94.5	108.0
	27.0	54.0	81.0	108.0	135.0	162.0	189.0	216.0
	40.5	81.0	121.5	162.0	202.5	243.0	283.5	324.0
	54.0	108.0	162.0	216.0	270.0	324.0	378.0	432.0
	81.0	162.0	243.0	324.0	405.0	486.0	567.0	648.0
	108.0	216.0	324.0	432.0	540.0	648.0	756.0	864.0
	121.5	243.0	364.5	486.0	607.5	729.0	850.5	972.0
	135.0	270.0	405.0	540.0	675.0	810.0	945.0	1080.0
	162.0	324.0	486.0	648.0	810.0	972.0	1134.0	1296.0
	180.0	360.0	540.0	720.0	900.0	1080.0	1260.0	1440.0
400 ns GI	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0
	45.0	90.0	135.0	180.0	225.0	270.0	315.0	360.0
	60.0	120.0	180.0	240.0	300.0	360.0	420.0	480.0
	90.0	180.0	270.0	360.0	450.0	540.0	630.0	720.0
	120.0	240.0	360.0	480.0	600.0	720.0	840.0	960.0
	135.0	270.0	405.0	540.0	675.0	810.0	945.0	1080.0
	150.0	300.0	450.0	600.0	750.0	900.0	1050.0	1200.0
	180.0	360.0	540.0	720.0	900.0	1080.0	1260.0	1440.0
	200.0	400.0	600.0	800.0	1000.0	1200.0	1400.0	1600.0

	80 MHz Channel							
Streams	1	2	3	4	5	6	7	8
800 ns GI	58.5	58.5	87.8	117.0	146.3	175.5	204.8	204.8
	117.0	117.0	175.5	234.0	292.5	351.0	409.5	409.5
	175.5	175.5	263.3	351.0	438.8	526.5	614.3	614.3
	234.0	234.0	351.0	468.0	585.0	702.0	819.0	819.0
	351.0	351.0	526.5	702.0	877.5	1053.0	1228.5	1228.5
	468.0	468.0	702.0	936.0	1170.0	1404.0	1638.0	1638.0
	526.5	526.5		1053.0	1316.3	1579.5		1842.8
	585.0	585.0	877.5	1170.0	1462.5	1755.0	2047.5	2047.5
	702.0	702.0	1053.0	1404.0	1755.0	2106.0	2457.0	2457.0
	780.0	780.0	1170.0	1560.0	1950.0		2730.0	2730.0
400 ns GI	65.0	65.0	97.5	130.0	162.5	195.0	227.5	227.5
	130.0	130.0	195.0	260.0	325.0	390.0	455.0	455.0
	195.0	195.0	292.5	390.0	487.5	585.0	682.5	682.5
	260.0	260.0	390.0	520.0	650.0	780.0	910.0	910.0
	390.0	390.0	585.0	780.0	975.0	1170.0	1365.0	1365.0
	520.0	520.0	780.0	1040.0	1300.0	1560.0	1820.0	1820.0
	585.0	585.0		1170.0	1462.5	1755.0		2047.5
	650.0	650.0	975.0	1300.0	1625.0	1950.0	2275.0	2275.0
	780.0	780.0	1170.0	1560.0	1950.0	2340.0	2730.0	2730.0
	866.7	866.7	**1300.0**	1733.3	2166.7		3033.3	3033.3

Note: 1300 Mbps is the highest data rate supported in off-the-shelf products as of this writing.

	80+80 MHz Channel							
Streams	1	2	3	4	5	6	7	8
800 ns GI	58.5	117.0	175.5	234.0	292.5	351.0	409.5	468.0
	117.0	234.0	351.0	468.0	585.0	702.0	819.0	936.0
	175.5	351.0	526.5	702.0	877.5	1053.0	1228.5	1404.0
	234.0	468.0	702.0	936.0	1170.0	1404.0	1638.0	1872.0
	351.0	702.0	1053.0	1404.0	1755.0	2106.0	2457.0	2808.0
	468.0	936.0	1404.0	1872.0	2340.0	2808.0	3276.0	3744.0
	526.5	1053.0	1579.5	2106.0	2632.5	3159.0	3685.5	4212.0
	585.0	1170.0	1755.0	2340.0	2925.0	3510.0	4095.0	4680.0
	702.0	1404.0	2106.0	2808.0	3510.0	4212.0	4914.0	5616.0
	780.0	1560.0		3120.0	3900.0	4680.0	5460.0	6240.0
400 ns GI	65.0	130.0	195.0	260.0	325.0	390.0	455.0	520.0
	130.0	260.0	390.0	520.0	650.0	780.0	910.0	1040.0
	195.0	390.0	585.0	780.0	975.0	1170.0	1365.0	1560.0
	260.0	520.0	780.0	1040.0	1300.0	1560.0	1820.0	2080.0
	390.0	780.0	1170.0	1560.0	1950.0	2340.0	2730.0	3120.0
	520.0	1040.0	1560.0	2080.0	2600.0	3120.0	3640.0	4160.0
	585.0	1170.0	1755.0	2340.0	2925.0	3510.0	4095.0	4680.0
	650.0	1300.0	1950.0	2600.0	3250.0	3900.0	4550.0	5200.0
	780.0	1560.0	2340.0	3120.0	3900.0	4680.0	5460.0	6240.0
	866.7	1733.3		3466.7	4333.3	5200.0	6066.7	6933.3

In addition to MCS adaptation, MIMO devices can also use a different MIMO modes, selecting in real-time the most suitable mode for the given channel conditions.

A few representative MIMO modes of transmission are explained in Table 3.

Table 3: *MIMO modes of transmission*

MIMO Mode	Explanation
Spatial Multiplexing	Use of multiple MIMO radios to transmit two or more data streams in the same channel.
TX diversity	Use of multiple MIMO radios to transmit slightly different versions of the same signal in order to optimize reception of at least one of these versions. TX diversity schemes include space time block coding (STBC), space frequency block coding (SFBC) and cyclic delay diversity (CDD).
RX diversity	Use of multiple MIMO radios to combine multiple received versions of the same signal in order to minimize PER. A common RX diversity technique is maximal ratio combining (MRC).
Combination of TX and RX diversity	Use of TX diversity at the transmitting device in combination with RX diversity at the receiving device.
Beamforming	Use of multiple MIMO transmitters to create a focused beam, thereby extending the range of the link or enabling SM.
Multi-user MIMO (MU-MIMO)	Forming multiple focused beams or using TX diversity techniques to enable simultaneous communications with multiple device. Typically beamforming is done by a base station or an access point (AP) to communicate simultaneously with multiple client devices.

Commercial wireless chipsets typically support a subset of the MIMO modes outlined in Table 3 and may implement other proprietary modes.

With the challenging real-time decision process and numerous factors involved in the MCS and MIMO mode selection, early stage wireless devices typically exhibit observable flaws in their adaptation algorithms. For example, throughput fluctuations similar to those shown in Figure 3 have been observed on several 802.11ac devices under stable time-invariant conditions [5].

The Figure 3 plot suggests that the 802.11ac link under test may have some hysteresis in its adaptation algorithm, flipping different MCS settings back and forth and thus causing throughput to fluctuate.

Observing and optimizing MCS algorithms in the field is nearly impossible due to time-variable interference and multipath conditions. Engineers need a controlled RF testbed, such as octoBox, which enables them to set up in a repeatable and reproducible manner a range of RF environments that evoke specific behavior of the radios. Once the test environment can be controlled and configured, engineers can observe, analyze and refine the adaptation logic.

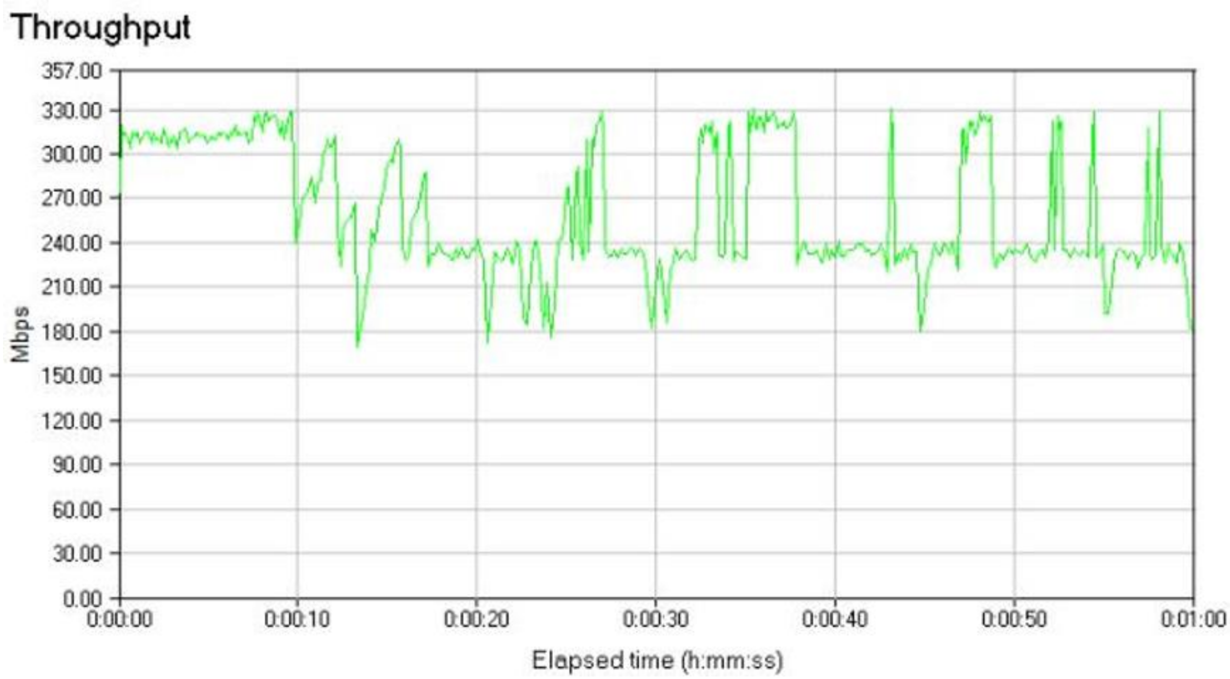

Figure 3: *Example of throughput measurement of an 802.11ac link using IxChariot™. In this example the test conditions are static, but it appears that the adaptation algorithm of the TX DUT keeps making adjustments resulting in throughput fluctuations vs. time.*

Conclusion

Modern MIMO radios use sophisticated stateful real-time algorithms to optimize their range and throughput performance. The radios are programmed to select the appropriate MCS and MIMO modes for the given channel conditions and can adapt these in real-time on a packet by packet basis. Because the algorithms are complex, they often get into unintended states, particularly in new implementations. octoScope's white paper, "Throughput Test Methods for MIMO Radios" [5] discusses test methods and metrics for evaluating the throughput performance and adaptation behavior of MIMO radios.

References

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