Minimization of power loss and distortion in a tuning circuit for a mobile terminal antenna

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Abstract

Broadband tuning circuits of small antennas may have high power losses and/or high distortion if the designer does not pay attention to the placement of the lossy and nonlinear components in the circuit. In this paper, experimental results of the distortion of an SPDT HEMT switch under different impedance environments are presented. The results motivate a broadband frequency tuning circuit design for a mobile handset antenna. The tuning circuit, using HEMT switches and lumped reactances, compromises between reasonable power loss and distortion caused by the switching components. The design is simulated and prototyped for E-GSM900 and GSM1800 using a capacitive coupling element based antenna.

1 Introduction

One possible method to limit the antenna volume in mobile communications handsets is to cover several radio systems in the handset with one inherently non-resonant antenna element and reconfigurable matching. The impedance is matched separately at each desired frequency band.

It has been shown earlier that compact capacitive coupling element (CCE) antennas, e.g. Figure 1a, can be tuned over a wide band of frequencies [1], [2], [3]. Broadband frequency tuning over one-octave tuning range of such antenna has also been demonstrated [4]. The tuning topology of [4] (Figure 1b), is general in the way that ideally the switches isolate the separate matching circuits at all frequencies. From the efficiency point of view, it is possible to improve this tuning circuit by optimizing the topology for the selected frequency bands. Also distortion has to be considered in these designs that include nonlinear components like switches, since the requirements for low power loss and low distortion might conflict.

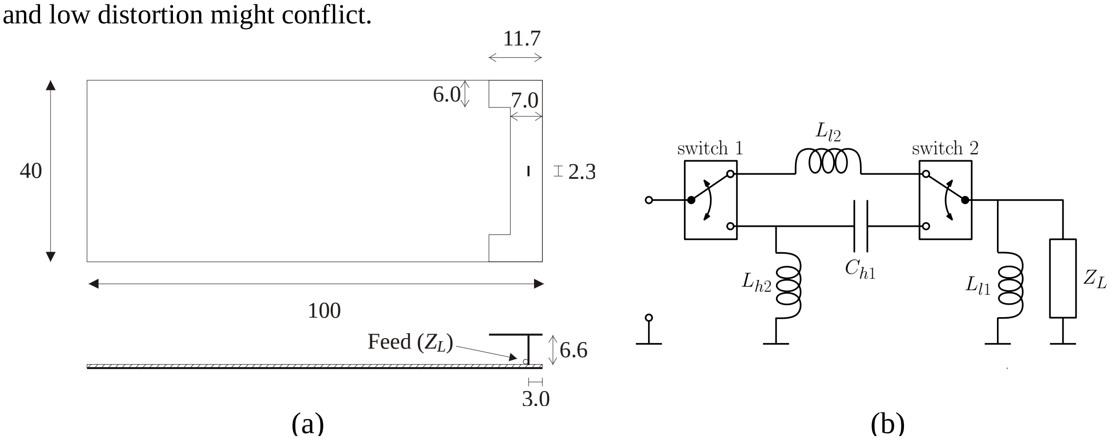

Figure 1: (a) Broadband tunable capacitive coupling element antenna. Dimensions in mm. (b) Starting point for the tuning topology, from [4]. Z_L represents the input impedance of the antenna element.

2 Power loss and distortion of RF switches

Generally, if a tuning circuit consists of RF switches and lumped reactances, it is the switching component which consumes the most RF power. The *on*-branch of an SPNT switch can be simplified to an equivalent circuit consisting of effective resistance and reactance in series at a given frequency. Similarly, the 'load' of the switch is a complex impedance. Power division between resistances in series is then indicative of the power loss in the switch: The higher the ratio between the switch effective resistance and the load resistance is, the higher is the loss. Decreasing the switch resistance requires practically the use of better switches, like MEMS instead of FET switches. The load resistance of the switch, for its part, can be manipulated by positioning the switch in a high-resistance location. However, creating a high-resistance location for all switches in a tuning circuit for a small antenna is not trivial. The typical input resistance of a CCE antenna is low at most frequencies of interest. Probably some circuitry between the antenna element and the switch closest to it would be required to create a high resistance environment for the switch. A piece of microstrip line as in [5] or the inductor L_{l1} in Figure 1b are used for this purpose. The feasibility of implementing this circuitry, regarding required circuit complexity and losses, depends on the frequencies and systems to be implemented.

Nonlinearity of the RF switches is a problem at high levels of transmission power. Consequently, the tuning circuit can not be designed only to minimize power losses, but the designer must pay attention to distortion as well. For reference, the third-order intermodulation distortion (IMD_3) of an antenna similar to the one presented in [4] was measured. At 900 MHz, +30 dBm/tone input power, and +3 V control voltage, the distortion was as high as -13 dBc.

Third-order intermodulation distortion of a GaAs HEMT SPDT switch [6] with specified third order input intercept point IIP_3 of +55 dBm was measured using a two-tone test with input power P_{in} = +30 dBm/tone. The load impedance at the *on*-port of the switch was varied. The result is shown in Figure 2. The IMD_3 in the case of a 50 Ω load in the *on*-port was between -30 and -55 dBc, indicating IIP_3 of +45 to +58 dBm, depending on the control voltage V_{DC}. Increase in V_{DC} decreased distortion. As a generalization, low load impedance indicates low distortion and high load impedance translates to high distortion. The explanation is that the variation of voltage is high at a high-impedance location. Hence the component is vulnerable to voltage distortion, as inferred also in [7].

Also the load impedance of the *off*-state branch of the switch was altered in the measurement, and it was found that also the *off*-state load impedance affects the distortion. The distortion was highest when the *on*-state branch load impedance was high and the *off*-state load impedance was relatively low.

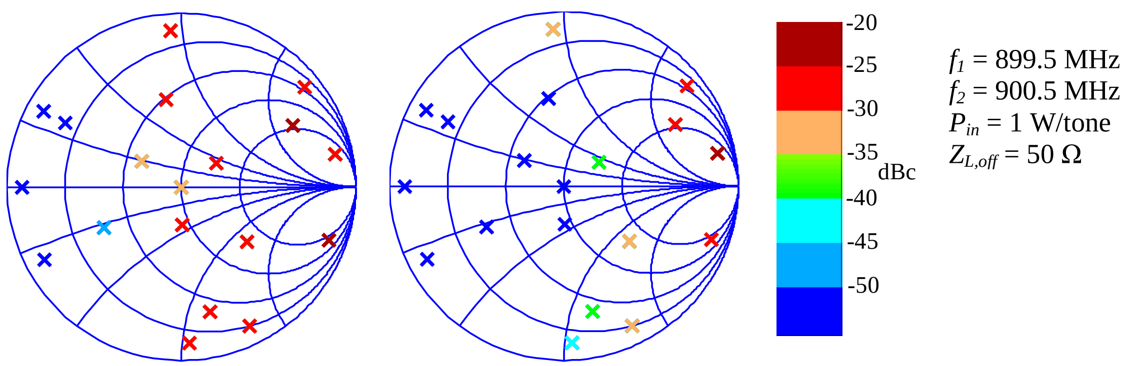

Figure 2: IMD_3 in HMC544 switch (dBc) with 3 V (left) and 5 V (right) control voltage, and with different *on*-state load impedances with respect to 50 Ω shown on the Smith chart.

3 Tuning topology considerations

The discussion above indicates that both high and low impedance locations have to be avoided when positioning nonlinear elements in a circuit. In the tuning topology of Figure 1, the switch close to the antenna has inherently either high losses or high distortion at some frequency. Hence it is wise to omit that switch and replace it with linear low-loss components. The remaining switch selects between the matching branches. Omitting switch 2 will significantly affect the isolation between the matching circuits unless the degradation of isolation is compensated. For a wide frequency band separation, like one octave in this case, the isolation between the matching branches can be improved by lowpass filtering in the lower frequency matching branch, and highpass filtering in the higher frequency branch.

The tuning topology of Figure 1b was modified by replacing one of the switches by reactances. The design was made for E-GSM900 and GSM1800 and the antenna element of Figure 1a, like in [4]. S-parameters of Murata LQG18 and LQW18 inductors and CQM18 capacitors [8], and the HMC544 switch [6] were used in simulations. The tuning circuit design was kept as simple as possible by using only one filtering component in each matching branch. Also other unnecessary complexity in the circuit was avoided. Combined electromagnetic and circuit simulations (IE3D) confirmed that a single low capacitance in the high-frequency branch and a high inductance in the low-frequency branch helped to isolate the branches from each other well enough to prevent the branches from seriously affecting each other's matching.

A price has to be paid for the increased isolation between the matching branches: The isolating reactances introduce additional reactive energy that causes decrease of bandwidth. If the isolating components can be used as matching elements, the loss of bandwidth is not as evident. In the opposite case, however, it might be necessary to further compensate the loss of bandwidth with yet additional components. Figure 3 shows a tuning circuit design having a return loss of 6 dB or better across the E-GSM900 (880-960 MHz) and GSM1800 (1710-1880 MHz) bands. The simulated bandwidth at the lower frequency band is 880-960 MHz, and 1650-1925 MHz at the higher band. The topology uses a few 'tricks' to allow a good matching for both of the branches. Firstly, there is no excess reactance causing loss of bandwidth in the 900 MHz branch since the series isolating inductor (L_i=22 nH) operates as a matching element (L_{l2}) as well. In addition, the position and inductance of the shunt reactance of the 900 MHz matching circuit (L_{l1}) are designed to improve the isolation, without affecting the matching too much at the 1800 MHz band. An extra series resonator (C_{h3}, L_{h4}) is used in the higher frequency branch to compensate the loss of bandwidth caused by the isolating series capacitor (C_i=1.1 pF), resulting in dual resonant matching.

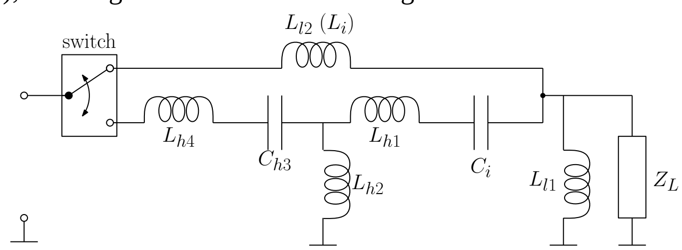

Figure 3: Prototyped circuit topology.

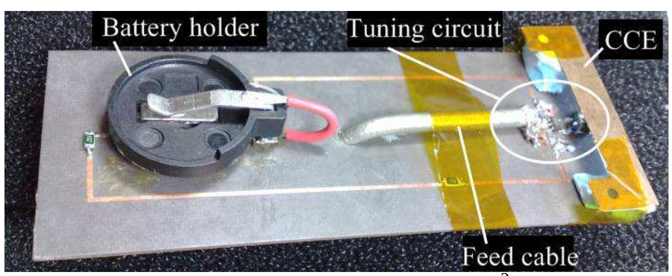

Figure 4: Prototype antenna on a 40×100 mm^2 ground plane.

4 Prototype circuit

A prototype tuning circuit using the topology of Figure 3 was built for a CCE antenna (Figure 1a), see Figure 4 for photograph. The reactance values used in simulation had to be adjusted a little to take parasitics into account. In Figure 5, the simulated and measured $|S_{11}|$ and total efficiency η_{tot} of the antenna are shown. A small difference between the measured and simulated $|S_{11}|$ exists due to parasitic effects in the circuit and possibly the effect of the feed cable and its connection to the circuit. At the lower frequency band, the measured bandwidth corresponds well the simulation result.

The simulated total efficiency η_{tot} of the prototype antenna is between 47% and 65.7% at the E-GSM900 band. At the GSM1800 band η_{tot} is from 51.5% to 61.1%. The measured efficiency agrees well with the simulated efficiency except for the Tx band of GSM1800, where the measured efficiency drops down to 40% at 1710 MHz, possibly due to a weak non-radiating resonance, which should be clarified in future work. The efficiencies are still up to 20 %-units higher than those reported in [4], indicating that omitting one switch from the design saves more power than the components compensating the resulting loss of isolation consume.

IMD_3 of the prototype was measured around the center frequency of E-GSM900 by performing the two-tone intermodulation distortion test with P_{in} = +30 dBm/tone at 919.5 and 920.5 MHz. The measured distortion was -49 dBc. In this case the *on*-state load impedance of the switch was around 50 Ω, which makes a compromise between low losses and low distortion. Still it would be desirable to have lower IMD_3, but the price would be probably additional power loss. An improvement of 36 dB compared to the IMD_3 of the antenna presented in [4] is, however, significant. Distortion measurements at the higher frequency band will be made in future.

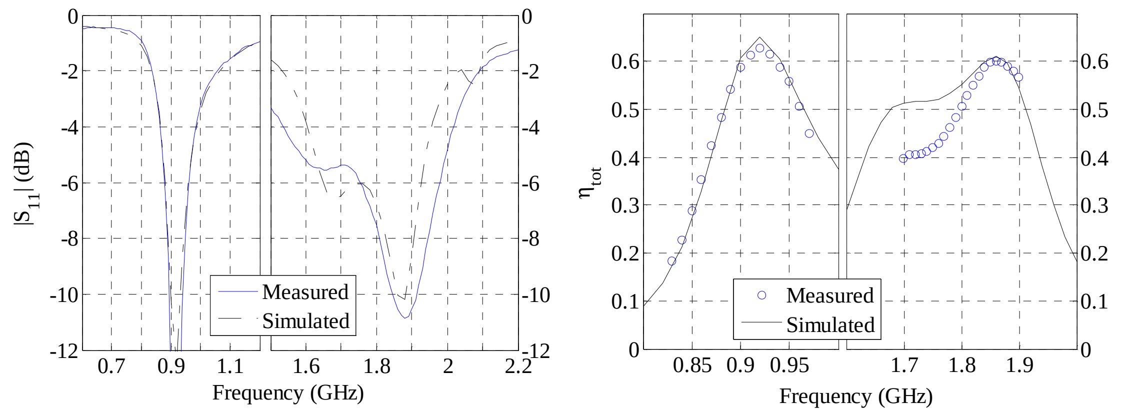

Figure 5: Simulated and measured $|S_{11}|$ (left) and total efficiency (right) of the prototype antenna.

5 Conclusions

The third order intermodulation distortion of a HEMT SPDT switch was measured with different load impedances. Both on-state and off-state loads were perceived to affect the distortion. This suggested that the distortion of a broadband tuning circuit for a mobile terminal antenna can be reduced by avoiding the use of nonlinear elements in certain impedance environments. It was exemplified with a prototype tuning circuit that, nonlinear elements can be replaced by linear elements in the tuning circuit without loss of performance. This can minimize both losses and distortion. The example tuning circuit topology is still rather simple, and could be applied to basically any pair of frequency bands that have a wide relative frequency separation.

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