Integration Creates Compact CDMA RF Front End with GPS Capability

AVAGO TECHNOLOGIES

White Paper

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Objective

The worldwide cell phone market is large and very competitive. Even during the 2009 economic downturn, forecasts for worldwide cell phone shipments are expected to reach 1.1 billion units with over 300 million shipments in the final quarter of 2009[1]. Consumers now demand long talk-time in tandem with more capability, such as GPS and multimedia. Selecting a long-term, reliable vendor with the best technology and system knowledge that can integrate the technology into a compact, low-cost design is essential in the fast moving mobile communications market where a missed market cycle can lead to lost market share.

In this whitepaper, design requirements, best practice PCB layout, component selection and system design will be addressed. A highly integrated CDMA plus GPS RF front end design with measured performance characteristics will be used as a concrete example. The three Avago RF modules used are: the ACPM-7353 dual-band Power Amplifier Module designed for CDMA (code division multiple access) cellular and PCS; the ACFM-7103 multiplexer; and the ALM-1412 GPS Low Noise Amplifier (LNA) with Integrated Filter. These three compact components replace seven discrete components.

The Avago component module pinout configurations are arranged to match the Qualcomm QSC60X5 chipset.

Introduction

Mobile handsets have always been amongst the most complex electronic systems, but today the complexity has a new dimension since many RF radios must be packed into an ever shrinking footprint. The 21st century designer must create a solution that puts multiple RF bands and protocols into a lightweight, compact and attractive package that consumers will place their trust in for business and personal use – how can this be accomplished?

Shrinking the individual radio components is an obvious step. It is dependent on the specific supplier's semiconductor process technology capability and experience. System integration of the individual building block components is an especially rich area for mobile communication device designers to consider as it can maximize the overall end-product customer value.

The reasons for integration have been well documented. Besides the actual space savings, there is also improved performance and less engineering effort. The whole design process is shortened and manufacturing and part procurement simplified. Faster time-to-market usually means greater market share and better financial results. An ideal situation may be a single plug-and-play module containing the entire RF front end that the system designer can just drop onto a PC board. One already successful example mirroring this goal is in the Wi-Fi area. Today, complete dual-band 802.11 a/b/g/n Wi-Fi front ends exist in single modules as small as 4 mm x 6 mm, just 24 mm^2. These modules contain the entire RF front end, including the power amplifier, low-noise amplifier, filters and switches all on a single substrate. These are true "plug-and-play" solutions between the RF integrated circuit (RFIC) and the antenna. Adoption of these modules is almost mandatory for all laptops and netbooks.

Complete circuit integration of CDMA (Code Division Multiple Access) and UMTS (Universal Mobile Telecommunications System) RF mobile handset front ends are not as advanced as current Wi-Fi front ends. One of the reasons for this is that the subcomponents of the UMTS RF front end are still changing and being refined. In addition there is a geographic, region-specific component to solutions as well. There are also semiconductor technology issues that limit complete integrated solutions.

The CDMA RF front end, however, is fairly standardized in North America as dual band PCS and Cell band, plus GPS (Global Positioning System) capability. Integrated module solutions have the potential to be widely implemented just as in the Wi-Fi case by suppliers with, or access to, advanced semiconductor processes capable of high volume manufacturing.

Integration Paths and Strategy

The two possible paths for RF integration are by-band, which combines a power amplifier and duplexer for a single band, or by-technology, which combines power amplifiers in a single module and filters in modules. Both provide the benefits of saving space and simplifying design, but the by-technology approach can also provide performance improvements through pin-map optimization. Of the two choices, integration by-technology has proven to be the most common solution in today's mobile phones.

There are fewer suppliers available, however, that actually have both power amplifier and filter capability in-house along with the expertise to integrate them together in a reliable system solution. A vendor must have good technical support and understand your system requirements and testing as well.

The design process and system performance expectations can best be discovered by reviewing an actual integrated CDMA RF front end with GPS capability. The design discussed here uses three highly integrated RF modules that take the place of seven discrete components found in less integrated designs.

Discrete Solutions vs Integrated Solutions

A typical discrete solution for a CDMA front end consists of seven RF components: PCS duplexer, Cell duplexer, triplexer, PCS PA, Cell PA, GPS LNA, and GPS filter as shown in Figure 1a. When used in combination with the Qualcomm QSC 60X5 series module, the average PCB space needed is approximately 525 mm2 or 0.81 in^2. It is a somewhat compact solution but not ideal, and there are several practical problems created by the implementation that would need to be overcome.

The first issue is of PCB line routing. Due to component placement and pinout, there will be RF traces crossing each other which then require inner layers of the PCB be used for routing. A transition from the microstrip lines used on the top layer of the PCB to more lossy striplines in the inner PCB layers increases total RF system loss. The large area also results in longer RF line traces which increase RF loss too. Lastly, the long crossing lines increase the possibility of receiving interference from other noise sources on the PCB, thus degrading system performance or causing reliability issues.

The Three-module Integrated Solution

Figure 1b shows the integrated solution with three modules replacing seven discrete components. This integrated solution requires a low 390 mm^2 or 0.6 in^2 of PCB space, about a 25 percent area savings over the discrete component solution. In a mobile product this is a substantial area use reduction. The integrated solution has fewer components and the pinout for each module has been optimized for the chipset pinout, reducing design and layout time.

In the integrated solution, the Avago ACPM-7353 is a 4 mm x 5 mm dual band, PCS plus Cell, power amplifier built with Avago's CoolPAM™ technology. It features a new bypass mode option for best-in-class current consumption at low output power.

The ACFM-7103 is Avago's third generation (PCS + Cell + GPS) FBAR (Film Bulk Acoustic Resonator) 4 mm x 7 mm multiplexer. It offers a 30 percent size reduction compared to previous generations and a new option that allows the multiplexer to be used with either single or dual antennas for increased design flexibility. In addition, the superior insertion loss and isolation performance results in "best-in-class" talk-time and system sensitivity.

The ALM-1412 is an industry-first, 3.3 mm x 2.1 mm GPS LNA-Filter module that integrates a pHEMT LNA and an FBAR filter together for low noise figure, high linearity and excellent out of band rejection. This integrated solution offers improved talk time, sensitivity, blocker immunity, and improved GPS sensitivity when compared against the discrete solution. If there is a single standout performance metric it is PCS sensitivity with Avago's integrated solution, an industry best sensitivity of -108 dBm minimum. Each of the Avago integrated modules has been designed with total system requirements in mind.

Good System Design Increases Talk Time and Minimizes PCB Area

As shown by use models for urban areas with dense base station coverage, the majority of the time handsets do not need to operate at high power. Technology that can take advantage of this fact gives consumers more talk time. For example, the Avago ACPM-7353 PA achieves higher efficiencies with its CoolPAM™ technology that bypasses various power stages in the PA to reduce current consumption at low output power. CoolPAM technology implements active stage bypass without using bulky and expensive RF switches – a significant design advancement. Operating models predict that by using CoolPAM technology talk time can be improved by 20 minutes.

The fifth generation CoolPAM technology has three operating modes: bypass, mid-power, and high power. In bypass mode, the driver and PA stages are inactive and only the Active Bypass Network is used. In this mode quiescent current is approximately 4 mA. In mid-power mode, only the driver stage of the amplifier is active. High power mode uses all stages of the PA.

In addition, the ACPM-7353 dual-band PA uses 20 percent less PCB area than the discrete component solution. The ACPM-7353 takes the place of two components in the discrete solution..

The Avago ACFM-7103 quintplexer combines PCS and Cellular band duplexer functions with a GPS filter, and it greatly simplifies handset the RF design for simultaneous voice service and GPS positioning. By integrating the PCS duplexer, Cell band duplexer, GPS filter and triplexer together, component count is cut and PCB area is conserved. The ACFM-7103 uses Avago's Film Bulk Acoustic Resonator (FBAR) technology, and Microcap bonded-wafer chip scale packaging technology. The module footprint is only 4 mm x 7 mm and the maximum height is 1.2 mm.

Insertion loss (IL) improvement is one of the main benefits of the integrated multiplexer. The transmit (Tx) IL has a direct relationship to battery life, while the receive (Rx) IL has a direct impact on receiver sensitivity. In the discrete solution, the triplexer contains high pass and low pass filters and a GPS band pass filter.

With discrete duplexers, triplexer loss, discrete duplexer loss and line loss all cascade together. An FBAR multiplexer uses a phase and impedance matching networks to link the filters together. This results in less RF loss than the triplexer solution. Compared to SAW based devices, FBAR filters have superior Q values and out-of-band rejection.

The Avago multiplexer's typical PCS Tx IL is 1.5 dB (3.1 dB maximum). The Tx IL means less transmit power is required and this can reduce current consumption by 50 mA to 70 mA. Battery life is improved.

The excellent Rx IL for PCS, 1.6 dB typical, and Rx IL for Cell band, 1.4dB typical, improves receiver sensitivity by 0.7 dB to 1 dB over the discrete solution. In addition, all the phase matching to the triplexer is integrated, further simplifying the design.

The integrated LNA filter module is used with the GPS pre-LNA filter in the multiplexer. The EpHEMT LNA allows can be operated from a single supply down to very low voltages while the highly desirable properties of traditional pHEMTs, such as low noise figure, high linearity and gain are maintained. FBAR filters feature superior out-of-band blocking and thus prevent jammers from compressing the GPS receiver chain. Low insertion loss and best-in-class noise figure are key advantages of FBAR technology.

The Completed Evaluation Board

The integrated modules were assembled onto a single evaluation board, as shown in Figure 2, and characterized. The pinouts of all the components have been designed to match the Qualcomm chipset I/Os so inner layer traces are not needed, nor do any of the RF lines cross each other.

For the PA layout, bypass capacitors were placed next to the PA to minimize noise. A Vdd choke was placed close to the GPS LNA module to minimize noise and output matching. The GPS LNA module should placed as close as possible to the multiplexer for best system noise performance. Multiplexer placement minimizes Tx and Rx line lengths, and orthogonal trace routing from the multiplexer was used, this is essential for best pin-to-pin isolation. In general, the shortest possible PCS and Cell Rx trace lengths to the IC will maximize receiver sensitivity.

Performance Results: Transmit

On the transmit side, current consumption of the RF front end is the key metric that determines battery life or talk time. Current consumption testing was done at 4 V, which is the "full battery" condition. ACPR (Adjacent Channel Power Ratio) testing is done at 3.4 V, which is the worst case "low battery" condition.

For the PCS chain, a 4 mA Icc was measured at -10 dBm antenna power, 10 mA at +0 dBm antenna power, and 391 mA at +24 dBm full output power. These current consumption levels give best-in-class talk time.

Similarly for the Cell band, a very low current consumption of 340 mA was demonstrated in high-power mode.

ACPR1 for PCS and cell band are both better than 50 dBc at an antenna power of +24 dBm. A summary of typical performance is listed in Table 1.

Performance Results: Receive

Sensitivity, the measure of the minimum power signal that a receiver can demodulate, is the key receiver specification. Any distortion added to the receive chain will lower handset sensitivity. There are many reasons why a handset may suffer from degraded sensitivity. The most common ones are poor TX to RX isolation, high PA noise floor, and high insertion loss in the RX path. Achieving good PCB board isolation with adequate grounding, well placed vias, and orthogonal trace routing is essential to maintain good receiver sensitivity. System sensitivity is also directly correlated to the RX path loss. This path loss is determined by the insertion loss of the Rx filters in the multiplexer plus the trace loss in routing to the antenna and the LNA.

The key receive channel component that gives superior sensitivity is the Avago ACFM-7103 multiplexer. Its Rx insertion loss is 1.6 dB typical in the PCS band and 1.5 dB typical in the Cell band. With -108 dBm sensitivity or better demonstrated in phones, the manufacturer is expected to have 4 dB of margin for manufacturing margin.

Single Tone Desense is very similar to sensitivity except that a -30 dBm jammer is added 1.25 MHz away from the RX channel of interest. Since sensitivity is harder to achieve in the presence of a jammer, the 3GPP2 specification relaxes the sensitivity specification from -104 dBm to -101 dBm. Phone service providers generally look for -108dBm minimum for sensitivity and -104 dBm for STD performance levels. With STD values of -104 dBm or better achieved, a 3-5 dB manufacturing margin can be expected with Avago's integrated solution.

Table 1 shows a summary of sensitivity and Single Tone Desense (STD) results.

Performance Results: GPS

The GPS path contains a pre-LNA filter, LNA, and post-LNA filter. Typically, the filter in front of the LNA is used to attenuate out-of-band blockers. This helps prevent signals, such as Bluetooth and Cell band signals, from mixing inside the LNA and impacting GPS sensitivity. The pre-LNA filter also prevents is PCS/Cell Tx leakage that can cause gain compression in the GPS LNA.

The GPS filter after the LNA is used for removing unwanted noise power or spurs generated from the LNA which might affect the down-converter that follows.

The complete GPS receive chain achieved 10.6 dB of gain with a 2.0 dB noise figure while consuming only 5 mA from a 2.7 V supply. As shown in Table 1, the integrated solution demonstrates up to 1 dB of improved GPS sensitivity versus a discrete solution using SAW filters. The improved sensitivity is primarily due to the low 0.8 dB typical IL of the FBAR pre-LNA filter.

Evaluation Boards and PCB Design

Evaluation boards are a critical part of any vendor's product portfolio. Evaluation boards provide a platform for the designer engineer to become familiar with the device and verify performance and options on a platform that has been verified by the component supplier's technical staff. Critical PCB layout and construction details have been proven can be incorporated in the system design without additional engineering effort.

Good PCB Layout is Essential

As shown, integration improves performance and lowers component count, but without a thoughtful PCB layout and design these benefits will be lost. The block diagram in Figure 4 below illustrates the location of the three RF front-end modules in a typical CDMA mobile application. The Avago evaluation board is an example of best-practice PCB design and layout.

PA PCB Layout and Power Supply

The RF front end layout must be taken into consideration for a high performance and reliable CDMA, GSM or WCDMA handsets. Power amplifier bypass capacitor layout and values are critical. Capacitors must be placed very near to the device pins, especially for the Vcc power lines. A good scheme is to use parallel capacitors of different value and of different dielectrics to maintain low impedance over a wide frequency band. Typical values are shown in Figure 4 where the Vcc line has both a 2.2 μF and a 1000 pF capacitor.

Capacitance is calculated with Equation 1 with the reactance, Xc, set to 1 Ω or 2 Ω. One capacitor bypasses frequencies below 100 kHz and a smaller value capacitor provides a low impedance at higher frequencies. The 2.2 μF capacitor bypasses low frequencies, such as below 100 kHz, and the 1000 pF capacitor will bypass higher frequency power line disturbances.

Multiplexer PCB Layout—An Essential Task

ACPM-7353 placement and PCB layout is very important. The PA to quintplexer interface is crucial in determining the linearity of the PAM (Power Amplifier Module). This includes both ACPR and Error Vector Magnitude (EVM). Also, any extra line length from the RX port to the LNA translates into higher RX insertion loss or lower sensitivity.

The ACFM-7103 has 54 dB of isolation from PCS TX band to PCS RX band. Vias that isolate the TX and RX ports from each other must also be added to maintain this isolation. The PCB must have 60 dB to 70 dB of isolation from TX to RX in order to maintain 54 dB multiplexer isolation. This is mainly accomplished by adding ground vias between the TX and RX ports.

The recommended land pattern for maintaining this high isolation is shown in Figure 5. In addition, the TX trace must be kept away from the RX trace to minimize mutual coupling. If TX, RX and ANT traces are perpendicular to each other the signal coupling should be minimal.

Finally, remember it is just as easy for a signal to leak from the TX port to the RX port as it is to leak from the ANT port to the RX port.

The ACFM-7103 datasheet has recommended solder mask and solder stencil details. The PCB design for the RF front end evaluation board uses only the top layer for TX, RX and ANT routing. Performance is excellent but if enough space is available on a bottom layer, the datasheet also shows a recommended land pattern for this situation. The best isolation is achieved with TX and RX traces separated by a ground layer. However, this option may not be possible on all designs.

Datasheets and design guides are available at www.avagotech.com.

Evaluation Kits Decrease Your Development Time

The *Avago Dual Band CDMA Reference Design for US PCS and Cell Bands* evaluation board contains most of the components needed for a handset front end design. Included are the PCS and Cell band PA modules, GPS LNA and matching network to the multiplexer's impedance. Two high band and low band AVX couplers are daisy chained together as one end is terminated and the other is a coupled into a connector port as shown in Figures 6 and 7. The detector is intentionally excluded since this evaluation board is targeted at the Qualcomm QSC60x5 chipset which comes with a detector built in.

The ACFM-7103 multiplexer was designed with the Qualcomm QSC chipset in mind. When married to the QSC transceiver, TX lines will not cross RX lines. This layout enables the phone board to maintain the high isolation provided by the multiplexer. Recall that isolation is the key factor in determining receiver sensitivity and single tone desense.

The ACFM-7103 also includes a GPS filter with the option to use single or dual antennas. If a single antenna is used a 5.1 nH inductor is required between the GPS antenna and the main antenna port. This inductor not only ties the two antennas together, but is also part of the pass-band match for the multiplexer. A 5% or better inductor tolerance is recommended.

GPS Band Performance

Very few suppliers have access to and control over the multiple technologies needed to create a GPS LNA with a high rejection filter that offers a best-in-class noise figure. Avago has both a GaAs ePHEMT process as well as a Film Bulk Acoustic Resonator (FBAR) filter process.

The FBAR technology is revolutionary because it is a bulk wave, high-Q technology. FBAR technology produces devices with better electrical performance than competing ceramic or SAW filters and in a miniature form factor that designers need.

Avago Technologies introduced FBAR devices based on a bonded-wafer chip-scale packaging technology known as "Microcap." The FBAR filters typically measure less than 1.0 mm x 1.0 mm x 0.3 mm and are ideal for integration into low-cost molded chip-on-board products in industry-standard and smaller footprints.

The GPS path consists of a GPS filter and GPS LNA. Typically the filter in front of the LNA is used to block out-of-band Bluetooth or WiFi signals or even Cell and PCS signals. This helps prevent signals from mixing inside the LNA and landing within the GPS band. For example, 830 MHz and 2406 MHz signals can easily create 2nd order products at 1575 MHz. Once created, the interference is impossible to filter out. The GPS filter after the LNA is used for removing unwanted noise power or spurs generated from the LNA which might affect the down converter that follows.

Table 2 lists cascaded GPS performance.

Summary

A highly integrated CDMA RF front end with GPS capability has been shown that uses three of Avago's highly integrated RF modules: the ACPM-7353 dual band PA, the ACFM-7103 PCS/Cellular/GPS quintplexer, and the ALM-1412 GPS LNA-Filter module. The three modules replace seven discrete components found in traditional designs. Module pinouts are arranged to match the Qualcomm QSC60X5 series.

The Avago three-chip integrated solution lowers PCB space requirements by 25 percent compared to a discrete solution, while simultaneously improving current consumption and sensitivity. Approximately 20 minutes of talk time improvement is demonstrated in PCS/CELL bands through a 50 mA to 70 mA current savings at a maximum antenna power of +24 dBm.

Receiver sensitivity in the PCS and Cell bands was improved by 1.0 dB and 0.7 dB respectively relative to the discrete solution. Finally, up to 1 dB of improved GPS sensitivity is achieved versus the discrete solution.

Proper use of ground vias, trace routing, and component location are critical to maintaining good system performance in handset applications.

References

1. Source: http://ca.news.yahoo.com/s/reuters/090731/tecnology/ctech_us_cellphones
2. CoolPAM is a trademark of Avago Technologies.
3. Data sheets, Evaluation Boards and Reference Guides
   a. ACPM-7353: http://www.avagotech.com/docs/AV02-1611EN
   b. ACFM-7103: http://www.avagotech.com/docs/AV02-1455EN
   c. ALM-1412: http://www.avagotech.com/docs/AV02-0205EN
   d. Wireless Semiconductor Solutions for RF and Microwave Communications http://www.avagotech.com/docs/AV00-0117EN

Appendix – List of Figures, Table and Equations Referenced in the Whitepaper

Figures

Tables

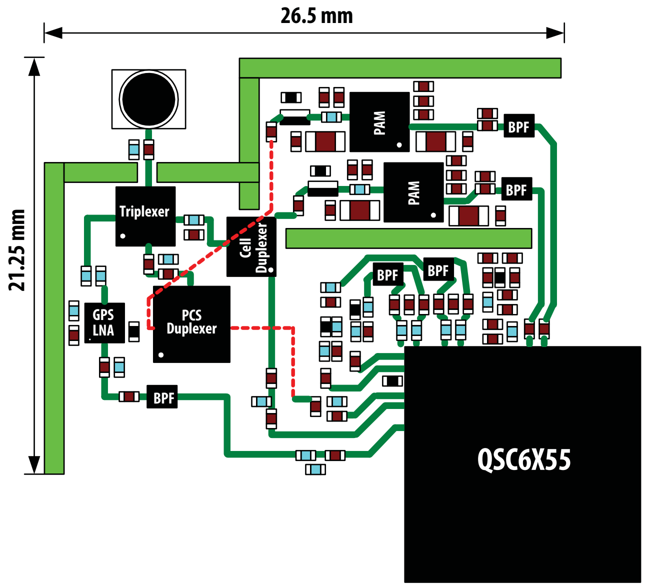

Figure 1a. Discrete CDMA RF front end solution

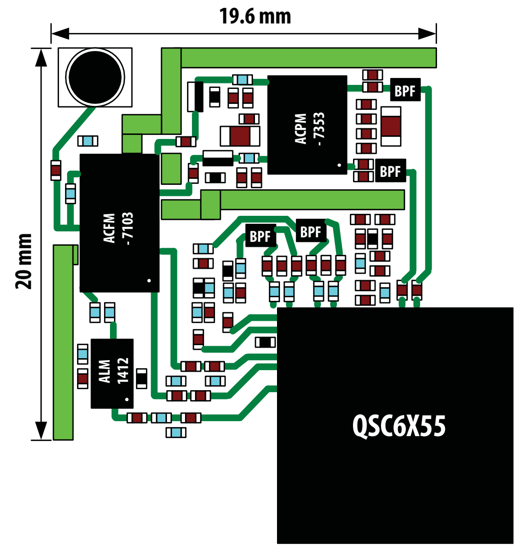

Figure 1b. Integrated CDMA RF front end solution.

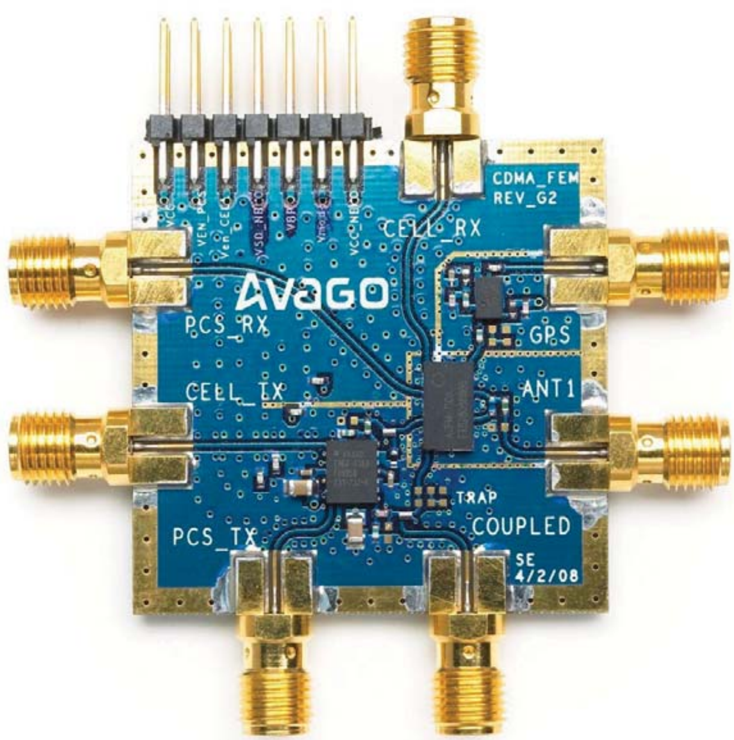

Figure 2. CDMA RF Front End Evaluation Board with the ACPM-7353, ACFM-7103 and ALM-1412 modules.

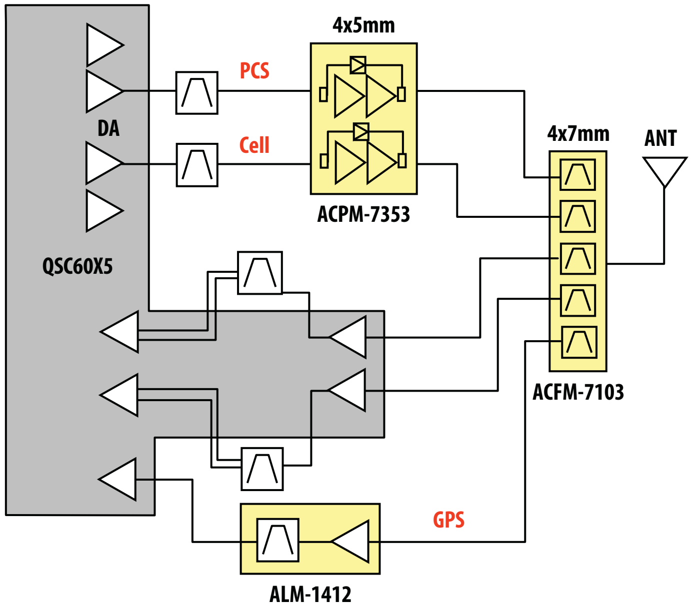

Figure 3. Typical Integrated RF Front-end CDMA Handset with GPS

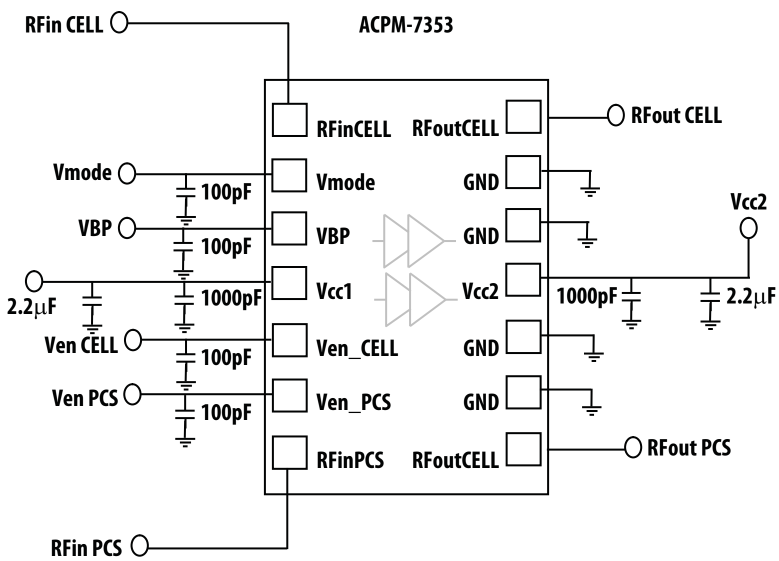

Figure 4. ACPM-7353 Power Supply Decoupling

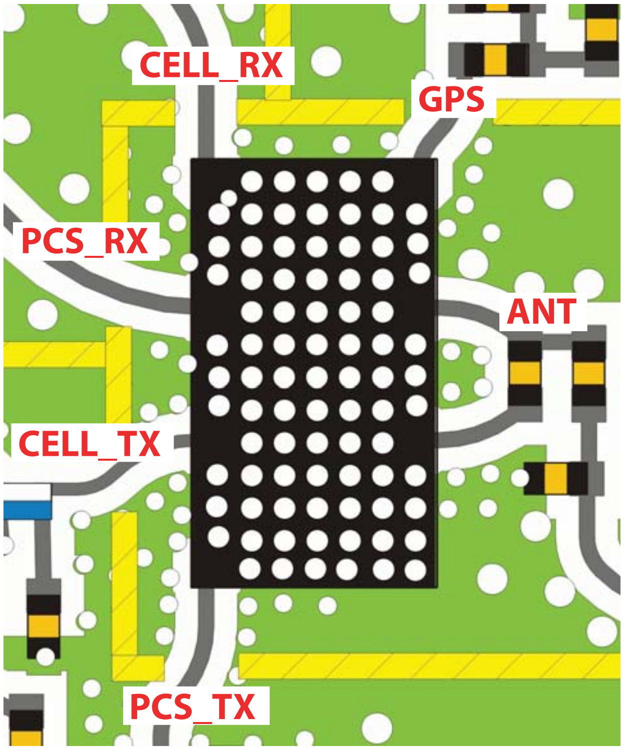

Figure 5. Multiplexer RF Layout and Via Location

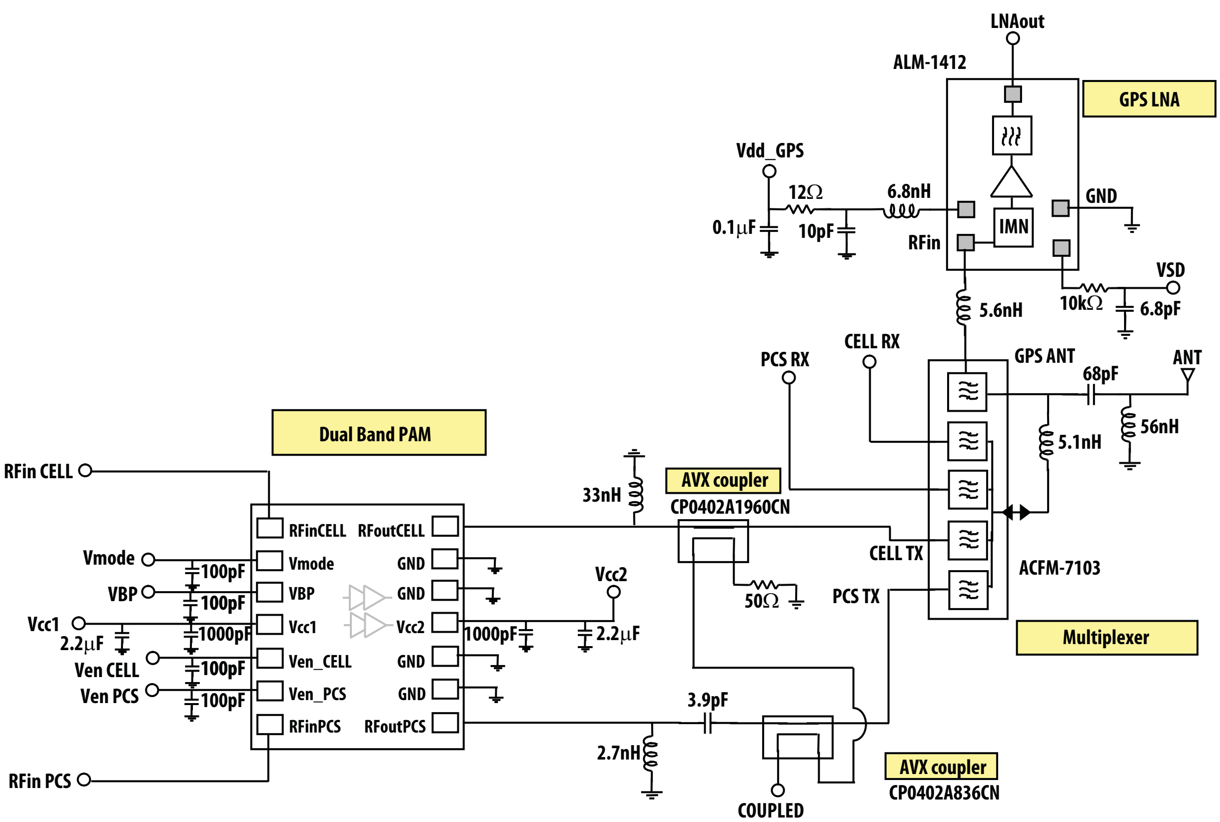

Figure 6. Dual Band Evaluation Board Schematic with GPS Capability

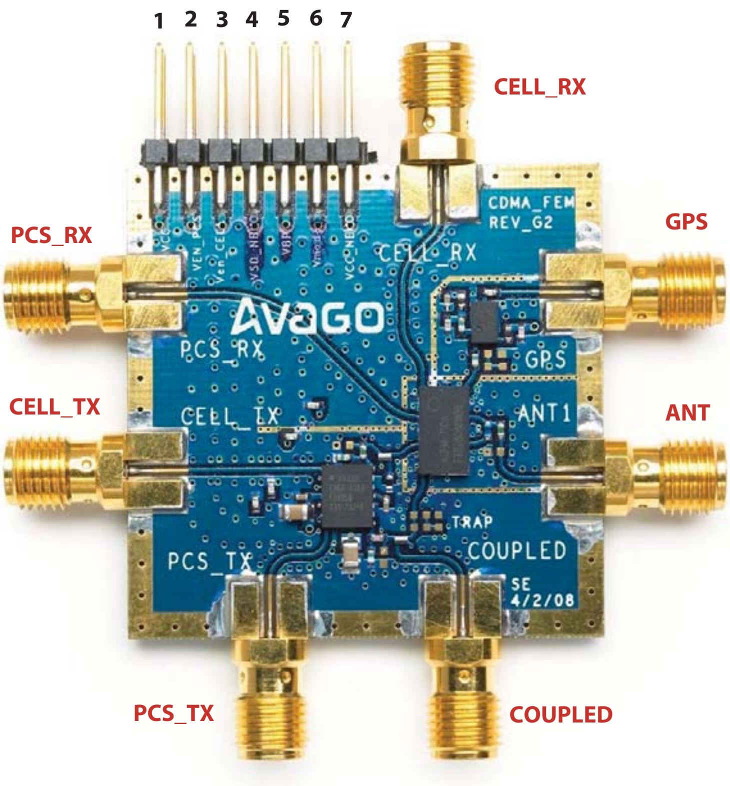

Figure 7. Evaluation Board I/O Connections

Table 1. Summary of PCS, Cell, and GPS Performance Data from Integrated CDMA + GPS RF Front End Solution.

		Channel		
		Low	**Mid**	**High**
PCS Band	Current (mA)	365	368	391
	ACPR 1- (dB)	-58	-56	-56
	ACPR 1+ (dB)	-59	-57	-56
	ACPR 2- (dB)	-62	-59	-61
	ACPR 2+ (dB)	-62	-59	-61
	Sensitivity (dBm)			
	Avago Integrated Solution	-108.2	-109.4	-108.3
	Discrete Solution	-107.2	-108.6	-107.7
	STD (dB)	-25.7	-26.9	-25.7
Cell Band	Current (mA)	340	317	335
	ACPR 1- (dB)	-53	-55	-56
	ACPR 1+ (dB)	-53	-54	-52
	ACPR 2- (dB)	-67	-64	-61
	ACPR 2+ (dB)	-68	-64	-62
	Sensitivity (dBm)			
	Avago Integrated Solution	-109	-109.7	-108.6
	Discrete Solution	-108.3	-108	-108.1
	STD (dB)	-25.2	-24.6	-25.3
GPS Band	Sensitivity (dBm)			
	Avago Integrated Solution		-157.7	
	Discrete Solution		-156.6	

Table 2. GPS Chain Performance Summary

Parameter	Performance
NF	2.36 dB
Ga	10.6 dB
IIP3	0 dBm
P1dB	8 dBm
Vds	2.1 V
Ids	8 mA
Sensitivity	-158 dBm/BW

Equations

Equation 1

$$Xc = \frac{1}{j\omega C} = \frac{1}{2\pi f C} \qquad \text{Equation 1}$$

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