A 60nm WiFi/BT/GPS/FM Combo Connectivity SOC with Integrated Power Amplifiers, Virtual SP3T Switch, and Merged WiFi-BT Transceiver

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***Abstract* — A highly integrated WiFi/BT/FM/GPS connectivity combo SOC is implemented in a 60nm CMOS process. This work presents the proposed WiFi/BT merged RF transceiver, a virtual SP3T switch, and DPD algorithm to save chip area, reduce BOM and enhance performance simultaneously. The WiFi/BT/FM/GPS RF transceiver areas are 1.7/1.3/0.8/1.0mm^2, respectively. The measured WiFi 11g 54Mbps RX sensitivity is -78dBm and Pout is 20dBm with EVM of -28dB. The measured BT GMSK RX sensitivity is -94dBm and Pout is 10dBm. FM sensitivity is -110dBm and GPS cold/hot-start TTFF sensitivity is -148/-163dBm.**

***Index Terms* — WiFi, BT, SP3T, coexistence, connectivity combo SoC, RF SOC.**

I. Introduction

In recent years, a significant growth in smart phones and tablets has been observed. These mobile devices provide users with ubiquitous wireless connections to the internet and many amazing new applications. The new applications require radios operating simultaneously to provide users a good experience. Meanwhile, the users prefer acquire compact mobile devices which motivate IC designers to reduce form factor and integrate connectivity radio functions onto a single SoC. However, coexistence becomes more challenging when multiple radios are co-located on the same small die. In this work, several techniques are used to ensure simultaneous operation among the four different radios including non-overlapping VCO frequency planning, power supply RC-filtering techniques for all aggressors such as DACs/ADCs, and layout considerations for reinforcing return current paths. Field-cancelling inductors are also used to minimize magnetic coupling on the SoC. In addition to electrical effects, thermal effects due to the integrated WiFi PA need to be addressed to minimize its impact on the frequency-precise GPS system.

Figure 1 shows the combo SoC block diagram, which is a 60nm CMOS connectivity combo SoC integrating WiFi/BT/FM/GPS RF transceivers supporting 2.4GHz WiFi 802.11 bgn applications, BT 2.1+EDR, FM radio with long/short antenna support, and GPS. Also integrated are the digital baseband modems, a shared processor, power management units including a SMPS and LDOs, a XTAL oscillator, and numerous interfaces to support a variety of standards. Among different radio co-existence scenarios, WiFi/BT is the most challenging case since they operate in the same 2.4GHz ISM band. Although BT and WiFi can operate concurrently by separating their operating frequency by 25MHz under specific BT/WiFi power levels for higher throughput [1], the crowded spectrum and limited user scenarios make concurrent operation impractical and suggest that the scheduled coexistence of 2.4GHz WiFi/BT is preferred, especially in mobile devices. To obtain optimal throughput performance in nonconcurrent mode, a technique of scheduled coexistence mode (SCM) is applied to schedule WiFi and BT traffic to avoid RF signal collision, as illustrated in Fig. 2. SCM dynamically adjusts the scheduling of BT and WiFi packets based on packet type and minimizes packet collision. Since BT supports audio/video applications, it warrants higher priority and WiFi utilizes the idle period of BT to transmit/receive its data packets. In this work, WiFi and BT do not operate simultaneously; therefore they can share a single antenna, and the RF transceivers can be merged extensively without sacrificing throughput performance.

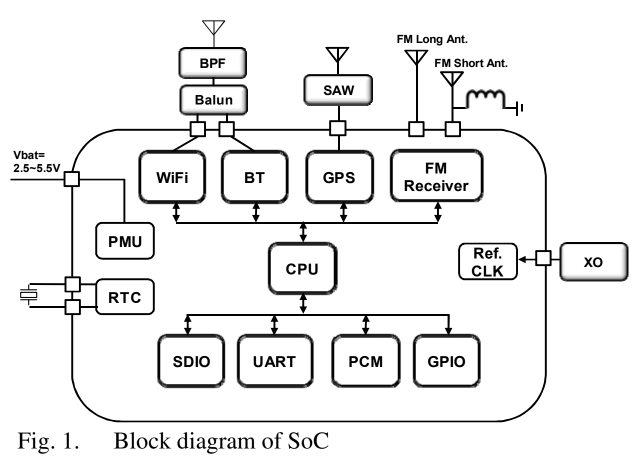

Fig. 1. Block diagram of SoC

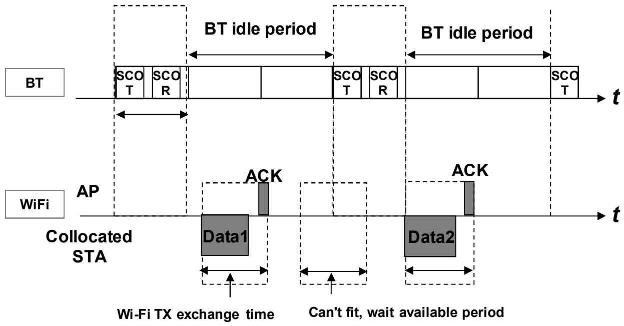

Fig. 2. Illustration of WiFi/BT scheduled coexistence mode

II. MERGED WIFI-BT RF TRANSCEIVER

Figure 3 shows the WiFi-BT merged transceiver architecture, in which BT RX/TX architecture is Low-IF/DCT and WiFi RX/TX architecture is DCR/DCT, respectively. Since BT and WiFi do not work concurrently, some BT/WiFi transceiver functions can be combined. Considering the frequency synthesizer (SX) takes the longest calibration time which impacts throughput performance, BT and WiFi still utilize individual SXs for shortest WiFi/BT turn around time. For instance, during the WiFi packet duration, the BT SX can be turned on in advance to finish VCO frequency calibration for its assigned BT channel. Fig. 3 also shows a shared LOGEN circuit which supports two different fractional numbers to generate the required LO signals complying with two different VCO frequency plans. To avoid coupling and reduce current consumption, MUX functions are embedded in the divider and mixer circuits themselves. In this work, the BT VCO runs at 8/5 LO frequency while the WiFi VCO operates at 8/3 LO frequency. The BT LO is generated by DSB mixing while the WiFi LO is generated by SSB mixing. Because BT LOGEN uses DSB mixing, the image tone cannot be attenuated by I/Q signal combination. With the mentioned frequency planning, the image tone is far away from the wanted signal and the LOGEN LC tank provides adequate rejection to suppress it. The generated LO signals are divided-by-two locally to create the wanted LO I/Q signals. Upon the start of the BT period, the front-end and LOGEN will be configured into BT mode and is able to transmit/receive BT packets immediately to obtain the best throughput performance.

The receiver front-end comprised of LNA, Mixer, TIA, and RXDIV2 is completely shared by WiFi and BT systems. The LNA uses an inductive load ac-coupled to a current-mode passive mixer with 25% duty cycle LO to attain high-linearity, sustaining strong close-in interferers and far out-of-band cellular blockers. For BT mode, the down-converted current is converted to voltage by the complex BPF. In WiFi mode, a TIA is used to convert current to voltage and a wideband RSSI ADC digitizes the TIA output for fast AGC RX. Because the output power requirements of BT and WiFi are very different, two separate PAs are designed for BT and WiFi respectively. For WiFi TX, the IQM and PGA are designed as a cascode structure to reduce power consumption and area simultaneously, as shown as Fig. 4. The proposed IQMPGA provides 24dB gain control range with steps of 6dB within +/-1dB accuracy. In conjuction with an on-chip TX power detector, this work can deliver TX output power with accuracy of +/-0.5dB over process and temperature. WiFi TX also implements "per packet" power control to maintain the throughput performance against TX power variation over different scenarios. For BT TX, the IQM uses a current-mode folded Gilbert mixer to get optimal linearity performance with a supply of 1.3V. The measured WiFi/BT RX NF with embedded SP3T switch is approximately 4/5.5dB, while measured WiFi PA Psat is +26.5dBm and BT TX OP1dB is 12dBm.

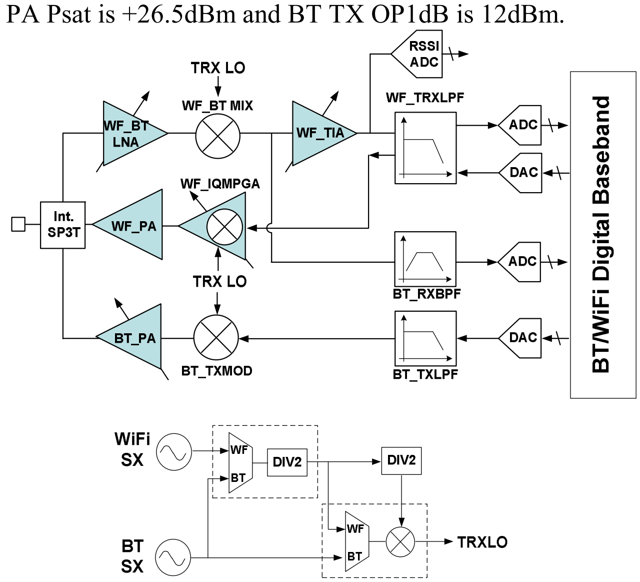

Fig. 3. Shared WiFi-BT RF transceiver architecture

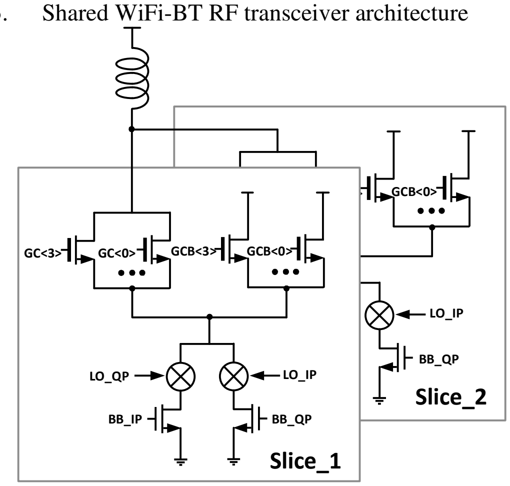

Fig. 4. WiFi cascoded IQMPGA topology

III. ON-CHIP VIRTUAL WIFI-BT SP3T

Conventional BT and WiFi transceivers use multiple RF IO ports and an external Single-Pole-Three-Terminal (SP3T) switch to connect BT and WiFi to share a single antenna, as shown in Fig. 5(a). However, the external component is expensive, occupies large PCB area, and requires many control signals. In this paper, a proposed virtual SP3T switch is presented to remove the external component. The design of an on-chip switch is required to handle the large swing of the high-power WiFi PA and provide low insertion loss to not degrade RX NF and TX output power. Moreover, the PA and LNA require different impedances to obtain optimal PA efficiency and LNA NF. As depicted in Fig 5(b), the different impedance requirements can be achieved by adding series capacitors C_{pi}, shunt switches of core devices, and a transformer, which act as an impedance-transformation network in front of the BT/WiFi LNA. At WiFi TX mode, pull-down switches are "ON" and C_{pi} becomes part of the TX matching network. The advantage of the proposed switch is the pull-down switches can be implemented with core devices because the switch impedance is small and does not sustain a large voltage stress. Therefore, there is no power handling issue for the proposed topology at WiFi TX mode. At WiFi RX and BT TX/RX mode, pull-down switches are "OFF" and the transformer resonates out the heavy parasitic capacitors of WiFi PA and performs impedance transformation simultaneously. The impedance after the transformer is 150ohm. The transformer provides higher source impedance to the LNA input to obtain lower NF in RX mode, while the BT PA acquires better power efficiency simultaneously.

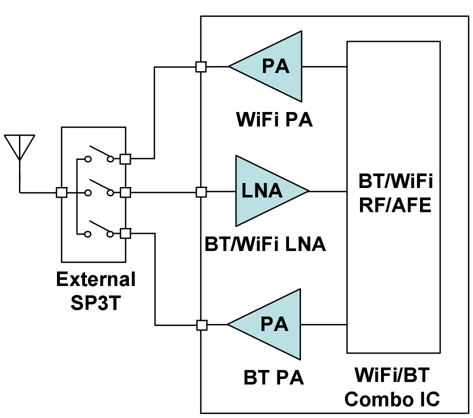

Fig. 5(a). Conventional WiFi/BT with external SP3T

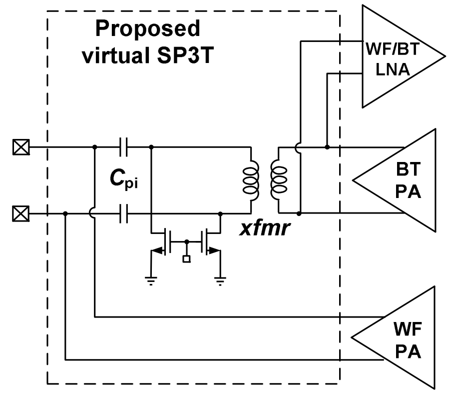

Fig. 5(b). Proposed virtual SP3T topology

IV. LINEARIZED WIFI PA WITH DPD

Within this work, many digital-assisted calibrations are implemented to maintain performance over process/ voltage/temperature (PVT) variations. One of the key calibrations is the technique of digital pre-distortion (DPD). As in most TX designs, its power consumption is dominated by PA. For a mobile device, it is highly desirable to integrate the WiFi PA to reduce the form factor; but the power efficiency must be improved. Due to the high Peak to Average Power Ratio (PAPR) in OFDM signals, a linear PA is needed. However, the PA needs to operate in its non-linear region to attain high power efficiency. To compensate the non-linearity caused by the PA operating in its non-linear region, a DPD algorithm is implemented. In brief, the PA non-linearity can be modeled with its AM-AM and AM-PM curves, which represents amplitude and phase distortions respectively. To get the non-linear characteristics of the PA, a closed-loop scheme is designed with a dedicated loopback path from the PA output to RX as shown in Fig. 6. During power-on, the closed-loop calibration will be executed. While doing the PA DPD calibration, pre-defined ramp signals are generated from the digital baseband, pass through PA and loopback path, and are finally recorded after RX ADC. Comparing the difference between the transmitted and received signals, the amplitude and phase compensation values are obtained and stored in the AM-AM and AM-PM tables. During transmission mode, the digital output signals will be pre-distorted based on the tables to pre-compensate for PA non-linearity. By applying DPD, PA performance is limited by Psat rather than OP1dB. Based on PA RAPP model, the theroretical improvement of DPD is around 3.5dB. In this work, the WiFi PA after DPD achieves a maximum HT20 MCS7 TX output power of +20dBm with EVM of -30dB and consumes 583mW.

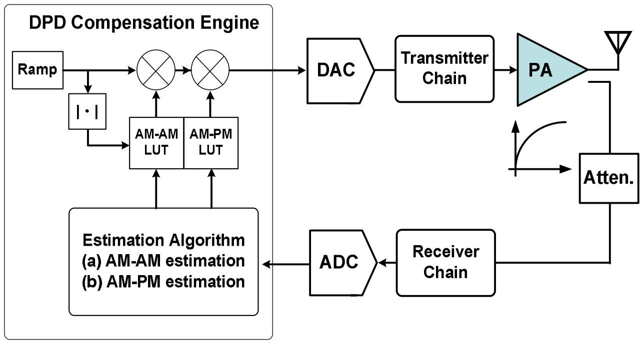

Fig. 6. Illustration of a Closed-loop DPD

V. MEASUREMENT RESULTS

The 4-in-1 combo SoC, packaged in WLCSP with direct bumps, is implemented in a 60nm CMOS technology and occupies 17.3mm^2. The WiFi/BT/FM/GPS RF transceiver areas are 1.7/1.3/0.8/1.0mm^2, respectively as shown in Fig. 7. The key performance metrics for the WiFi/BT/FM/GPS radios are summarized in Table I. Fig. 8 shows the measured Pout v.s. EVM of WiFi PA with and without DPD. It shows 3dB improvement for Pout at EVM of -30dB under the same PA current consumption. This translates to 33% lower current and improves the PA efficiency from 12% to 18.2% with DPD. For 11g compliant EVM of -25dB, the WiFi PA can deliver an output power of 21dBm, which PAE is 25.2%.

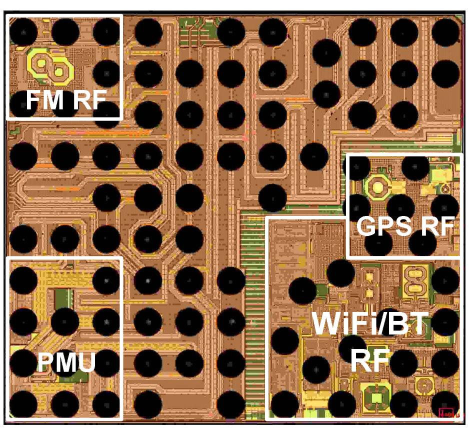

Fig. 7. Die photo of the combo SOC

VI. CONCLUSION

This paper presents a 60nm WiFi/BT/FM/GPS connectivity combo SOC. With careful design considerations of coexistence and desense, this work demonstrates the performances of the four radios are not compromised under concurrent operations. This work also presents the proposed virtual SP3T switch and DPD algorithm to reduce BOM and enhance performance simultaneously.

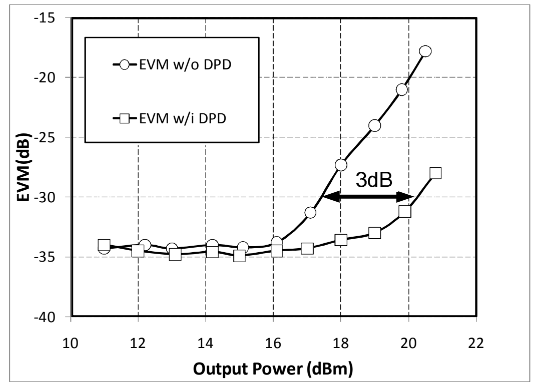

Fig. 8. WiFi TX EVM w/i v.s. w/o DPD

TABLE I
PERFORMANCE SUMMARY

Sub-Sys	Parameter	[2]	[3]	This work	Unit
WiFi RX	11g 54M Sensitivity	-76	-74	-78	dBm
	RX mode Current	72	137	46.8	mA
WiFi TX	11g 54M Pout w/i TX EVM of -25dB	21*	21*	21*	dBm
	11g 54M Current w/o PA	81	88	32	mA
	11g 54M PAE w/i TX EVM of -25dB		19.7	25.2	%
BT	RX BDR Sensitivity	-92	-	-94	dBm
	RX mode current	21	-	26.3	mA
	TX BDR Pout	14	-	10	dBm
	TX BDR current w/o PA	33	-	22.3	mA
FM	Sensitivity	-107	-	-110	dBm
	Current	10.8	-	10	mA
GPS	Cold/Hot-start TTFF Sensitivity	-	-	-148/ -163	dBm
	Cold-start TTFF	-	-	12.4	sec
	Hot-start TTFF	-	-	0.4	sec

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