A 2.4 & 5 GHz Dual Band 802.11 WLAN Supporting Data Rates to 108 Mb/s

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Abstract

A three chip se, and its associated reference design, implementing a dual mode, dual band 802.11a/b WLAN is presented. The reference design achieves -91dBm sensitivity at 6Mb/s, -73dBm at 54Mb/s, and -70dBm at 108Mb/s. 18dBm transmit power is achieved at 6Mb/s, 14dBm at 54 and 108Mb/s. An overview of 802.11a is given. World-wide spectral allocations are summarized. Required RF component performance is described including PA linearity and achievable PA efficiencies.

INTRODUCTION

Since 1999, the WLAN market has experienced tremendous growth. This is due to a confluence of factors including the adoption of industry standards and interoperability testing, the progression of WLAN equipment to higher data rates, rapidly dropping product prices, and an industry shift towards mobility and the use of laptops. A 2002 In-Stat market report [1] estimated the unit volumes (in millions) shown in Table 1.

Table 1. 2002 In-Stat WLAN Market Estimates (in millions of units)

WLAN type	2002	2004	2006
802.11b (2.4 GHz)	12.8	25.2	23.6
802.11a (5 GHz)	0.7	6.5	16.3
Dual mode, dual band	0.7	7.0	29.3

The market estimate shows a strong shift from 2.4 GHz to 5 GHz. The 5 GHz band offers the advantages of higher data rates, far more available spectrum, and less sharing with other uses such as cordless phones and Bluetooth devices.

Roughly 20% of the cost of current dual band solutions is in the RF components. There is a tremendous need for low cost components that can meet the stringent performance requirements for WLANs in the 5 GHz band.

This paper presents an overview of the 802.11a WLAN standard [2]. Following that, a dual mode, three chip set, with associated RF components, that implements the 802.11a and 802.11b WLAN standards operating at 5 GHz and 2.4 GHz is presented.

SPECTRAL ALLOCATIONS

The IEEE 802.11a standard was adopted in 1999. It was defined to take advantage of the bandwidth being allocated at 5 GHz, which could support higher data rates and more available channels than the 83 MHz available at 2.4 GHz. The following table summarizes the current worldwide 5 GHz allocations.

Table 2. Worldwide Frequency allocations (allowed Tx power in mW EIRP)

Region	5.15-5.25	5.25-5.35	5.47-5.725	5.725-5.825	Total (MHz)
USA	200	1000		4000	300
Europe	200	200	1000		455
Japan	200				100
Asia (Korea, HK, China, Singapore, NZ, Aus.)	200 (Sing., Aus., NZ)	200 (Sing., Aus., NZ, Taiw.)		100 to 1000 (all, at var. power)	100 - 300

In addition to the allocations shown above, Japan will be allocating 4.9-5.0 GHz in '03. In the US and Canada, 802.11a has been chosen as the system for the Dedicated Short Range Communications (DSRC) band. This band is dedicated to communication with automobiles, and will have safety as well as commercial application. The spectrum allocated to DSRC lies from 5.850-5.925 GHz. Creating radios that can operate from 4.9 to 5.925 GHz is one of the major challenges faced by developers of 802.11a equipment.

802.11 OVERVIEW

A good overview of the 802.11 protocol and Media Access Control (MAC) can be found in reference [3]. To the PHY level, the most important aspects of the protocol are:

- The radio transmits and receives on the same frequency, but not at the same time.
- The radio must switch between receive and transmit in under 5us.
- The radio does not need to change channel frequencies rapidly (several ms is acceptable).

802.11b is a 2.4GHz physical layer that provides 1, 2, 5.5, or 11Mb/s raw data rates. It is based on QPSK modulation, with either Direct Sequence Spread Spectrum (DSSS) at 1 and 2 Mb/s, or Complementary Code Keying (CCK) at 5.5 and 11Mb/s.

The 802.11a PHY is based on coded Orthogonal Frequency Division Multiplexing (OFDM) modulation. The OFDM signal consists of 52 carriers, generated with an iFFT in the digital domain. Four of the carriers are used as pilots to aid in frequency recovery at the receiver. Because the pilots can be tracked at ~250kHz, low frequency phase noise can be largely removed from the signal and does not degrade performance.

The remaining 48 carriers are used to transmit data. A variety of data rates are provided so that the data rate can be optimized for the range required at any given time. The various data rates are supported by changing the amount of redundancy in the Forward Error Correction (FEC) coding, and by changing the complexity of the modulation constellation on each carrier. BPSK (6 & 9Mb/s), QPSK (12 & 18Mb/s), 16-QAM (24 & 36 Mb/s), or 64-QAM (48 & 54 Mb/s) are applied to all the data carriers to achieve the given data rates.

The center carrier, which would fall at DC in the baseband and exactly on the carrier frequency at RF, is not used. This was done to allow the use of direct conversion transceivers, which might have DC offset or carrier leakage. However, due to the +/-20ppm crystal accuracy, the DC offset can end up closer to the first data carrier, making it difficult to remove without degradation to the waveform.

OFDM has a number of advantages that make it uniquely suitable for high data rate WLANs:

- OFDM provides resistance to narrow band fading and interference.
- OFDM achieves good performance in multi-path environments, at significantly reduced computational complexity compared to other modulations that require a time domain equalizer.
- OFDM is spectrally efficient, allowing 54Mb/s data rate with a 20 MHz channel spacing.
- OFDM modulation is resistant to phase variation (group delay) across the channel.

However, there is a disadvantage to OFDM. Because OFDM is a multi-carrier modulation, the peak to average power ratio of the signal can be quite large.

OFDM Peak to Average Ratio and PA Efficiency

Since the 802.11a waveform consists of 52 carriers, its peak to average ratio can theoretically be as high as 17dB. However, such extreme peaks are in practice rare and brief. It is not necessary to preserve these extreme peaks in order to demodulate the signal correctly. Therefore, both the transmitting and receiving circuitry are allowed to clip or compress the signal during its extremes in practical OFDM transceivers.

A large peak to average ratio is most expensive to support in terms of cost and power in the power amplifier. There are three limits that must be considered when choosing the appropriate back-off of the signal from the PA's Psat: the 802.11a transmit spectral mask, the transmit signal accuracy (Error Vector Magnitude), and the regulatory out of band transmission limits. The 802.11a transmit spectral mask and the required EVM limits can be found in reference [2]. In this analysis, regulatory limits are not considered.

As a demonstration of the requirements on the PA, an idealized PA with a transfer function described by the Rapp model:

$$Vout = \frac{Vin}{(1 + Vin^{2R})^{\frac{1}{2R}}}$$

was simulated. Based on this model, the following back-offs (in dB from Psat) are required.

Table 3. Required backoff (dB from Psat)

R (Rapp co-efficient)	6-24 Mb/s	36 Mb/s	48 Mb/s	54 Mb/s
1	5	6.4	7.9	9.1
2	4	5.1	6.3	7.2
infinite	3.4	4	4.8	5.4

At the lower data rates (6-24Mb/s) the EVM required by the standard is low (-16dB), such that the spectral mask is the limiting factor. At data rates above 24Mb/s, the EVM requirement becomes the limiting factor (-25dB is required at 54Mb/s), such that larger back-offs are required.

Note that R infinite is an ideal PA with perfectly linear transfer characteristic to a hard saturation at Psat. This can be approximated in a real PA using pre-distortion or other linearization techniques.

Such large back-offs can easily result in poor efficiency. The effectiveness of three approaches to increase efficiency are shown in figure 1. In each case, some form of linearization is assumed such that each power amplifier corresponds to the ideal R = infinity transfer curve. The input signal to each PA is an 802.11a OFDM signal, scaled to provide the back-off indicated.

Receive Dynamic Range

Two types of receive dynamic range are required. The first is the dynamic range of the desired signal due to the receiver being close or far from the transmitter. This type of dynamic range requirement can be satisfied using variable gain amplifiers in an automatic gain control loop. The 802.11a specification calls for a maximum receive signal size of −30dBm and a minimum sensitivity of −82dBm. However, -20dBm to −91dBm (71 dB desired signal dynamic range) is a more appropriate signal range for quality equipment.

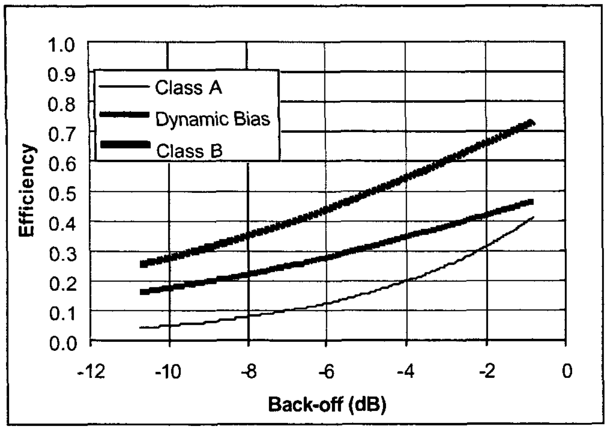

Figure 1. PA Efficiency vs. Back-off for OFDM

A second requirement is the instantaneous dynamic range. The 802.11a specification calls for blocking signals that can be 16dB stronger than the desired signal in the adjacent channel and 32dB stronger in the alternate channel. These blocking signals cannot be allowed to saturate the receiver too frequently, or the desired signal will become corrupted. Back-offs a few dB less than those shown in the table for the PA are sufficient as clipping of an adjacent or alternate signal is not as detrimental as clipping of the desired signal. In addition, the receiver is able to correctly demodulate the signal even if it has been distorted beyond the transmit EVM limit.

In addition to not saturating any blocking signals, the signal must be sized at each stage to insure that sufficient signal to noise ratio is preserved. The 54Mb/s case is the most demanding. Theoretically this signal can be received with as little as 20dB SNR. 24dB is a more appropriate practical limit. In addition, it is desirable to insure that the noise of a stage in the receive chain is not the limiting factor. The dynamic range required in the RF and IF (before the channel filter that would remove the blocking signals) can be calculated as:

$$30dB\ (SNR) + 32dB\ (blocker) + 5dB\ (backoff) = 67dB$$

This is a fairly high instantaneous dynamic range for some of the stages in the receiver. It is therefore important to have the signal optimally sized in each stage. Most designs will employ adjustable gain in nearly every stage, and control the gain of the stages intelligently from the digital baseband.

Switch losses and Attenuation

RF switches are used to switch the antenna between the transmit PA and receive LNA, and to select between two antennas for diversity. Despite the wideband nature of the OFDM signal and the redundant coding, antenna diversity can provide more than 5dB gain in link budget in typical WLAN environments. Switch loss should be as low as possible since it adds directly to the Rx noise figure and decreases the Tx power. Switch isolation of 15dB is sufficient. The transmit powers typically employed are not great enough to cause damage to the LNA with 15dB of isolation. 15dB of isolation is also sufficient to achieve nearly all the available antenna diversity gain.

THE ATHEROS AR5001X CHIPSET AND REFERENCE DESIGN

The Atheros AR5001X is a three chip set implementing the 802.11a and 802.11b WLAN standards operating at 5 GHz and 2.4 GHz. Figure 2 shows a block diagram of the solution. All three chips are implemented in 0.25um standard digital CMOS. The AR5211 baseband processor includes all MODEM and Media Access Control (MAC) functions, as well as I/Q ADCs and DACs. It is similar to the 802.11a only device described in reference [5].

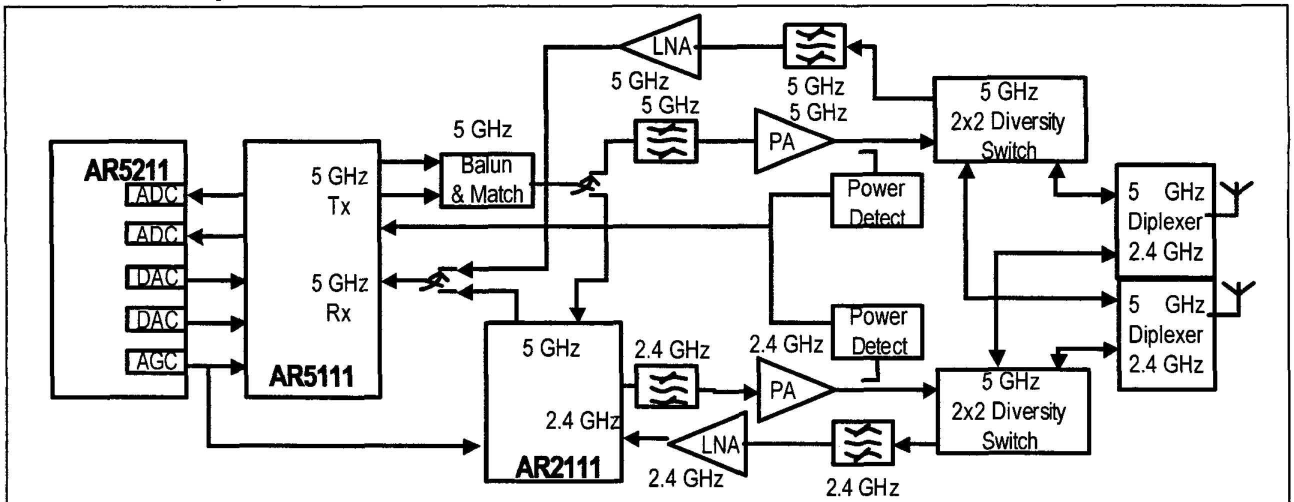

Figure 2. Block Diagram of Atheros Reference Design

AR5111 5 GHz Transceiver

The AR5111 converts the baseband signals from and to 5 GHz. This chip includes two frequency conversion steps, with adjustable gain and on-chip filtering in all frequency domains. The receive gains are adjusted digitally from the baseband chip. The VCO, synthesizer, and crystal oscillator are all on chip. The VCO uses on-chip spiral inductors and does not require any off-chip components. A transmit power control loop is provided that can connect to an off-chip power detector. The chip includes an LNA with 6 dB NF, and a PA that can deliver +22 dBm Psat. The PA is included due to the relative scarcity of inexpensive 5 GHz PAs.

However, in the reference design presented in this paper, an off-chip PA and discrete LNA were added to enhance performance. The PA is a commercially available two stage InGaP HBT MMIC. It provides 20 dB gain and has Psat=26 dBm. The LNA is a discrete enhancement-PHEMT with 1 dB NF and 13 dB gain at 5 GHz.

AR2111 2.4 GHz Transceiver

The AR2111 can be added if operation in the 2.4 GHz band is desired. It converts the 5 GHz signals from/to 2.4 GHz. It also has transmit and receive variable gain, controlled digitally from the baseband chip. It includes a synthesizer and VCO. As in the AR5111 only the synthesizer loop filter elements are required off-chip. The on-chip 2.4 GHz LNA has a noise figure of 4.5 dB. The AR2111 does not include a PA. The output signal from the chip is roughly +7 dBm, so a separate PA IC is required. This design decision was based on the availability of a wide variety of 2.4 GHz PAs at attractive prices. In the reference design presented here, the external PA is a commercially available two stage InGaP HBT, similar to the device used at 5 GHz. It provides 25 dB gain and has a Psat of 27dBm. A 2.4 GHz off-chip LNA is also added to improve receiver sensitivity in the reference design. It is a SiGe discrete BJT, providing 12 dB gain and 1.1 dB NF.

RF Discretes

The remaining RF circuitry required on the board includes Tx/Rx and diversity switches implemented using commercially available low capacitance PIN diodes in low inductance plastic packages. The off-chip power detectors are implemented using printed directional couplers and zero bias Schottky diodes. The diplexers use a combination of discrete components and printed structures, as does the matching to the chip. There are also LTCC bandpass filters for both the 2.4 GHz and 5 GHz band. The chip outputs are differential, so discrete ceramic baluns are employed in the transmit paths.

Reference Design Results

The solution has been implemented on a mini-PCI card in a total area of 22 cm2. The overall receiver NF is 4.5 dB at 2.4 GHz and 5.5 dB at 5 GHz. Psat at the antenna port is 23 dBm at 2.4 GHz and 22 dBm 5 GHz. The following table summarizes system results for 802.11a at 5 GHz.

Table 4. AR5001X Chipset Reference Design Performance

	6Mb/s	54Mb/s	108Mb/s
Sensitivity (dBm)	-91	-73	-70
Average transmit power (dBm)	+18	+14	+14

In 5 GHz 802.11a mode, the power consumption of the reference design breaks down as shown in table 5. Note the large amount of power consumed by the PA when transmitting:

Table 5. 802.11a Power Consumption

	AR5211 (digital and data converters)	AR5111 (RF and baseband analog)	Discrete RF (PA, LNA, Switches)	Total
Transmit (mW)	380	562	749	1691
Receive (mW)	483	291	99	873

CONCLUSION

The WLAN market is rapidly migrating towards 5 GHz and 802.11a to achieve higher data rates and greater capacities. The chipset and reference design presented in this paper is a highly integrated, low cost design that fits on one side of a mini-PCI card. To our knowledge, this is the first 802.11 dual band, dual mode WLAN solution. In addition, it is the first wireless LAN implementation to achieve greater than 100Mb/s raw data rate.

REFERENCES

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