RF Lecture Series
Modulation Fundamentals 3
802.11b/a/g Modulation Standard

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1. Introduction

WLAN standards have appeared as a result of mobile computer users who need to remain connected to the network. As an extension to Fixed-LAN networks, WLAN needs to be compatible to the previous standard. The fact that now the radio channel is used, adds lots of complexity to the standard because of the RF error-prone nature of this medium. To avoid any kind of interference, to avoid collisions or to assure security, many challenging changes have been implemented and tests have been defined to enable the manufacturability of WLAN devices. This article will focus on the standards 802.11a/b/g.

2. 802.11b

This has been the first highly deployed standard. 802.11b operates at the 2.4 GHz ISM band. Its frame structure can be seen in Figure 1.

Preamble 1 Mbps DBPSK		**Header 1 Mbps DBPSK**	**PSDU - [FRAGMENTED] User Data**	
SYNC [128bits] Scrambled 1's	Start Frame Delimite r [16bits]	Signal[8] Service[8] Length[16] CRC for Header[16]	Variable Length	FCS CRC [32bit s]

16us

Figure 1: IEEE 802.11b Frame Structure

802.11 was the original standard, previous to 802.11b. This standard covers the 1 Mbps and 2 Mbps data rates. 802.11b uses also these data rates. They are achieved as described in Figure 2. For 1 Mbps, each bit gets modulated using DBPSK and later DSSS (Direct Sequence Spread Spectrum) is performed by applying a static 11 bit Barker sequence to the BPSK symbol. What DSSS achieves is to spread the spectrum from 1 to 11 MHz. The Bandwidth of the signal is increased without increasing the data rate in order to spread the gain versus narrow band interference signals and spread the transmit signal across a wide range. As a result, for a narrow band receiver, it is nothing but noise. Spreading data through a bigger bandwidth increases the signal resistance to noise.

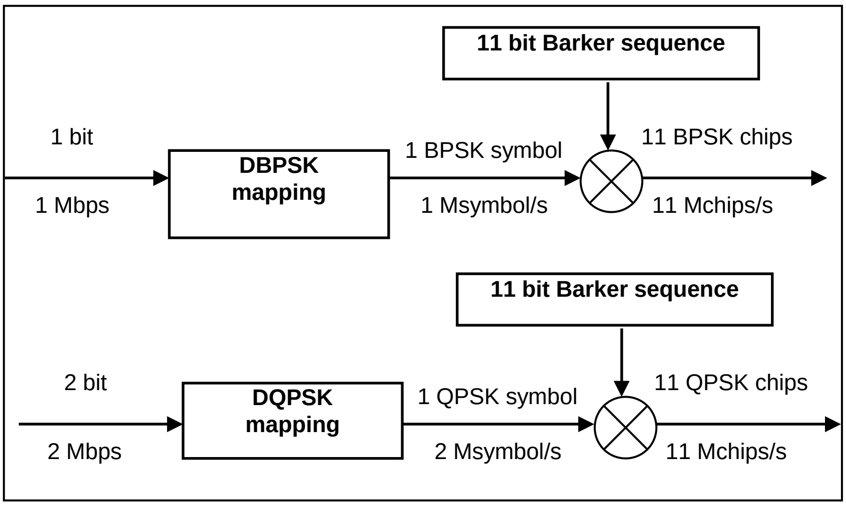

Figure 2: IEEE 802.11b 1 and 2Mbps data rates

802.11b also adds 5.5 Mbps and 11 Mbps data rates. These data rates are achieved by using CCK (Complementary Code Keying). CCK applies a code sequence of 8 bits that is calculated depending on the incoming data. The outcome is that by increasing the modulation efficiency, the data rate is increased although the bandwidth is maintained. There is an optional technique called Packet Binary Convolutional Coding (PBCC) that increases its robustness to noise.

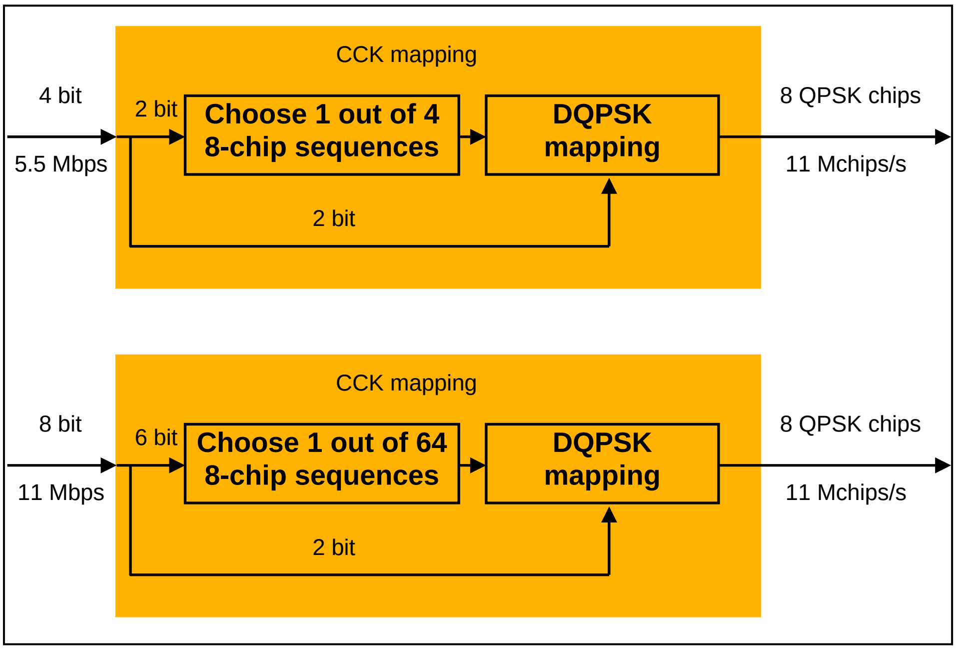

Figure 3: IEEE 802.11b 5.5 and 11Mbps Data Rates

Its spectrum is divided into 14 overlapping staggered channels of 22 MHz bandwidth. The spectral mask of each channel needs to be 30 dB from the peak energy at ±11MHz offset and of 50 dB at ±22MHz offset. Figure 4 shows the spectral content of an 802.11b waveform, obtained from the Agilent 89600 Tool. Although the channel bandwidth is 22 MHz, the occupied channel bandwidth is around 16.6 MHz. The side lobes do not contain any modulation information and need to be kept as low as possible in order to avoid any Adjacent Channel Interference. For test engineers, related tests are Spectrum Mask and Adjacent Channel Rejection.

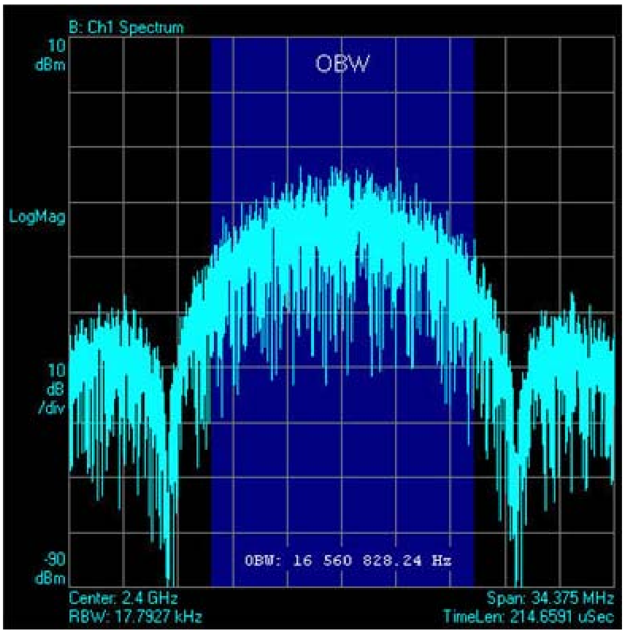

Figure 4: IEEE 802.11b Spectrum

Figure 5 shows a typical QPSK constellation of 802.11b obtained from the Agilent 89600 Tool. For 802.11b, the standard sets the maximum EVM test at 35%. This EVM could be very poor for QPSK, although the symbol separation (and EVM tolerance) for this modulation is very big. Due to DSSS coding gain and spreading spectrum, the transmitted signals can still be resolved at 35%.

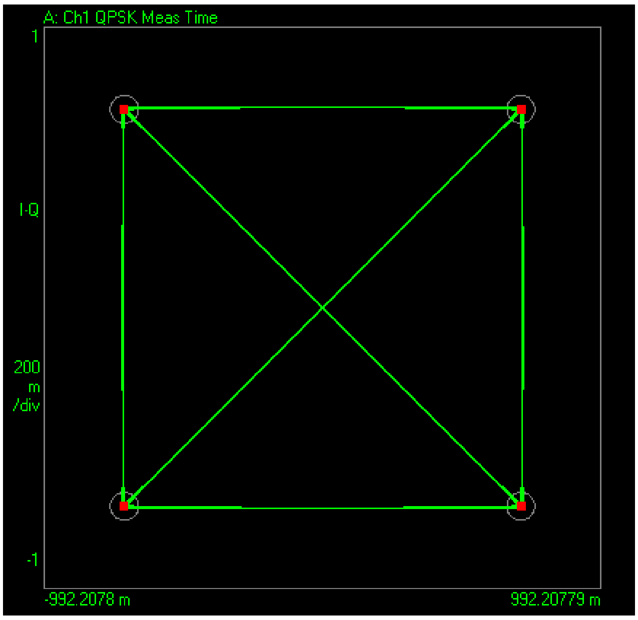

Figure 5: IEEE 802.11b Constellation

3. 802.11a

Because the 2.4 GHz band is heavily used, it was decided that 802.11a operates at the 5GHz ISM band. This way, interferences can be avoided, although due to the physical properties of this higher frequency, operation to the line of sight is restricted.

The modulation format used is OFDM (Orthogonal Frequency Division Multiplexing). The standard consists of 16 non-overlapping channels. A total of 64 subcarriers are allocated in each channel. The maximum data rate can be of 54Mbps, though it is very flexible and can be reduced to 48, 36, 24, 18, 12, 9 and 6 Mbps depending on the conditions. From all the subcarriers, a total 52 subcarriers are used (48 are used for data and the rest are used as pilot). The carrier separation is of 0.3125 MHz and each data carrier can be modulated with BPSK, QPSK, 16-QAM or 64-QAM. BPSK is always used for the pilots. The center carrier is not used. This reduces the data capacity but relaxes the carrier leakage requirements.

The total bandwidth of an 802.11a channel is 20 MHz and the OBW (Occupied Bandwidth) is around 16.6 MHz. The symbol duration is of 4msec with a guard interval of 0.8msec. Figure 6 shows the frame structure of 802.11a.

Preamble 6 Mbps BPSK ½ rate		**Header BPSK**		**[FRAGMENTED] User Data**				
10 short training every 4th carrier	2 long training every carrier	"Signal" Rate[4] Reserved[1] Length[12] Parity[1] Tail[6]	"Service" MAC Header Start of user data	USER DATA	USER DATA	USER DATA	...	Last USER DATA + pad bits + FCS
16us		4us	4us	4us				4us

Figure 6. IEEE 802.11a frame structure

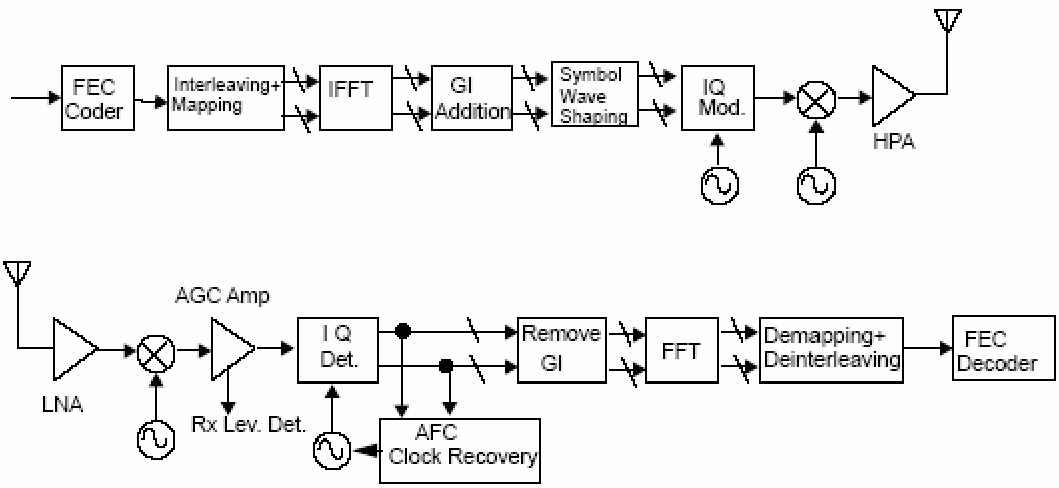

Figure 7. Transmitter And Receiver Block Diagram For The OFDM PHY

4. OFDM Modulation Technique

One of the benefits of OFDM is that it reduces multipath effects in reception and increases the spectral efficiency due to the reduced carrier spacing.

OFDM is a powerful modulation technique. Its motivation was to deal against multipath effects. The problem of single carrier modulations is that as symbol rate increases, the symbol interval becomes smaller than the spread delay. Multipath carrier modulations solve this problem by decreasing the symbol rate and increasing the number of carriers. Basically, the data is distributed over multiple lower symbol rate carriers instead of a single high rate carrier in order to avoid inter symbol interference (ISI).

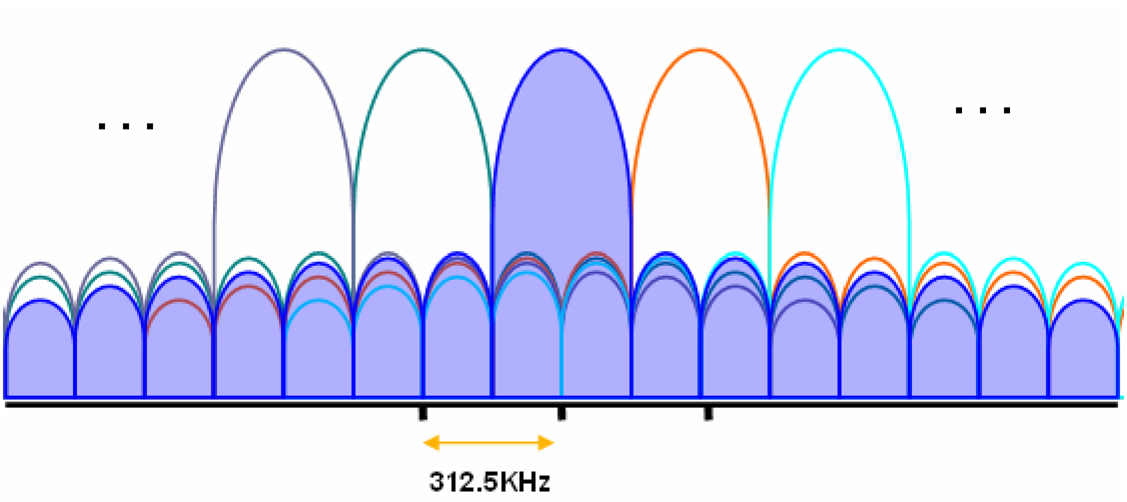

Figure 8. OFDM Spectrum With Subcarriers

The orthogonal signals used by OFDM are sinusoids (RECT * sin(x) / x). As orthogonal signals, the result of the multiplication and integration during the interval gives a result of zero.

Traditional frequency multiplexing techniques choose channel spacing bigger than the symbol rate to avoid spectrum overlap between channels. OFDM can overlap subcarriers due to the orthogonal principle. The carriers do not interfere with each other, as they have a spectral null at other carrier frequencies peaks.

The problem is that any non-linear distortion, phase noise or poor receiver frequency estimation can result in inter-carrier interference (ICI). Phase Noise will modify the sin (x) / x spectrum by reducing the depth of the nulls. If receiver is off frequency, nulls of each carrier will not land on the FFT bins and create leakage. For test engineers it is important to understand that modern day modulation techniques require lower phase noise than earlier standards.

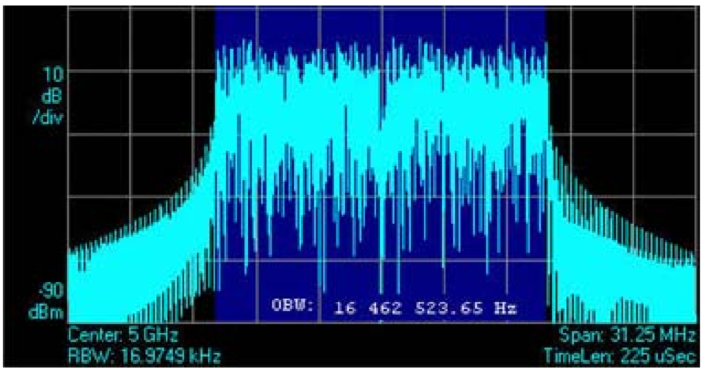

Figure 1: 802.11a Frequency Spectrum

The OFDM modulation is very efficient. The spectrum is very flat at the top, and the side lobes are not 3rd order intermodulation, but they are part of the modulation. Most contributors to these side lobes are the subcarriers located at the extremes. It can be seen that the spectrum is much more efficiently used than in 802.11b, as many carriers are allocated in the same bandwidth. Also, it is visible that the center carrier in not used. For test engineers it is important to make sure that the spectrum is flat in all the frequency ranges.

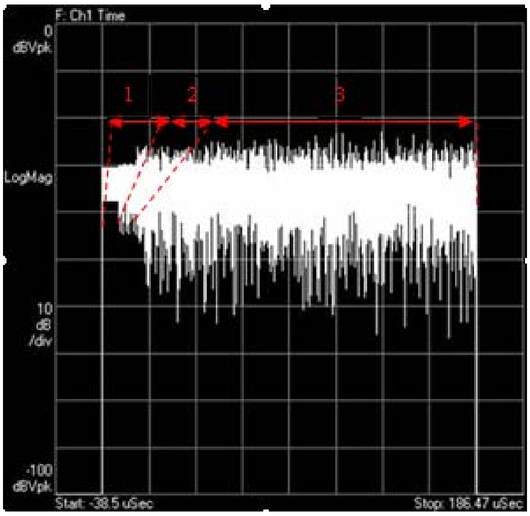

Figure 2: Time Domain of a Packet

The time domain graphic of an 802.11a frame, shows three differentiated portions. The first one is the short training symbol. This is modulated with BPSK and uses every fourth carrier. The second portion is the long training symbol, also with BPSK and uses all the carriers at same amplitude. Finally comes the big portion of the signal with data. It is quite visible that this is a more complex modulated signal (QAM in our case) because the big amplitude differences. It is important to remember, that unlike QPSK or BPSK, QAM symbols have different amplitudes (distance to the origin). The devices have bigger power consumption and amplifiers need to be designed as efficient as possible because of the high peak-to-peak ratio.

This is an example of the constellation of an 802.11a waveform with 64-QAM modulation. The two white symbols belong to the BPSK modulation used in the preamble and header. For test engineers, it is important to remember that the EVM results for this data rate cannot be too big because the symbols are very close from each other. Test engineers should be aware, for example, that any IQ imbalance, Phase Noise, frequency drift, etc., will affect the constellation and the EVM. For 802.11a, the specification sets the limits for EVM depending on the data rates.

Data Rate (Mbit/sec)	**EVM (%rms)**
6	56.2
9	39.8
12	31.6
18	22.3
24	15.8
36	11.2
48	7.9
54	5.6

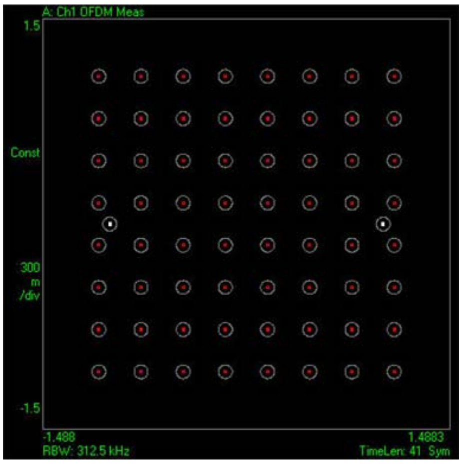

Figure 3: Constellation Plot of 802.11a 64-QAM

5. 802.11g Standard Description

802.11g can be described as the merger of 802.11a and 802.11b technologies. This modulation can use the same modulation techniques as 11a (OFDM) but can also work on 11b mode (DSSS). 802.11g keeps compatibility with 802.11b networks and devices by maintaining its timing and frequency arrangements and operating at the 2.4 GHz ISM band. The modulation scheme used in 802.11g is orthogonal frequency-division multiplexing (OFDM) for the data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps, and reverts to CCK for 5.5 and 11 Mbps and DBPSK/DQPSK+DSSS for 1 and 2 Mbps.

6. Conclusion

This paper has introduced the modulations used in 802.11a/b/g standards and pointed out important factors (IQ balance, linearity, spectrum flatness, spectrum ask, etc.) that a test engineer needs to take into account when testing WLAN devices. 802.11a/g demonstrates how by using a more efficient modulation type, higher data rates can be achieved than on 802.11b. The drawback of a more efficient modulation type is that the requirements become more challenging.

If we look at newer technologies, like WiMax and LTE, more efficient modulations are used. Testing these devices gets even more challenging as symbol separation becomes smaller and, for example, better linearity and phase noise is required.

	802.11	**802.11b**	**802.11a**	**802.11g**
Frequency Band	2.4 GHz	2.4 GHz	5 GHz	2.4 GHz
Channel Separation	25 MHz for DSSS, 1 MHz for FHSS	25 MHz	20 MHz	25 MHz
Max Raw Data Type	2 Mbit/s	11 Mbit/s	54 Mbit/s	54 Mbit/s
Carrier Type	FHSS or DSSS	DSSS	OFDM	OFDM or DSSS
Modulation	GFSK (FHSS), DBPSK or DQPSK (DSSS)	CCK	BPSK & QPSK, 16-QAM, or 64-QAM	BPSK & QPSK, 16-QAM, or 64-QAM
Number of Carriers per Channel	79	1 (DSSS)	48 data & 4 pilot	48 data & 4 pilot
Max Power Out	30 dBm	30 dBm	30 dBm	30 dBm

7. References

[1] Agilent Application Note, "IEEE 802.11 Wireless LAN PHY Layer (RF) Operation and Measurement," Part Number 5988-5411EN (2002).
[2] Agilent Application Note, "RF Testing of WLAN Products," Part Number 5988-3762 (2001).
[3] Rohde&Schwarz Application Note, "WLAN Tests According to Standard 802.11a/b/g", Application Note number 1MA69
[4] IEEE Std 802.11 (ISO/IEC 8802-11: 1999): IEEE Standards for Information Technology -- Telecommunications and Information Exchange between Systems -- Local and Metropolitan Area Network – Specific Requirements -- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.