A Compact 5-6 GHz T/R Module Based on SiGe BiCMOS and SOI that Enhances 256 QAM 802.11ac WLAN Radio Front-end Designs

Chun-Wen Paul Huang, Mark Doherty, Lui (Ray) Lam, Anthony Quagliaetta, Mark Johnson, and Bill Vaillancourt

Skyworks Solutions, Inc., Andover, MA 01810, USA

Abstract — A compact high linearity 4.9-5.9 GHz T/R FEM is presented, which consists of a SiGe BiCMOS PA and a SOI switched LNA realized in an ultra-compact 2.3 x 2.3 x 0.33 mm³ QFN package. The Tx chain has > 30 dB gain and meets -35 dB DEVM up to 17 dBm at 3.3 V and 20 dBm at 5V, insensitive to modulation bandwidths and transmission data length up to 4 mS. With digital pre-distortion (DPD), the PA can be down-biased to save 30 mA while maintaining its linearity. The Rx chain features <2.5 dB NF and 12 dB gain with 4 dBm IIP3 and 8 dB bypass attenuator with 29 dBm IIP3. All the unique features enhance the front-end circuit designs of complex 802.11ac radios.

Keywords- WLAN 802.11ac front-end ICs, PA design, T/R switch designs, LNA designs, WLAN front-end module.

I. INTRODUCTION

In recent years, the applications of wireless local area networks (WLAN) have been one of fastest growing areas in data communications. Originally, WLAN radios were designed for computer networking, but currently WLAN has been used in many other communication electronics [1]. The demands of more bandwidth and higher throughput rates result in the development and applications of multiple-input multiple-output (MIMO) techniques to increase the data rate from the original 54 Mbps of a single-input single-output (SISO) radio to a minimum of 108 Mbps. For further demands of wider bandwidths and higher data throughput, the 802.11ac standard can provide up to 780 Mbps per transmit/receive path. When 802.11ac radios operate in MIMO modes, the data rate can be up to 6 Gbps [2]. The early generations of WiFi and MIMO radios operate in the 2.4-2.5 GHz b/g band. With the continually increasing demands for bandwidth and higher data throughput rates, dual-band WLAN radios are widely adopted in recent computers and portable communication electronics [2]. The main reason for using dual-band WLAN radios is the high band (a-band) radio operating at 4.9-5.9 GHz, which provides more frequency channels. In addition, dual-band WLAN radios support concurrent operation, allowing the low and high band radios simultaneous operation that results in significantly increased data throughput.

As shown in Fig. 1, the low and high band paths can be combined with a diplexer to increase selectivity of each band prior to connection to the dual-band antenna. The dual-band MIMO front-end (FE) design can be realized by the repetition of the topology shown in Fig. 1. To simplify radio designs, the FE circuit can be realized with 3 building blocks and a diplexer as shown in Fig. 1. In addition, the embedded WLAN radios in portable electronic devices require more compact and integrated designs than a WLAN radio used in computer networking applications. In fact, a front-end module (FEM) is often the preferred design implementation. Specifically in cases where MIMO is used in portable electronics, FEMs can simplify the design and radio printed circuit board (PCB) layout and reduce the number of components in a multi-channel MIMO configuration.

Fig. 1. Block diagram of a dual-band WLAN radio

Fig. 2. The high linearity 4.9-5.9 GHz 802.11ac FEM in a 2.3 x 2.3 x 0.33 mm³ QFN package.

To increase the FEM design versatility, system requirements should be included in design considerations. For PC networking applications, there are often two power supply voltages available in the system, 3.3 V and 5.0 V. For embedded and mobile applications, the power supply can be sourced from the transceiver chip-sets or the battery. Moreover, for battery operation, the voltage can vary from...
the PA is frequently enabled and disabled by a pulsing trigger to reduce current consumption which introduces the problem of dynamic variation in the amplifier’s key figures of merit including linearity and gain [3]. The amplitude distortion of the preamble in the first few microseconds of the amplified data stream will result in degraded modulation quality [3]. The PA design herein employs patented methods [4] and circuit techniques to mitigate the thermal difference between PA stages, which results in no degradation in both linearity and gain under dynamic mode operations.

As shown in Fig. 3, one of the challenging tasks in SiGe PA design is the on-chip matching networks. The use of measurement based transistor models and large-scale electromagnetic-based models can significantly enhance the accuracy of design simulations. The out-of-band rejection filtering is well integrated in the input matching network and 1st and 2nd stage inter-stage matching networks. The L-C networks of a dual-pole matching network will also effectively reduce the harmonic emissions.

The switched LNA consists of a SPDT switch and a LNA with a bypass mode attenuator. The SPDT switch schematic, shown in Figure 4 is architected to support high linearity and low loss RF paths.

During high data throughput WLAN communications, the PA is frequently enabled and disabled by a pulsing trigger to reduce current consumption which introduces the

3.0 V to 4.8 V. Therefore, the FEM is preferred to operate for a wide supply voltage range.

In this paper, a compact highly linear a-band transmit and receive (T/R) module is presented (see Fig. 2). The FEM is implemented in a 2.3 x 2.3 x 0.33 mm3 QFN. The functional block diagram of the design is illustrated in Fig. 1. The design consists of a single-pole-double-throw (SPDT) T/R switch, a PA, and a LNA with a bypass attenuator. The switch-LNA is realized with Silicon-on-Insulator (SOI) technology, which combines both advantages of CMOS FETs for digital circuitry and low substrate loss RF FETs for the T/R switch design. The PA is based on SiGe BiCMOS, which integrates CMOS control circuitry for the PA and includes SiGe HBT for the PA RF power transistors. The SiGe PA integrates all matching networks, filters, regulator and bias circuits, power detector, and CMOS compatible enable circuitry. In addition, the PA is controlled by an on-chip temperature and voltage compensated bias controls. The Tx path operates from 4.9 to 5.9 GHz and delivers > 30 dB of gain. When testing against 802.11ac requirements, the Tx path can deliver > 17 dBm at 3.3V with current consumption < 190 mA and > 20 dBm at 5V with current consumption < 240 mA meeting the linearity requirements of dynamic mode error vector magnitude (DEVM) < -35dB. In addition, theTx path is also insensitive to duty cycles and modulation signal bandwidths used in 802.11n and 802.11ac communications. Furthermore, in contrast with the traditional data transmissions of a few hundred microseconds, the design supports long data transmissions up to 4 mS without degradation in linearity. With implementation of digital pre-distortion (DPD) in the transceiver, the FEM can reduce bias current by 30 mA and maintain the same linearity. As for the Rx path, the FEM features 12 dB gain from 4.9 to 5.9 GHz with noise figure (NF) < 2.5 dB and 8 mA current consumption. The Rx path also has an 8 dB bypass attenuator of 29 dBm input third order intercept (IIP3), which prevents the receiver from over-stress under high field illumination. All these unique features significantly simplify the dual-band 802.11ac radio front-end designs.

II. DESIGN

The FEM design is illustrated in the following 2 subsections.

A. SiGe BiCMOS PA

As shown in Fig. 3, the PA is a 3-stage amplifier. A major consideration for using a 3 stage a-band PA is that most 802.11ac transceivers cannot deliver sufficient linear output power directly to the antenna. Insertion of a high gain PA before the antenna allows the transmitter to operate at the linear output levels. In this design, the PA is managed by an integrated CMOS controller providing the reference currents for current mirrors, DPD modes, and on/off control.

During high data throughput WLAN communications, the PA is frequently enabled and disabled by a pulsing trigger to reduce current consumption which introduces the
of the LNA in the presence of high level receive signals, an 8-dB bypass attenuator is implemented in the dashed line box in Fig. 5.

![Conceptual schematic of the a-band LNA design.](image)

Fig. 5. Conceptual schematic of the a-band LNA design.

### III. PERFORMANCE

Measurements of the FEM are presented in this section. Fig. 6 shows the S-parameters of transmit and receive paths. The gain variation over frequency is within 2 dB for the Tx path and within 1 dB for the Rx path with >30 dB and >12 dB of gain, respectively. Linearity of the transmit path is validated using an 80 MHz 256 QAM 802.11ac VHT80 signal at 433 Mbps and under dynamic mode. As shown in Fig. 7, with a 3.3V supply, the transmit chain delivers >17 dBm at -35 dB dynamic EVM with 190 mA current consumption. The scalability over supply voltage is shown in Fig. 8. The Tx path linearity can be effectively scaled with the supply voltage and can deliver 20 dBm at -35 dB DEVm with 240 mA current consumption. Typically, it is a design challenge to maintain the linearity over a wide supply voltage due to the matching impedance dependency of each stage on the supply voltage.

To support 802.11ac radio FE designs, the PA is also required to be insensitive to various modulation bandwidths and data rates. The design is validated with a 20 MHz MCS7 HT20, a 40 MHz MCS7 HT40, and an 80 MHz MCS9 VHT80 test signals as shown in Fig. 9. The variations between modulations are only observed at the DEVm level below -40 dB. Another important application for an 802.11ac radio is the use of long data transmission, which can increase the data throughput rate. The Tx path is tested against the regular data length of a few hundred microseconds and a 4 mS long data length at both 3.3 V and 5V. The measured Tx path showed no significant degradation between the short data and long data length transmissions. When the PA is transmitting a long data frame, the transient gain of the PA will vary with time due to the transistor junction temperature rising with time. The integrated CMOS controller effectively compensates the PA temperature changes, minimizing impact on linearity.

Typically, PA designs for 802.11ac applications are biased at higher current density to achieve low back-off DEVm. Recently, numerous studies in digital pre-distortion techniques were done for 802.11n radios. The initial study of DPD effects on the design for 802.11ac applications is shown in Fig. 11. In Fig. 11, the comparisons of DEVm at MCS9-VHT80 and associated Icc were made between the original design, the design with a 30 mA lower bias, and the 30 mA lower biased design with DPD compensations. When the PA is down-biased by 30 mA, the linear power meeting -35 dB DEVm is degraded by 1 dB from that of the original design. With the DPD compensation, the design can operate at 30 mA lower bias current and remain the same linearity as that of the original design.
Fig. 9. Measured dynamic EVM versus various modulations.

Fig. 10. Measured dynamic EVM of the FEM of various data lengths at 3.3 V and 5 V.

The Rx path has 12 dB gain and NF < 2.5 dB with the current consumption of 8 mA. Due to the on-chip out-of-band rejection filter, the band selectivity between b/g band and a-band is measured > 25 dB, which provides the immunity from a b/g band jamming signal level up to 10 dBm without any degradation of the 5-6 GHz in-band NF. The input 1dB compression is measured at -4 dBm for the LNA mode. The bypass path attenuation is 8 dB with a current consumption of 15 uA. The IIP3 of the bypass attenuator is measured >29 dBm.

Fig. 11. Measured dynamic EVM and current consumption with and without digital pre-distortion.

IV. Conclusions

In this paper, a compact high linearity 4.9-5.9 GHz WLAN FEM for emerging 802.11ac applications is presented and realized in a 2.3 x 2.3 x 0.33 mm³ QFN package. The PA is based on SiGe BiCMOS process and the switch LNA is based on SOI process. With a 3.3 V supply, the transmit achieves >27 dB gain with >17 dBm output power at -35 dB DEVM with MCS9 VHT-80 test signals, while consuming <190 mA. Similarly, with a 5 V supply, the FEM achieves -35 dB DEVM power at 20 dBm with 240 mA of current. The receive path has an integrated 12 dB LNA with <2.5 dB NF with IIP3 of 3 dBm and an 8-dB bypass attenuator with IIP3 of 29 dBm. All these unique features of the design greatly simplifies dual-band radio FE designs and enables the reduction of the radio board form factor and consequently results in simple constructions of complex dual-band MIMO radios for 802.11ac applications.

REFERENCES


