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MEMS-based Reconfigurable CMOS LNAs for Wireless Applications

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ABSTRACT

This study investigated on the requirements of covering multiple standards in portable wireless devices. A comparison in terms of system and circuit performance between the wideband devices and narrow-band reconfigurable devices was presented. Also, these devices were compared in terms of physical specifications such as area and number of pins. To overcome the limitations of Radio Frequency (RF) components and to optimize their RF performance, available RF microelectromechanical systems (MEMS) components with feasibility of integration with RF Complementary Metal-Oxide Semiconductor (CMOS) circuits were discussed. Finally, the study results on pros and cons of CMOS-MEMS integration.

Key words: CMOS-MEMS integration, reconfigurable, multi-band, multi-standard, tunable

INTRODUCTION

The growing market of multimedia mass using portable devices in twenty first century causes designers to develop mobile devices as compact and low-power as possible (Assadi, 2008; Hmida *et al*., 2007) so, that multi-band multi-standard multi-medias can be integrated in one compact handset to have customers avoided using different devices at a same time. Different TV standards such as Digital Video Broadcasting-Terrestrial (DVB-T), Advanced Television Systems Committee (ATSC), Terrestrial Integrated Services Digital Broadcasting (ISDB-T), Digital Terrestrial Multimedia Broadcast (DTMB) and also different radio standards such as Frequency Modulation (FM), In-band on-channel (IBOC), Integrated Services Digital Broadcasting-Terrestrial (ISDB-T), Digital Audio Broadcasting/Digital Multimedia Broadcasting (DAB/DMB) give the major idea for multi-standard TV and radio reception on one portable device (Babla, 2009). However, to make this idea practical, it should be noted that one receiver might not be enough since some standards need to be operated simultaneously. This means that a multi-standard receiver can be implemented for horizontal integration of functions which do not operate in parallel. Figure 1 shows cross-functional integration of such standards to make this concept more clear (Babla, 2009).

These ideas are rising up in commercial products from concept to reality such as Avago dual-band Low Noise Amplifier (LNA) which operates in IEEE 802.11a standard (5-6 GHz) and IEEE 802.11b g^{-1} standard (2.4 GHz) using two CMOS LNAs in a single package with separated inputs for each standard. Although, integration of two LNAs in a small area is easy for implementation, it is not cheap in cost and not reasonable in size. This means that for covering more standards in one single chip, using separated LNAs have some disadvantages which will be indicated later. FlexiRF introduced a radio tuner that can cover multiple standards from high

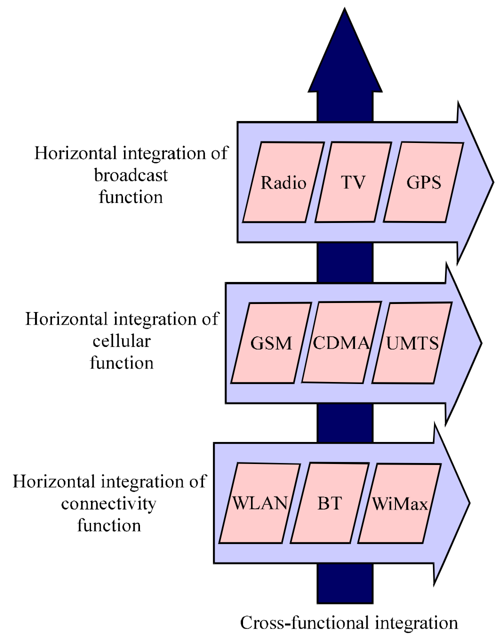

Fig. 1: Cross-functional integration of different standards for different applications (Babla, 2009)

Table 1: Global navigation satellite-based systems and their operating frequencies

GNSS band	GPS L1/L5	Galileo E5a/E5b	Glonass L1/L2
Frequency (MHz)	1575.42/1176.45	1176.45/1207.14	$1602+n\times0.5625$
			$1246+n\times0.4375$

frequency (HF) up to L-band which is known as MSi 002 FlexiRF tuner. The mentioned chip is also suffering from the identical disadvantages with previous chip (Babla, 2009).

Other popular radio receivers are the Global Navigation Satellite System (GNSS) receivers which help us to navigate air, navy and ground crafts. The most famous system is the Global Positioning System (GPS) which was launched by USA. There are other systems such as Galileo from Europe and Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) from Russia. These positioning systems follow their own individual standards which are summarized in Table 1.

Xiaoli *et al*. (2006) introduces architecture of a GPS/Galileo software-defined radio receiver. Using two or more standards gives more accurate positioning, faster acquisition and continuous tracking of satellites.

A radio frequency spectrum for cognitive radios is given by Okada (2010). Reconfigurable radio frequency (RF) Complementary Metal-Oxide Semiconductor (CMOS) circuits are developed to cover various bands in this spectrum. A single-ended input is typically recommended for RF circuits (Besser and Gilmore, 2003).

Qualcomm has developed a multi-standard transceiver chip known as RTR6285 to cover different cellular standards such as GSM (850, 900, 1800, 1900) UMTS (850, 1900, 2100) and also GPS. Parallel LNAs are implemented to operate in these standard bands and RF switches are used to select the proper paths from antenna through LNAs (http://www.qualcomm.com). AN26210A is a parallel W-CDMA LNAs Integrated Circuit (IC) which is developed by Semiconductor Company with dual-band 900-MHz and 2100-MHz separated inputs. This is a conventional topology with parallel LNAs for each separated band frequency (Ko *et al*., 2004).

MULTI-STANDARD PORTABLE DEVICES ROADMAP

The roadmap in recent trade market is to integrate cellular, digital TV and radio standards in a single chip with a single LNA rather than using many parallel LNAs for each standard (Okada, 2010). Nowadays, cell phones have the capability to operate with GSM/UMTS/LTE, GPS, WLAN, BT, DTV/FM. This idea leads the designers to design reconfigurable RF front-end receivers including multi-band multi-standard reconfigurable LNAs and PAs that their operating frequency can be tuned while maintaining their performance.

Wang *et al*. (2005) introduces a multi-band multi-standard front-end for IEEE 802.16 a (3.5 GHz) and IEEE 802.11a/b/g (5-6/2.4 GHz) applications. It uses a wideband LNA and wideband antenna with switchable parallel pre-selector filters to select the desired band. The same method is used by Kim *et al*. (2007) with switchable passive pre-selector filters followed by a 2~6-GHz wideband LNA and tunable mixers for operating in 1.9/2.1, 2.4, 5.2, 5.8 GHz standards using a single wideband antenna. A reconfigurable receiver with tunable LNA and mixer is presented by (Kakerow *et al*., 2005) for fourth generation (4G) applications such as WLAN and UTMS. However, as noted before, switching among cross-functional standards is not reasonable as they might be needed to be used simultaneously. TriQuint semiconductor offers mobile device products such as highly-integrated transceiver modules to cover standards such as GSM/GPRS, 2G/3G CDMA and 4G LTE in a single chip.

Reconfigurable building blocks: The question that arises is why the reconfigurable devices are recommended instead of many devices in one-chip for different bands. The answer can be listed as follows:

- Smaller number of input/output (I/O) pins and footprint
- Smaller number of components with the identical specifications
- Smaller area, more integration
- Smaller power consumption
- More appropriate for mobile and portable devices
- More selectivity
- More tolerance to out-of-band interferers

To manage a reconfigurable front-end receiver, two methods can be considered: (1) to use a wideband LNA with switchable preselector filters; so just the desired band will flow in the receiver string and (2) to use a tunable narrow-band LNA which eliminates the needs of employing filters which are necessary for rising receiver selectivity.

Wideband versus reconfigurable narrowband device: Table 2 is given as the case of comparison in terms of receiver system performance while one receiver uses a wide-band LNA and the other one uses a narrow-band reconfigurable LNA (Noh and Zulkifli, 2010).

Wideband LNAs can be implemented in different techniques. Some of these techniques are pointed here. One of the traditional techniques is staggered amplifier. Chiang *et al*. (2007) presents a three-stage amplifier in which each step is tuned at lower cut-off, center and upper cut-off frequency. These amplifiers suffer high ripple in pass band, low rejection in stop band and high

Table 2: Comparison between wideband and narrowband LNAs in terms of system overall performance

Parameters	Narrow-band	Wide-band
Noise figure	Seldom improved	Seldom degraded
Linearity	Identical	Identical
Compression	Identical	Identical
Carrier/noise	Identical	Identical
Spur	Identical	Identical
Gain	Identical	Identical

power consumption due to large number of stages. The larger, the number of stages is, the lower the ripple is. For a wide pass band, more stages are required. Additional stages cause an increase in chip area and in power dissipation. The other useful method is to employ a resistive feedback in the LNA such as Park and Jung (2010) and Eshghabadi *et al.* (2008). These amplifiers benefit from low-power topology of non-feedback LNAs but higher noise factor due to inserted thermal noise by employing resistance in the feedback. One technique is to con vert a narrow-band LNA to a wide-band LNA by inserting a wide-band matching network at the input of the circuit such as (Chen and Kuo, 2005). These amplifiers have the same specifications as narrow-band amplifiers but occupy more area due to large-size inductors that are used at input matching network. A solution can be a common-gate amplifier which has wide-band input matching due to the resistive part in its input impedance. By setting that real part equal to the source impedance, a wide-band matching can be provided. The noise factor in this topology is not as low as a common-source amplifier due to high equivalent noise resistance (R_n) of the circuit. An identical method is used in (Cai *et al.*, 2009).

Reconfigurable LNAs are usually tunable or multi-band narrow-band LNAs. Chang *et al.* (2005) presents a switchable dual-bad LNA which is based on a cascode LNA with two separate input paths which each one is tuned for different standard band. This circuit consumes power identical to a single cascode LNA and in area, it is still comparable. One common method is an LNA with switchable external gate-source capacitor that tunes the input matching reactance to the desired frequency. An example for this technique are given by Song *et al.* (2008) and Mustaffa *et al.* (2009). This amplifier benefits a single input path for both standard bands. To tune the input resonant frequency, switching input gate inductor is another solution. Phan and Farrell (2010) presents an LNA using this method which shows acceptable power consumption while maintaining gain in different bands. However, this topology suffers from parasitics of the switches which are in series with input and can degrade the noise factor and causes mismatches. Table 3 presents physical specifications comparison between wide-band and multi-band LNAs.

Based on Table 3, multi-narrow-band LNAs have a smaller size because of fewer building components. They are more talented for simultaneous input and noise matching. Using High-Q MEMS components leads to better performance such as noise improvement. MEMS-based Narrow-band LNA would have better overall performance than conventional ones.

RF MEMS IN INTEGRATION WITH CMOS

iSuppli now expects the market to take off starting in 2011 as the first cell phones start to implement MEMS based antenna tuning and matching networks from the company WiSpry. At the same time, the market will expand with test and instrumentation applications as more price competitive MEMS relays appear from companies like ADI, Omron and XCOM. Advantest and Rohde and Schwarz, are now much more confident in the offer of RF MEMS. RF MEMS rapid

Table 3: Comparison between wideband and narrowband LNAs in terms of circuit specifications

Parameters	Narrow-band	Wide-band
Power consumption	Significantly lower	Higher
Noise figure	Significantly lower	higher
No. of inductors	Lower	Much higher
Area size	Lower	higher
Talented for integration with MEMS components	Higher	Lower
Talented for interference	Lower	Higher
Talented for optimum noise and matching achievement	Higher	Lower
I/O pins/footprint	Lower/smaller	Higher/larger
Talented for high-speed communications	Lower	Significantlyhigher
Talented for extremely high-frequency applications	Lower at the moment-Integration with MEMS is a solution	Much higher

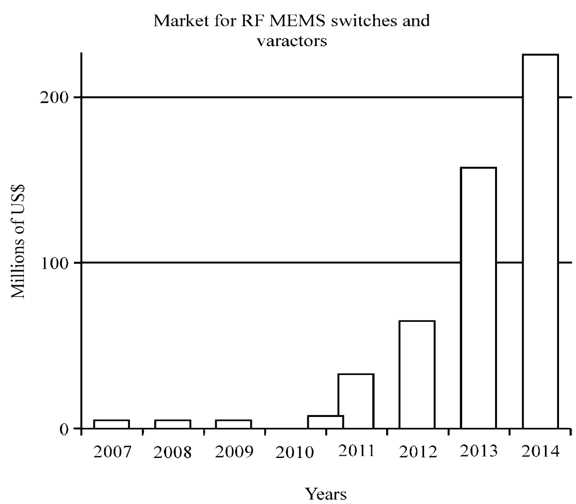

Fig. 2: Growing market for RF MEMS components (Bouchaud, 2010)

growth in market from 2009 to 2014 is predicted to be 131%. Figure 2 shows the market growth of RF MEMS switches and varactors from 2007 to 2014. The curve shows a rising slope of MEMS contribution in the market (Bouchaud, 2010).

Bouchaud (2010) lists the market segments as the order of opportunity as follows:

- Tuning and matching circuits used in the front-end modules of mobile handsets
- Test and instrumentation, including automated test equipment (ATE) for semiconductors
- Wireless infrastructures
- Medical applications (non-RF)
- Aerospace and defense applications

The most RF MEMS usage can be found in the front-end modules in the mobile phones by 2014. Also, it is finding its way in test and instrumentation, medical and aerospace applications (Bouchaud, 2010). Growth of High-Q RF MEMS passive components allows integration of this technology alongside transistor circuits. MEMS components are substituted with CMOS components in issue of CMOS limitations in that desired application. However, the MEMS devices have a long journey to overcome their own limitations such as switching voltage and speed in RF MEMS switches, tuning range and stress control in MEMS capacitors and so on. A brief but useful description about available RF MEMS components, their performances, applications and research issues for wireless architectures can be found by Nguyen (2005). In theory, many building blocks in a transceiver can be replaced by high-Q MEMS components such as multi-band preselector filter bank including filters and switches, switchable high-Q resonators, PAs, T/R switches and so on. The CMOS circuits can helps the functions of MEMS devices, vice versa (Banitorfian and Soin, 2011; Matsumoto *et al*., 2008).

RF MEMS components, pros and cons and applications: MEMS components integrated with CMOS circuits are listed below with their RF/MW wireless applications:

- MEMS inductor-based circuits for MN, LNA, VCO applications to improve the gain, power dissipation or phase noise
- MEMS varactor-based circuits for variable matching circuits, tunable filters (Islam *et al*., 2008) and VCO
- MEMS switch-based circuits for T/R switch, filter bank, dual Antenna or LNA switch for the advantages that already discussed
- Micromachined cavity resonator-based/resonator-based/transmission Line-based Circuits

RF MEMS switches: MEMS Switch in terms of its actuation mechanism is categorized as follows (Richards and De Los Santos, 2001):

- Electrostatic
- Piezoelectric
- Thermal
- Bi-Metallic

The most important features of a MEMS switch are much lower insertion loss, higher isolation and higher power handling and linearity in comparison with pin diodes and CMOS switches. However, high actuation voltage is still an issue that prevents their extensive usage in mobile transceivers.

RF MEMS varactors: Types of MEMS varactors that are reported until now is collected by Xie (2005) and listed as follows:

- Electrostatic parallel-plate varactor reported with a CMOS-compatible process, a 15%-capacitance variation at 3 volt and a high-Q of 60 at 1 GHz
- Electrostatic three-plate varactor fabricated using poly-si process with a tuning range of 3.4-6.4 pF at 4.5 volt and a Q of 16 at 1 GHz
- Electrostatic zipper varactor by MIT fabricated using poly-Si process by employing zipping motion with a tuning range of 0.55-1 pF at 40 volt and suffering from high inductance and high tuning voltage

- Electrostatic tunable interdigital capacitor benefiting from large capacitance and large tuning range (1.3-6 pF at 5 volt) and high Q at low frequencies, but suffering from large area due to required large number of interdigitated fingers
- Piezoelectric varactor by LG-Electronics employing metal-PZT-metal sandwich technique bonded on glass substrate and thick gold layer with a capacitance ratio of 3.1 at 6 volt and extremely high Q of 210 at 1 GHz
- Thermal varactors employing Thin-film CMOS-MEMS process with a tuning range of 42-148 fF at 12 volt and high Q of 52 at 1.5 GHz
- MEMS switched capacitor reported by Raytheon that a MEMS switches are implemented in series with Metal-insulator-metal (MIM) capacitors to insert one in the path and the others out of path, with a Q of 40-80 and large capacitance ratio but large inductance
- MEMS capacitor with discrete values which is two-value MEMS capacitor or a beam-array MEMS capacitor

In McFeetors and Okoniewski (2006), a high-tuning (6.2:1) with a high-Q (50 at 30 GHz) can be found. These RF MEMS varactors are applicable to very high tuning receivers. The instability occurs in these devices with a movable conducting electrode due to pull-in voltage/deflection which is modeled in details by Salekdeh *et al.* (2012) and Kooch and Abadyan (2012).

RF MEMS inductors: Some types of MEMS inductors are as follows (Xie, 2005):

- Spiral type inductor with nH-range value and high Q over 40 for RF/MW frequencies applications
- Solenoid type inductor with μH-range value and small Q up to 10 for base-band applications
- Tunable spiral type transformer reported by (Chang and Sivoththaman, 2007) with a tuning range of 5.5-8 nH with a control voltage of 2-0.5 volt

Sarkar *et al.* (2005) introduced a variable inductor with tuning range of 1-5 nH with maximum quality factor of 10. This micro inductor can be applied to LC tank, VCO and DC-DC converters.

Mizuochi *et al.* (2009) introduces some configurations to implement MEMS inductors with large variations such as meander-type inductors for large inductance variations and Air-suspended MEMS inductors for wide- and multiband RF systems.

El-Gmati *et al.* (2010) presented a variable inductor that its value can be varied from 2.6 to 7.4 nH with Q of 15 at 2.5 GHz. This is a new class of liquid RF variable inductor using SU8 laminated films to implement the fluidic part of the inductance.

Practical cases of CMOS-MEMS integration: A 5.8 GHz VCO based on MEMS inductor was implemented by Tseng *et al.* (2007). The result shows a 5 dB lower phase noise improvement at 1 MHz offset in this 5.8 GHz VCO.

Ramstad *et al.* (2009) presents multiple RF MEMS front-end components which are easily possible to replace off-chip units in future transceivers using conventional 0.25 um CMOS process from ST-Microelectronics. MEMS parts are implemented by post-processing etching. Two lateral varactors with high tuning range were designed. The area tuning of moving combs is used as the technique for implementing these varactors. A common problem with post-CMOS is the out-of plane curl that can cause offset between two electrodes or sensing nodes which causes a significant reduction in sidewall capacitance. This issue is minimized by aligning the anchors along a common axis (Ramstad *et al*., 2009). This study shows sufficient results for integration of MEMS in an analog RF front-end transceiver. By avoiding off-chip components, a significant improvement in performance is also achieved.

MEMS-based CMOS LNAs: CMOS technology has the advantages of low-power dissipation, high integration, low cost and easy to acess and integrate with other application circuits such as MEMS (Touati *et al*., 2007a). The front-end of a wireless transceiver contains a good number of off-chip high-Q components that are potentially replaceable by micromechanical versions (Babazadeh and Keshmiri, 2009). Combining silicon-based microelectronics with micromachining technology has the potential to revolutionize both industrial and consumer products (Miskam *et al*., 2009).

One of the most effecting ideas to optimize the noise figure of an LNA is to minimize the series resistance in input of the circuit. This prevalently happens in case of series CMOS inductors. The very low-Q MMIC inductors in series with input gate degrades the noise factor intensively (gate inductor L_G is shown in Fig. 3). This happens in the cost of on-chip implementation (Touati *et al*., 2007b). Replacing a high-Q MEMS inductor can be a solution to overcome this issue. However, in tunable input matching to realize a reconfigurable LNA, a variable inductor to set the input resonant frequency is required.

In dual-band dual-LNA receiver, lossy CMOS switch for selecting the LNAs causes degradation in signal to noise ratio. Also, the CMOS switch suffers from low ports isolation which causes undesired interferers or image issues in other port (Fig. 4). Also, one the most common usage of the CMOS switches is to switch a common antenna between the receiver and transmitter, well-known as T/R switch. The high output power of the power amplifier in transmitter string can cause saturation and distortion in receiver. Using a MEMS switch with high-isolated ports is an appropriate solution (Fig. 5).

In an inductively-degenerated LNA based on simultaneous input and noise matching (SNIM) technique, an external capacitor is applied between the gate and source of the transistor to match the optimum noise impedance with the source impedance. In a reconfigurable LNA based in this topology, the external capacitor is required to be varied to set the input resonant frequency equal to center frequency of desired band. Applying MEMS varactors with high tuning range and high-Q can play this role while the circuit performance is maintained (Fig. 6).

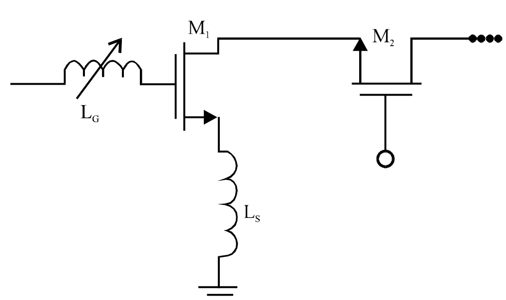

Fig. 3: A simple view of a cascode LNA with feasibility of tuning

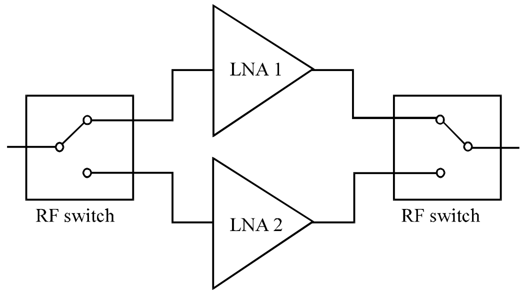

Fig. 4: Dual-band receiver with RF switches to select the receive path

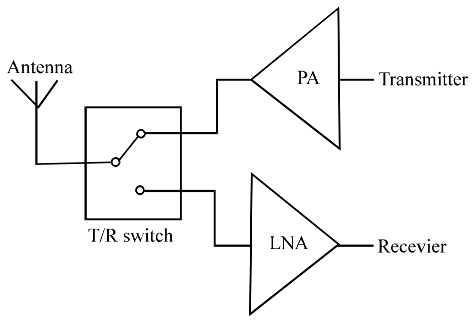

Fig. 5: A radio transceiver with a T/R switch to select either receive path from antenna or transmit path to antenna

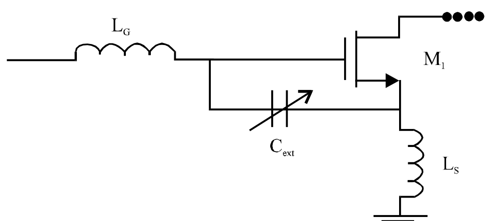

Fig. 6: Reconfigurable common-source LNA with external varactors to tune the input matching network for desired band

CONCLUSION

This study investigated on the wide-band and reconfigurable multi-narrow-band receivers which can cover multiple standards. These modern front-ends are especially designed for software-defined radios to achieve the mobility and compact features at the same time. The narrow-band reconfigurable LNAs and their talent to become integrated with MEMS devices were discussed. The reviewed studies indicated that the designers' aspects are directing to the growing mobile devices market. The MEMS components are replacing with off-chip components and integrating with CMOS chips to result more compaction and lower price. The reviewed studies showed the improvements in circuit performance caused by addition of MEMS components. Finally, some MEMS-based solutions were suggested for reconfigurable LNAs to overcome the limitations in CMOS components.

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