Reconfigurable components in SDR RF Front-end with emphasis on reconfigurable antennas

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Abstract: For successful implementation of a multi-standard transceiver, reconfigurable architecture and reconfigurable component design technique are essential. In this paper reconfigurable component application are reviewed and then most enabling frequency reconfigurable antennas for small terminals are proposed.

Keywords: SDR RF Front-end, reconfigurable components, reconfigurable Antennas, PIFA, SPA

1. Introduction

To clarify importance of reconfigurable component, first we consider two approaches on SDR[1] RF Front-end design.

Classical approach: in this approach, the analog front end is wide band and main role of analog front-end (AFE) is providing wide band signal to digital front-end (DFE), the wide band signal contains several frequency bands of different standards, so channelization and other primary signal processing is performed in DFE. Therefore a fast DFE is needed. Classical architecture is shown in Figure 1.

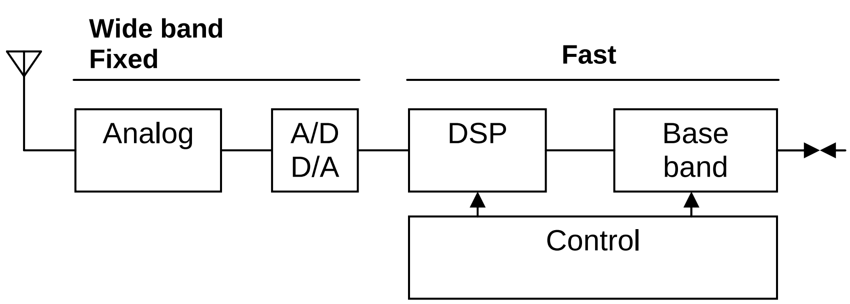

Figure1. Classical architecture

Refined approach: in alternative approach AFE is narrow band and reconfigurable. Channelization and other primary signal processing can be performed in AFE, so slow DFEs can be used. Refined architecture is shown in Figure 2.

[1] -software defined radio

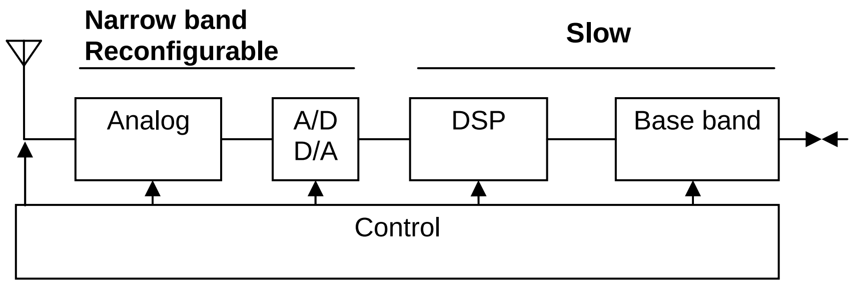

Figure2. Refined architecture

There are several trade offs between two above approaches which are presented in Table 1.

Table 1.Trade offs between classical and refined approach

Approach	**AFE**	**DFE**	**Dynamic range**	**Linearity**	**Cost**
Classical	Wide band Fixed	Fast	high	Critical in both AFE and DFE	Can be high
Refined	Narrow band Reconfigurable	Slow	low	Not critical at DFE	Can be low

In classical approach there is high level of interferers and blockers at A/D input so high dynamic range at DFE is needed. Receiving wide band signals demands high dynamic range at AFE. [10]

In refined approach spurious signals shall be filtered at AFE so linearity is not critical at DFE. In most cases cost of refined architecture is less than classical architecture. [1]

Paper organization: in section 2 the solutions are presented and most common ideas of reconfigurable antennas, LNA, PA, synthesizer, matching networks, phase shifters and filters briefly was reviewed. In section 3 frequency reconfigurable antennas for small terminals are proposed. To ease the architecture proposition after a brief theorical introduction an practical component is presented.

2. Reconfigurable component solutions

2.1. Switched elements

Antenna: single radiator elements can be connect together to change characteristic of antenna. In a different way a lumped element (like a capacitor) can be switched to the antenna radiator. (See section 3)

Duplexer, matching networks and filters: by switching tuning elements reconfigurable frequency response can be reached . [1]

Synthesizer: by switching tuning elements can change the value of resonant elements and resonant frequency response in coarse steps can be reached. [1]

LNA, PA and mixers: custom on chip compact designs are a good solution. [11]

2.1.1. Switch Technologies

A key enabling technology for the successful development of reconfigurable multi-band components is the development of switches with low- loss, high- isolation and low bias power requirements. Below approximately 1 GHz, PIN diodes are extremely efficient and are suitable

switching elements. Above 1 GHz, various photonic switches have been proposed for microwave antenna applications, but have met limited success for one reason or another.
Recently micro-electromechanical system (MEMS) switches have been receiving a lot of attention as potential antenna switching elements. [9] A comparison between switch technology is represented in Table2.[10]

MEMS switches have several characteristics that are attractive for reconfigurable antenna development. Among these are their inherent wide bandwidth, low insertion loss (~0.2 dB), and low bias current in both the ON and OFF states. The low bias current is due to the fact that the switch operates using electrostatic force. A voltage excitation is required to actuate the switch, but once actuated, the switches hold their ON/OFF state with very little bias power. Hence, these switches can be very efficient. Another advantage is that the MEMS devices are being manufactured using silicon IC batch-processing techniques, thereby leveraging previous investments in processing facilities. [9] Main disadvantage of MEMS switches is relatively high actuation voltage that can be handled using charge pumps.

Table2. Comparison among switch technologies

Switch Type	Insertion loss	Isolation	Power consumption	Actuation DC Voltage	Speed	Band width
PIN/Schottky diode	~0.15 dB	45 dB	1-5 mW	1-10	1-5 ns	Narrow/ wide
GaAs FET	1-2 dB	~20 dB	1-5 mW	1-10	2-10 ns	Narrow/ wide
HBT/PIN	0.82 dB	25 dB	1-5 mW	1-10	1-5 ns	Narrow/ wide
Best FET	0.5 dB	70 dB	5 mW	3.5	2 ns	Narrow/ wide
MEMS-segio	0.06 dB @ 20 GHz	30 dB	~1 mW	12-14	>30 us	Wide 1-40 GHz
MEMS-scott/jeremy	0.3 dB @ 30 GHz	50-60 dB	~1 mW	~20	>30 us	Wide 10-40 GHz

2.1.2. Electronically tunable elements

Electronically tunable elements such as varactors are an alternative. Especially in chip components where electronically tunable element can be fabricated with high accuracy, so reconfigurable LNA, PA and Mixers, can be fabricated using this technology. [12, 13] also a Varactor reconfigurable antenna is presented in section 3.1.1.
Figure 3 represents the switched elements and the electronically tunable elements opportunities.

3. Frequency reconfigurable antennas for small terminals

The growth of new generations of voice services (UMTS[1] to GSM[2] for instance), and the offer of new services incorporated in phone terminals (like Bluetooth, GPS[3]) require antennas which provides multi-band possibilities. Indeed, a frequency reconfigurable antenna solution is often smaller and less costly than a solution with a distinct antenna for each frequency band. [2]

There are several reconfigurable parameters in antennas and each of them has its own application. Main reconfigurable parameters are operating frequency, bandwidth, pattern and polarization. Most enabling antennas in multi band and multi-standard application is frequency and bandwidth reconfigurable antennas, other parameters such as, pattern or polarization can be used to improve performance. (removing interferer, diversity, beam forming and etc).

[1] -third generation (3G) European mobile phone technology
[2] -Global System for Mobile communication
[3] -Global Positioning System

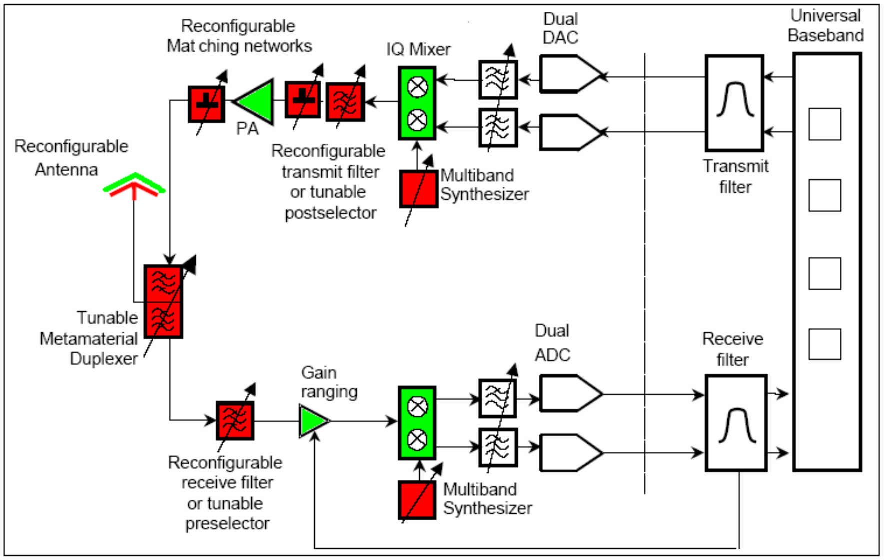

Figure3. Solutions in reconfigurable components

Use of frequency reconfigurable (operating frequency and/or bandwidth) antennas make it possible to remove, out of band interferers and noise at the beginning of RF front-end chain, in this way primary RF filtering (in some cases channelization) performs in antenna which results in lower noise floor. In a practical example [7], noise figure of RF front-end was reduced from 4.3dB to 2.3dB at frequency band of GSM1900.

Frequency reconfigurable antennas; however is not unique solution for SDR. Wide band antennas and multi-frequency antennas are two alternative. Main disadvantage of two latter solution compared to the former is weak noise and interferer blocking; furthermore frequency reconfigurable antennas can easily cope with new bands where wide band antennas and multi-frequency antennas have fixed structure and should be redesign for each multi band application. As mentioned above, there are many reconfigurable antennas. [4] But in the reminder of this paper we study frequency and bandwidth reconfigurable antennas (the most enabling antennas for SDR) that are suit for small terminal applications.

3.1. Planar Inverted Folded Antennas (PIFA antenna)

The planar version of the inverted-F antenna, planar inverted-F antenna (PIFA), is a popular antenna for reduced size environments. Figure 4 shows the general structure of the inverted-F antennas. The PIFA can be viewed a modification of the wire-form inverted-F antenna (IFA). [4] The wire horizontal radiating element of the IFA is replaced by a plate and results in an increase in bandwidth. Some variations of the PIFA also replace the vertical shorting wire of the IFA with a vertical strap or plate to further enhance the bandwidth performance. A flush mounted PIFA extends in height approximately 1/20 of a wavelength as opposed to a conventional 1/4 wavelength monopole. The compactness of PIFA made it suit for hand held devices. The PIFA offers very high radiation efficiency and adequate bandwidth for mobile applications in a compact antenna. A typical bandwidth of 10% can be realized with the PIFA.

The size and aspect ratio of the top radiating plate, the height of the plate above the ground plane, the size and position of the shorting plate and the feed point location all have considerable impact on the electrical performance of the antenna. The size of the radiating top plate can be calculated approximately using [4]

$$f_{res} = c / 4(W + L)$$

where L and W are, the length and width of the plate respectively, c is light velocity in free space and f is first resonant frequency.

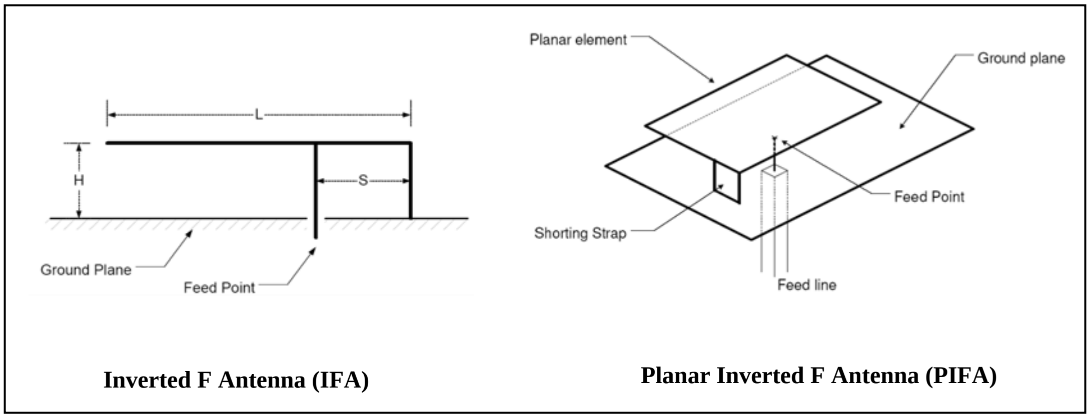

Figure4. Inverted F Antenna (IFA) and Planar Inverted F Antenna (PIFA)

The resonant frequency is also influenced by the aspect ratio of the top plate (L/W) and the width of the shorting plate, S, in relation to the width of the top plate. Figure 5 shows how the current flow on the top plate varies with different top plate and shorting plate configurations [4].

As a general rule one can say where the current flow degrades from straight line the bandwidth of antenna shall be smaller. There is some modification to compensate this effect like Chamfering rectangle edges and adding rectangle patches to rectangle corners. (See the top plate of Varactor tunable PIFA antenna with U-shaped slot in 3.1.1)

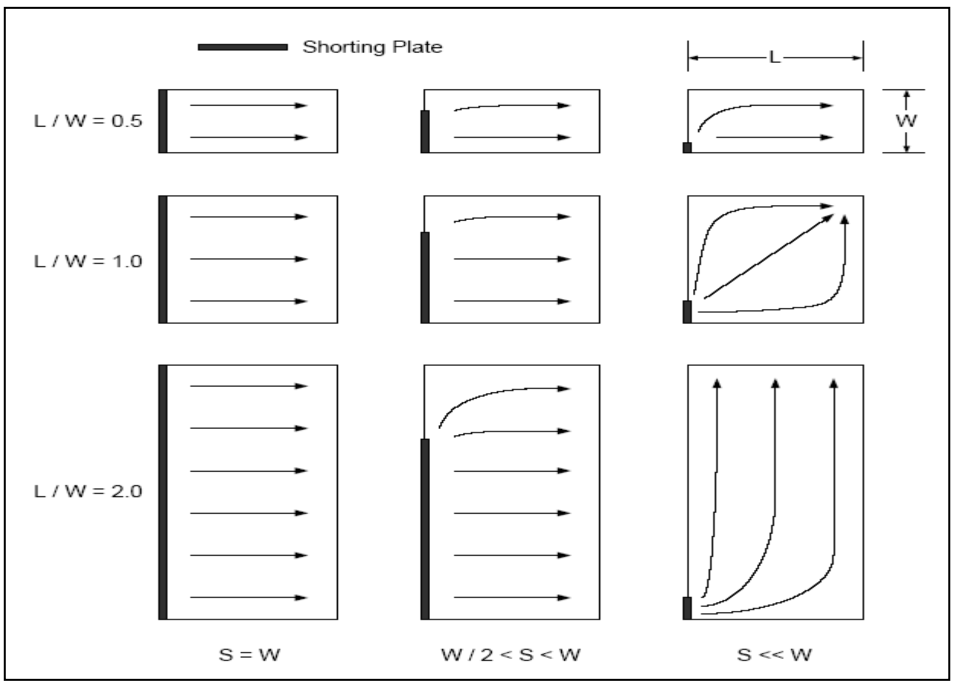

Figure5. Surface current on PIFA top plate for various top plate aspect ratios and grounding strap widths.

In general, a greater top plate aspect ratio will result in a lower the resonant frequency for a given grounding strap width.

In general, the bandwidth increases with increasing top plate height. However, as the height of the top plate approaches the magnitude of L or W, the height begins to influence the resonant frequency. When the grounding strap width is very small, S << W, the resonant frequency is given by:

$$f_{res} = c / 4(W + L + H)$$

The width of the grounding strap similarly affects the bandwidth. The limiting case, where the grounding strap is the same width as the top plate, the bandwidth of the PIFA is greatest.[4] Finally, we consider ground plane dimension effects. The bandwidth increases from 4% for a ground plane length of 0.2 λ to 10% for a ground plane length of 1.0 λ.
However, the bandwidth does not grow unbounded for increasing ground plane length. Once the ground plane length reaches about one wavelength, band width remains around 8%.
The ground plane length can have a great influence on antenna gain. Very small ground planes ($< 0.5\lambda$) results in small peak gain values of around 1 dB and as the ground plane length reaches 0.65-0.75λ the peak gain have a value around 4 dB. However, radiation pattern of PIFA antennas usually consist of two over lapped main lobs and looks like semi omni-directional.

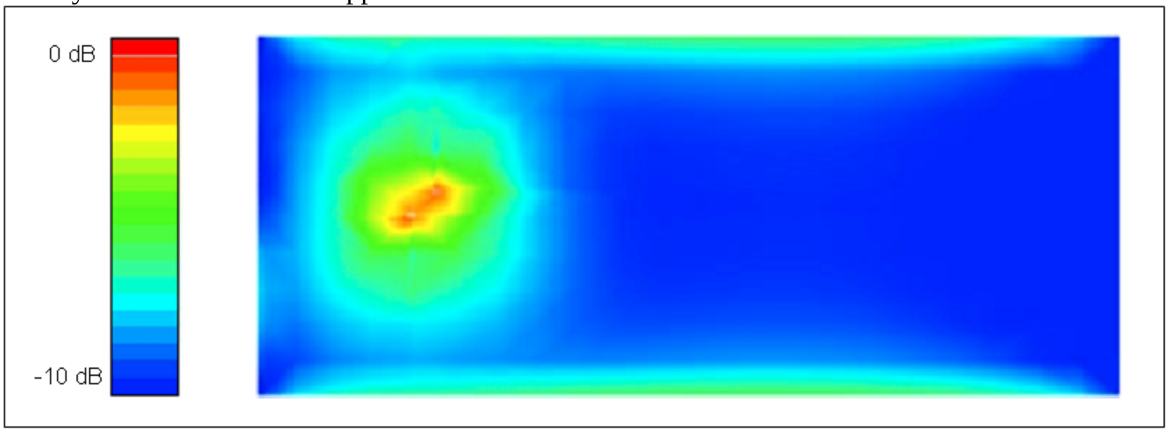

Figure 6. Average current distribution on PIFA ground plane computed using IE3D.

As shown in Figure 6, for a rectangular-shaped ground plate (and rectangular-shaped top plate) the current is primarily constrained to the long edges of the ground plane. This fact will be used to achieve the reconfigurable bandwidth.

3.1.1. Practical examples of reconfigurable PIFA antennas

In the case that operating frequency should be sweep on a narrow range and on discrete values. SPA (shorted patch antenna, simplest type of PIFA) is a good choice. It has very low cost, good radiation efficiency (in comparison to other compact antennas) and excellent compactness.

SPA antenna:[7]
Figure 7 shows the SPA antenna and its equivalent circuit. As shown in Figure 7, the equivalent circuit consist of two transmission lines one with S length and another with $L_{eff} - S$ length. Note that L_{eff} is greater than its physical length due to tuning capacitor. It is necessary to model the antenna as a two-port device to account for the effect of its frequency response on the system.

It is shown that the transfer function of the antenna is equal to its total efficiency, which includes mismatch loss. Conductor loss (correspond to the physical L) and tuning circuit loss contribute to reduced efficiency and also affect the bandwidth.

In an instant case [7] it has been shown that reducing quality factor (Q) of variable capacitor from 1000 to 250 reduced efficiency of 3dB, thus it is important that the tuning circuit (including switches) must have very low losses but high quality factor of the tuning capacitor, results in low antenna bandwidth.

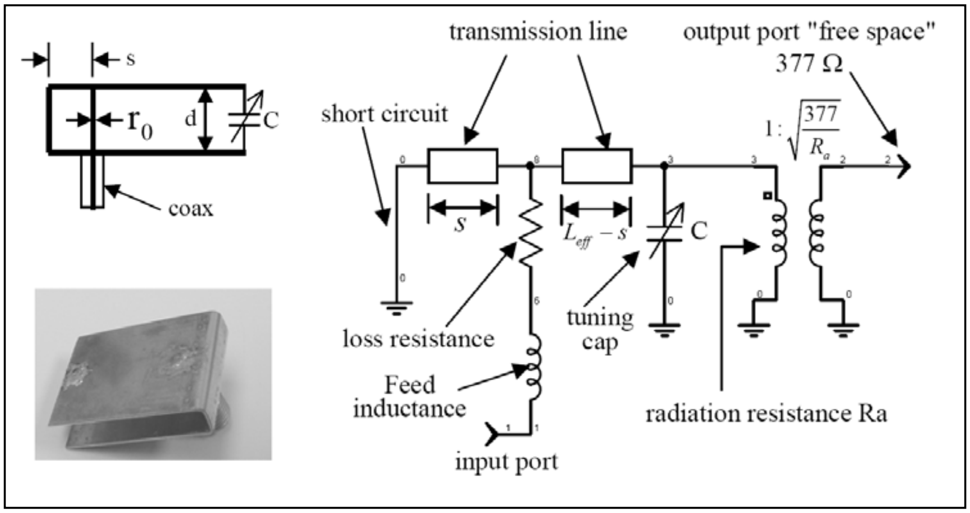

Figure7. SPA antenna and its equivalent circuit

The interdependency between bandwidth and efficiency is represented in Figure 8.

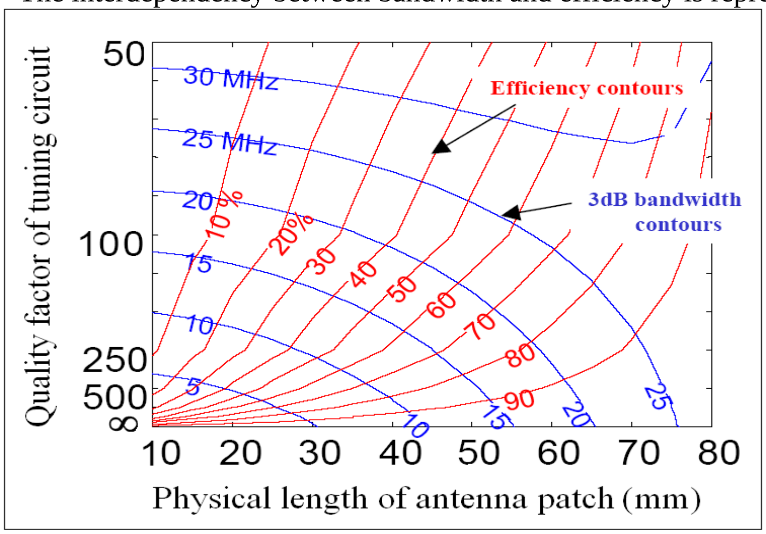

Figure8. The interdependency between bandwidth and efficiency

We can conclude from Figure 8, that there is a trade off between efficiency and antenna compactness and conductor losses (correspond to physical length of antenna patch) can be compensated using high quality factor tuning capacitor.

Another effect that is more difficult to calculate is the proximity of external lossy objects like a human operator's head or hand that decrease the efficiency and, in some cases, de-tune the antenna. Compensation for this effect is possible with a tunable antenna (using tuning capacitor or other tunable parameter) thus we need to quantify this phenomena through measurements.

According to the above design consideration, a pair of SPA antennas are fabricated, one of them acts as receiver antenna (Rx) and another act as transmitter antenna (Tx). They can be configured to operate at different frequency band of GSM850 and GSM900. These antennas are shown in Figure 9.

Note that two antennas placed perpendicular to each other that minimize cross talk between receiver and transmitter antenna. (Maximum of measured cross was -20dB) The transmitter antenna has greater dimension than receiver antenna in order to have higher efficiency. (That results in lower power consumption) Each antenna has two tunable capacitor one of them can be switch using a 3V PIN diode. When the switch is off Tx/Rx antennas operate on frequency band of GSM900, and when switch in on (higher tuning capacitance) they operate on frequency band of GSM850.

The evaluation environment and measurement results are shown in figure 9. Antenna efficiency is 15% where efficiency of 30-40% was expected in theatrical calculation. As mentioned earlier this phenomenon is due to human's hand and head proximity. (In evolution a virtual had and head is used that is similar to real human electromagnetic characteristics)

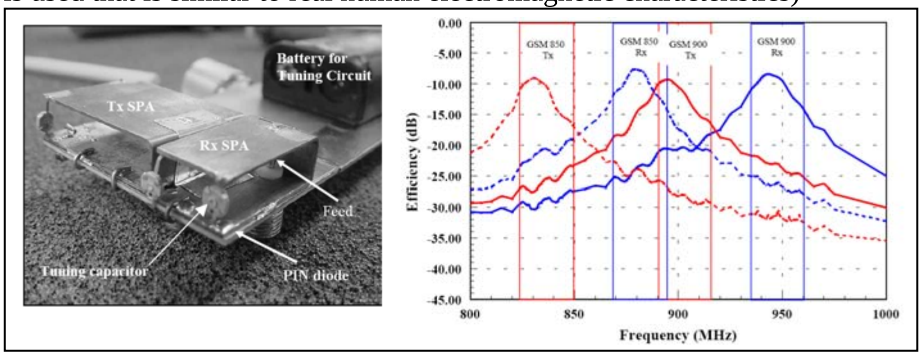

Figure9. The SPA antenna hardware and the measurement results

In the case that operating frequency should be change in a relative wide range with continuous values Varactor tunable PIFA can be a good choice.

Varactor tunable PIFA antenna with U-shaped slot: [3]

As shown in Figure10. A varactor diode is integrated between the slot and bias feeding strip line for tuning the operating frequency. This antenna covers from 1.64GHz to 2.05 GHz refer to the dc bias voltage from 0V to 20V. The frequency tuning range is about 410 MHz which covers several mobile communication bands of DCS (1710~1880MHz), PCS[1] (1750~1870MHz) and PCS(USA)(1850~1990MHz).

This antenna occupies a compact volume of 40 x 15 x 8 3 *mm* Antenna structure is in Figure 10. The diode is attached between the inner radiating element at U-shaped slot and bias feeding strip line with folded L-shape, as shown in Figure10. This folded L shape of antenna structure suppresses the first resonance frequency by the outer element of PIFA, but create another new resonance frequency which can cover several mobile communication bands. Folded L-shape strip line is terminated to 20mm open stab (as shown in Figure10). The stab length is a quarter of wave length at mid frequency (1.845 GHz) so acts as a short circuit.

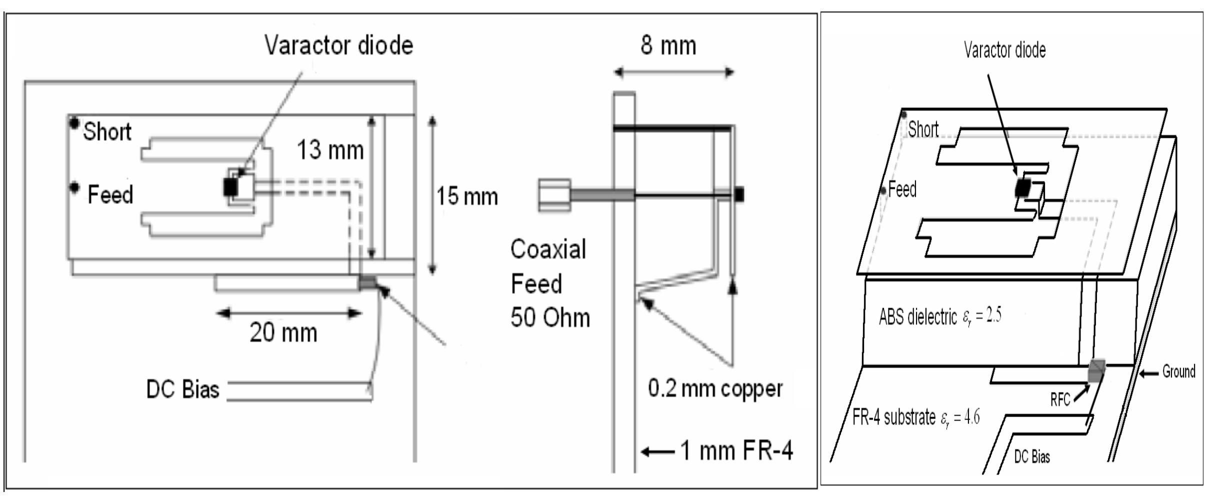

Figure10. Varactor tunable PIFA antenna with U-shaped slot structure

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[1] -personal communications services

The antenna is fabricated in 0.2 mm copper plate. The top plate mounted on ABS dielectric with thickness of 6 mm and relative permitivity of 2.5 and whole of the structure is placed on FR-4 substrate with relative permitivity of 4.6 and 1 mm.

The antenna has an almost omni-directional radiation pattern. The maximum antenna gains of the measured and simulated values have about 1.85 dB and 1.9 dB at the frequency of 1.8GHz. The antenna bandwidth at the center frequency of 1.85 GHz is around 22% . This magnificent bandwidth is obtained by using the outer radiating element. Simulation and measurement of scattering parameter, S11[1] in dB, is shown in Figure 11.

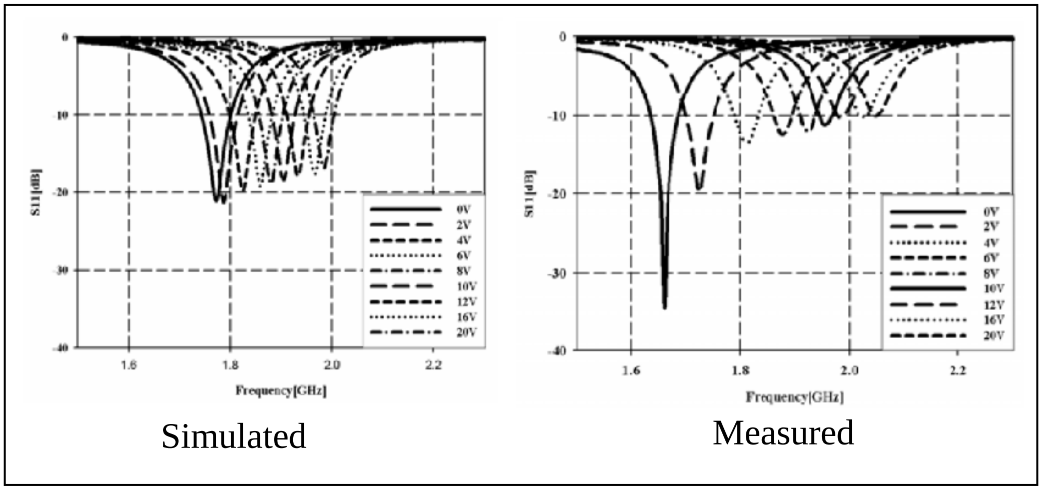

Figure11. Varactor tunable PIFA antenna with U-shaped slot results (S11 in dB)

In the case that antenna operating frequency should be changed in a relatively narrow rage the varactor tunable PIFA antenna is a good choice, but in most cases operating frequency should be changed in a relatively wide rage. For example different cellular bands in USA and Europe are distributed on a wide range as shown in Figure 12. [6]

In such cases use of MEMS switched PIFA antenna can offer wide range tunability.

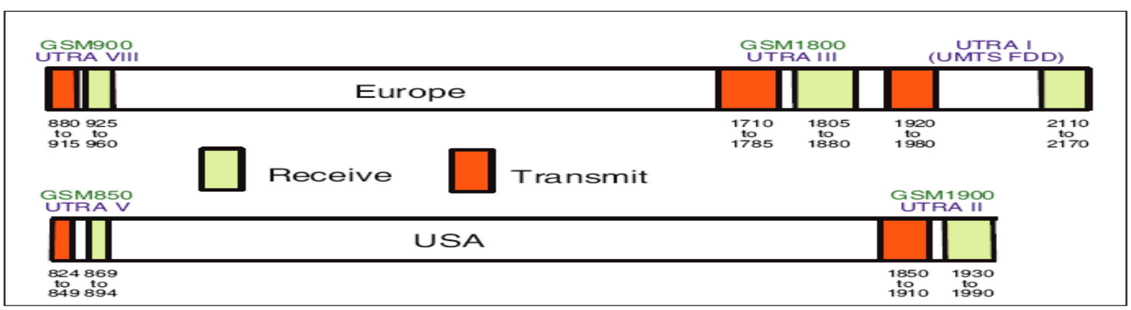

Figure12. Common cellular frequency bands used in Europe and the USA (MHz).

Multi-band MEMS Switched PIFA: [6]

The antenna geometry and MEMS circuitry is shown in Figure 13. The antenna has dimensions 40 *x* 12 *x* 8 mm, The PCB has dimensions 40 *x*100 *x*8 mm and is metalized on the back surface to provide an RF ground.

The MEMS devices (shown as variable capacitors in Figure 13) require an actuation voltage of between 30V and 50 V. MEMS Die 1 controls the antenna impedance and Die 2 controls the antenna resonant frequency. The circuit values for each operational mode are given in Table 3.

[1] -first element scattering matrix of a two port network

The matching inductor, L1 is fixed and is realized as a meander line on the PCB.(see Figure 14) L2 is used for DC biasing and is realized using a surface mount device (SMD) of value 10 nH. Capacitors CB1 and CB2 are used for DC blocking, CD1 to CD4 are for decoupling. All are 200 pF. Resistors R1to R4 have a resistance of 10 kohm are used for decoupling the DC actuation voltages of the MEMS switches applied at terminals VDC1 to VDC4.

Table3. MEMS capacitor values (pF) with operational mode

Mode	CDT	CM1a CM1b	CM2A CM2B	CM3A CM3B	CM4
GSM850/900	12	10	0.2	3.4	5.7
GSM1800	12	10	4.0	3.4	5.7
GSM1900	12	.5	4.0	3.4	0.57
UMTS	12	.5	4.0	0.17	0.57

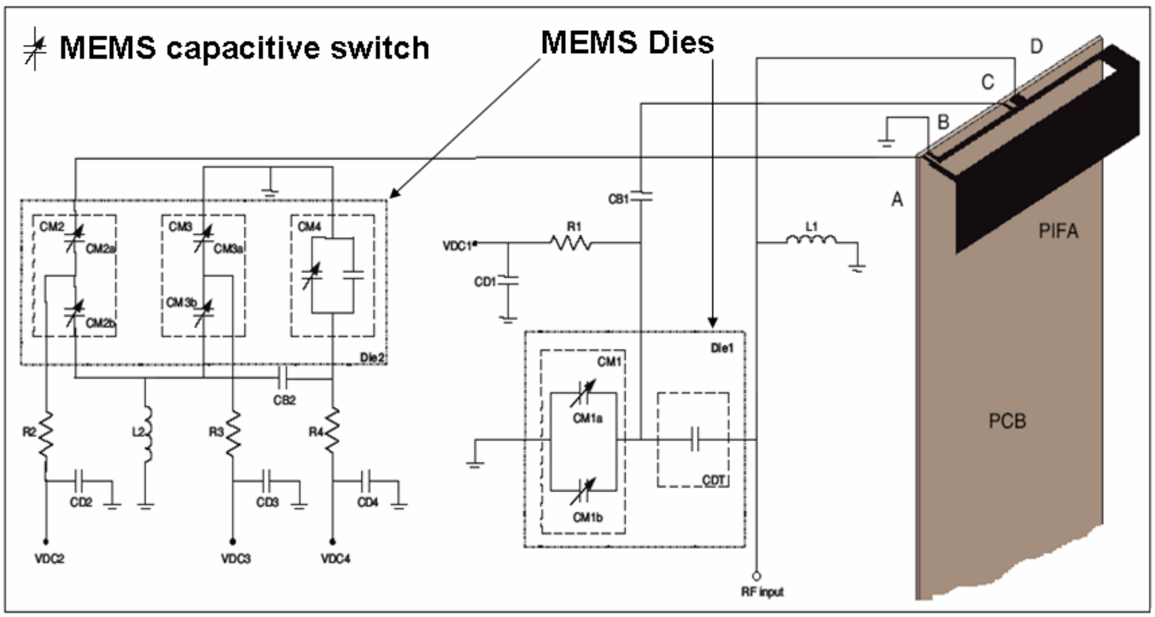

Figure13. MEMS switched PIFA and its circuit

The MEMS capacitors CM2 and CM3 are series of two capacitive switches in order both to reduce the OFF state capacitances and to improve voltage handling. CM1 is a parallel combination of two capacitive switches to increase the ON capacitance and CM4 is the combination of a fixed and a MEMS capacitor. CDT is a fixed capacitor that is used to double-tune the antenna in the lowest frequency mode. It is realized on the MEMS die to allow the use of non-preferred values.

The implemented antenna is shown in Figure 14 and simulation and measurement scattering parameter, S11, is shown in Figure 15.

As shown in measurement results (Figure 15) high resonant frequencies are shifted in comparison to simulation results due to uncertainties in the capacitance density of the MEMS devices and the long (un-simulated) bond wires used. A solution is proposed in section 4.

The antenna is fabricated from a polyimide flexible PCB that is folded over a Rohacell block. The antenna/PCB combination is fed via a coaxial cable at a central point on the PCB to avoid excessive perturbation from the feeding cables. The MEMS capacitors are placed on two dies under the antenna, as shown in Figure 14. It can be seen that the bond wires used to connect from the MEMS dies to the PCB interconnects are rather long, in part due to the solder used to connect the SMDs. To compensate for device and assembly uncertainties, MEMS devices with slightly varying layouts are implemented.

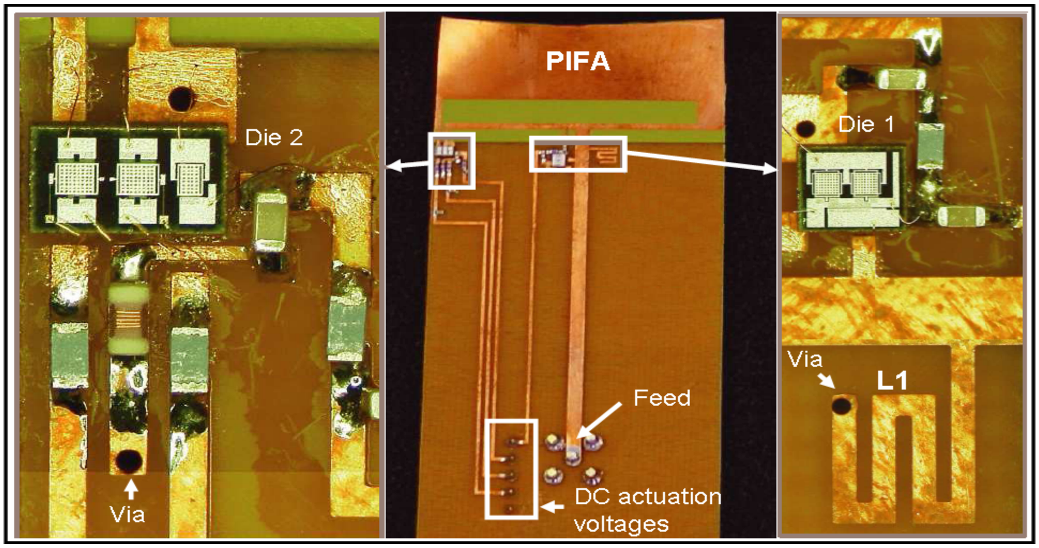

Figure14. Multi-band MEMS Switched PIFA

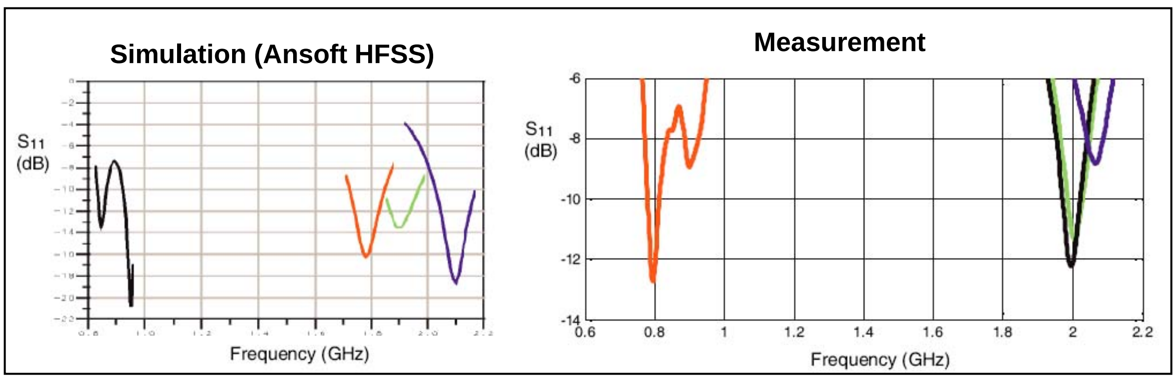

Figure15. Multi-band MEMS Switched PIFA results

PIFA reconfigurable bandwidth antenna: [4]

As mentioned in section 3.1 and Figure 6, ground plate length have a marked influence on the antenna bandwidth. Based on this idea a reconfigurable bandwidth antenna is proposed. As shown in Figure 16, one can use RF switches to extend ground plate length. For convenience, a simple copper plate is used as RF switch that can be replaced with appropriate RF switch.

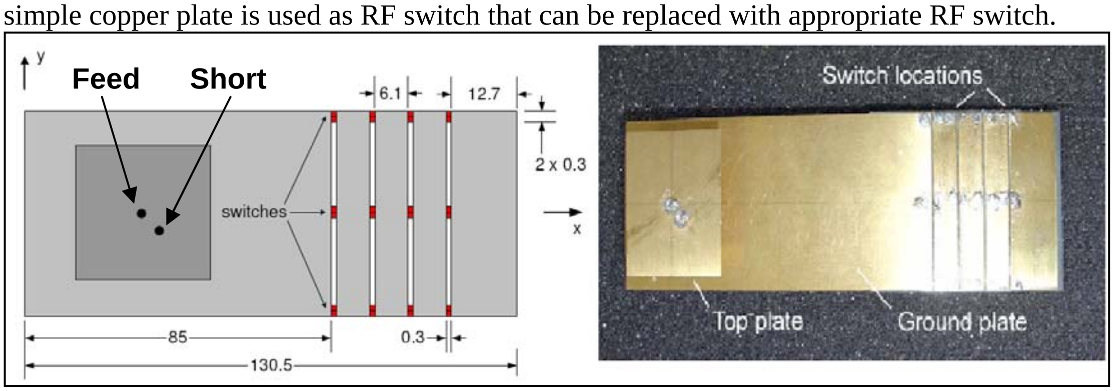

Figure16. PIFA reconfigurable bandwidth antenna with extendable ground plate

The antenna designed to have five different bandwidth (242, 191, 145, 79, 0 MHz) at center frequency of $f_0 = 1.54$ GHz . The bandwidth increases with ground plate length. Return loss[1] and radiation pattern measurement results are presented in Figure 17. The radiation pattern does not degrade too much.

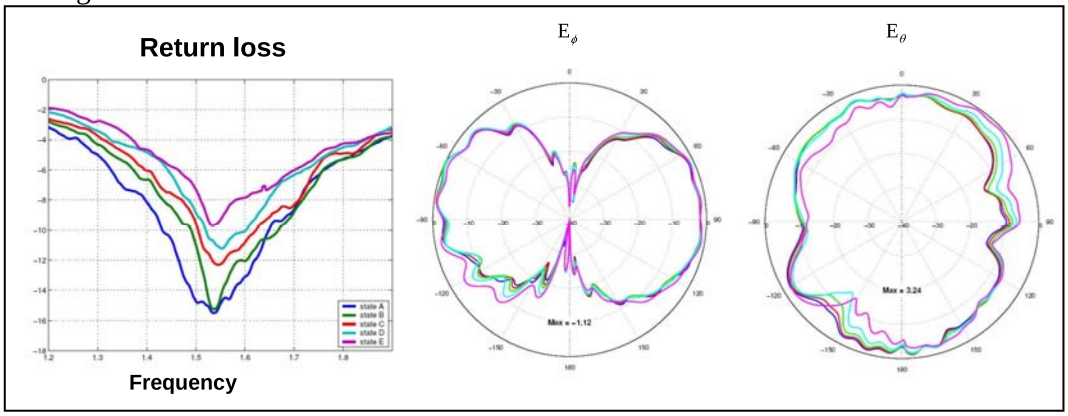

Figure17. PIFA reconfigurable bandwidth antenna, return loss and pattern measurements

4. Conclusion and A proposition for future works

For successful implementation of a multi-standard transceiver, reconfigurable architecture and reconfigurable component design technique are essential. Reconfigurable post antenna blocks (LNA, PA, Mixer, synthesizer, filters and etc) can be realized using on chip techniques. [11, 12, 13]

There are three solutions for a multi-standard transceiver antenna. The solutions are wideband antenna, multi-band antenna and reconfigurable antenna.

Main disadvantage of wide band antennas and multi-frequency antennas compared to the reconfigurable antenna is weak noise and interferer blocking. Furthermore frequency reconfigurable antennas can easily cope with new bands where wide band antennas and multi-frequency antennas have fixed structure and should be redesign for each multi band application. Most enabling antenna techniques for small terminals are proposed. In small terminals cost, power consumption and compactness are essential.

In the proposed reconfigurable antennas the Multi-band MEMS Switched PIFA in general has good characteristics but the practical results are degraded from simulation results. (see related section in 3.1.1 where high frequency bands are shifted from desired values) The differences between simulation and measurement are attributed predominantly to uncertainties in the capacitance density of the MEMS devices and the long (un-simulated) bond wires used.This degradation can be compensated using variable capacitor in combination with switches that affects antenna bandwidth. So we need to change the bandwidth using reconfigurable ground plate like the work that is done for reconfigurable bandwidth antenna (See related section in 3.1.1)

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