# Tunable Antenna Design Procedure and Harmonics Suppression Methods of the Tunable DVB-H Antenna for Mobile Applications

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***Abstract*— Using a high-efficiency tunable antenna to cover wide band with good match is an interesting topic, especially in the case when the physical size of the terminal and the antenna is too small to allow for coverage of the full band. A design procedure for tunable mobile antennas is presented. A tunable antenna with the volume of only 6 $\mathrm{cm}^3$ has been designed and fabricated to cover the DVB-H band (470 MHz to 702 MHz) with a return loss of at least 7 dB.**

**A limitation of the tunable DVB-H antenna is its non-linear behavior when it is required to coexist with the GSM transmitter in the same mobile phone. The harmonics generation and radiation is the most critical issue. Low-loss methods to suppress the harmonics are presented and the second tunable prototype DVB-H antenna shows excellent linearity.**

## I. Introduction

Today, broadband mobile services are becoming more and more popular, e.g. DVB-H which features a large fractional bandwidth and low operating frequency. On the other hand, due to the trend of miniaturization, mobile antennas are required to be designed with limited volume. The attainable bandwidth of the antenna is subjected to the fundamental physical limits depending on the size of the terminal [1]. As a result, it is unfeasible to design a mobile antenna to cover all the required bands with good match. A tunable antenna is a solution to this problem.

In this paper, a design procedure for the tunable antennas is given. Following this procedure, an internal small-volume tunable DVB-H antenna constructed on a short printed circuit board is designed and fabricated, which features a simple tuning circuit and shows excellent compared to the published results [2] [3] [4] [5] considering size, efficiency and matching.

As for the DVB-H tunable antenna in the mobile application, coexistence with the cellular transmitter is important. Special attentions are paid to the GSM 850 and GSM 900 systems because their operation frequencies are close to the DVB-H band. A tunable antenna is in principle non-linear when non-linear tuning devices are introduced. Thus, it gives rise to intermodulation, distortion and harmonics radiation.

Methods to suppress the harmonics radiation which is the most critical issue are given. A second tunable antenna is designed and fabricated. The antenna is highly linear with the measured harmonics radiation more than 20 dB below the requirement in standard [6].

## II. Tunable Antenna Design Procedure

The design of a tunable antenna starts with designing a non-tunable prototype antenna, which should fulfill the following requirements: volume, size of the printed circuit board, port definition, etc. The antenna should cover part of the desired band with required matching and efficiency. It should be noted that the optimum bandwidth achieved by the non-tunable prototype antenna in most cases is larger than the instantaneous bandwidth of the tunable antenna at the same center frequency due to the resonances introduced by the tuning elements.

The second step is introducing the tuning devices to make the prototype antenna tunable. In designing the non-tunable prototype antenna, especially during the process to control the operating center frequency $f_\mathrm{c}$, some components of the antenna whose changes affect (almost) only $f_\mathrm{c}$ can be found. The electrical tunability of these antenna components can be implemented by the following ways:

- The tunability of a capacitor can be achieved by a varactor diode whose capacitance range covers the required one.
- The tunability of an inductor with the maximum inductance $L_\mathrm{max}$ to achieve the operating band centered at $\omega_\mathrm{L}$, and the minimum inductance $L_\mathrm{min}$ for $\omega_\mathrm{H}$ can be implemented by a series of two inductors. A control-FET shunts the one with the inductance $L_\mathrm{max} - L_\mathrm{min}$. The other inductor has the inductance of $L_\mathrm{min}$. More tuning states can be achieved by a series of more inductors which are shunted by control-FETs. It can also be approximated by a series of an inductor $L_0 > L_\mathrm{max}$ and a varactor diode with the maximum and minimum capacitance $C_\mathrm{max}$, $C_\mathrm{min}$. The values of $L_0$, $C_\mathrm{max}$ and $C_\mathrm{min}$ should fulfill

$$C_\mathrm{max} = \frac{1}{\omega_\mathrm{L}^2 (L_0 - L_\mathrm{max})}, \tag{1}$$

$$C_\mathrm{min} = \frac{1}{\omega_\mathrm{H}^2 (L_0 - L_\mathrm{min})}. \tag{2}$$

- Two single-pole-$n$-throw switches can be used to electrically choose among $n$ different circuits, e.g. matching networks.
- One switch can be used to change the position of the connection, e.g. to change the feed point position. It should be noted that, for most of the switches in market, the output pin is either grounded or connected to a 50 $\Omega$ internal load when it is "off". Only a few switches present open pins.
- The tunability of the length of the transmission line can be implemented by using a control-FET to shunt part of the transmission line, or using two SP$n$Ts with $n$ transmission lines of different lengths in between.
- Mechanical tuning elements e.g. MEMS or piezoelectric elements can also be used

The control-FET (e.g. AF002C4-39 and AF002C1-39 from Skyworks Solutions, Inc.) is different from the switches like single-pole-single-throw switch. The control-FET has three pins, the gate for control, the source and drain for the RF signal, like a conceptual switch. It can be described by a close-state resistance and an open-state capacitance. Switches have more pins, whose output pin is normally grounded or connected to 50 $\Omega$ load to improve the isolation, when this pin is "off". They are usually described by their S-parameters.

## III. DVB-H Design Consideration

The specifications of DVB-H are given in [7]. For a mobile phone supporting EGSM 900, the DVB-H antenna is required to cover the band from 470 MHz to 702 MHz (fractional bandwidth of 40%). The fundamental physical limit on the attainable bandwidth is given in [1]. A somewhat tighter, more realistic limit was derived in [8]. For a DVB-H antenna mounted on a $110\,\mathrm{mm} \times 55\,\mathrm{mm}$ printed circuit board, which is typical for a bar-type mobile phone, it predicts an upper bound on the fractional bandwidth of 34% for 7 dB return loss. Since this bound is still optimistic compared to the practical results, use of a tunable antenna is an obvious choice to overcome the bandwidth limitation without adding volume.

The second consideration for the DVB-H application in mobile phone is the coexistence with GSM. To suppress the noise tail of EGSM transmitter in DVB-H band, a bandpass filter instead of a lowpass filter is put between the EGSM transceiver and the EGSM antenna. Another bandpass filter is placed between the DVB-H receiver and DVB-H antenna to attenuate the EGSM TX (880 - 915 MHz) signal below $-25$ dBm, which is the maximum allowed out-of-band unwanted signal level of DVB-H receiver [7].

## IV. Design of the 1st Prototype

The tunable DVB-H antenna is mounted on a $110\,\mathrm{mm} \times 55\,\mathrm{mm}$ printed circuit board. It is designed as a capacitive coupler in front of the short edge of the printed circuit board (Fig. 4). To avoid the exposure of the non-linear tuning devices to the EGSM TX signal, a two-port antenna structure is selected. The TX signal will first couple from the EGSM coupler to the printed circuit board, then couple to the DVB-H coupler from the printed circuit board [9]. These two coupling processes provide attenuation of the TX before it enters the tuning circuit. To maximize this isolation effect while maintaining good coupling between each coupler and the printed circuit board, DVB-H and EGSM couplers are put at the opposite edges of the printed circuit board.

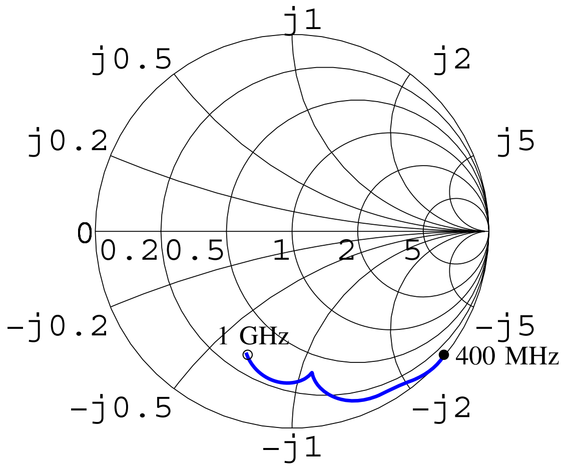


Fig. 1. Simulated input impedance of the DVB-H coupler from 400 MHz to 1 GHz, by CST Microwave Studio.

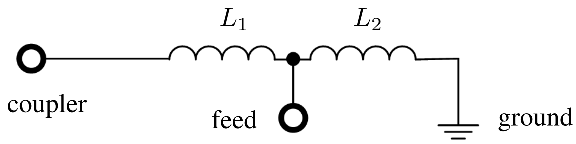


Fig. 2. Schematic of the matching circuit for the non-tunable prototype DVB-H antenna.

The simulated input impedance of the DVB-H coupler from 400 MHz to 1 GHz by CST Microwave Studio is shown in Fig. 1. The matching circuit shown in Fig. 2 is used in the non-tunable prototype antenna to match this impedance to a 50 $\Omega$ feed. $L_1$ is used to change $f_\mathrm{c}$, the larger the $L_1$, the lower the $f_\mathrm{c}$. The non-tunable prototype antenna estimates $L_\mathrm{max} = 30\,\mathrm{nH}$ for $\omega_\mathrm{L} = 2\pi \cdot 470\mathrm{MHz}$, and $L_\mathrm{min} = 9\,\mathrm{nH}$ for $\omega_\mathrm{H} = 2\pi \cdot 702\mathrm{MHz}$. The optimum 7 dB bandwidth attained by the non-tunable prototype antenna is around 25 MHz with $f_\mathrm{c}$ of 470 MHz, and 60 MHz with $f_\mathrm{c}$ of 702 MHz. The bandwidth becomes larger when $f_\mathrm{c}$ approaches the resonance frequency of the printed circuit board (about 1 GHz) [9] [8]. It is estimated by the non-tunable prototype antenna that at least 7 tuning states are needed to cover the whole DVB-H band.

To implement the 7-state tunable inductor, the structure with two single-pole-7-throw switches and 7 different inductors in between is not preferred, due to the high insertion loss introduced by the two switches (over 0.7 dB each), and complicated layout. The structure with series of inductors shunted by control-FETs in this application introduces resonance near DVB-H band due to the open-state capacitance of the control-FETs.

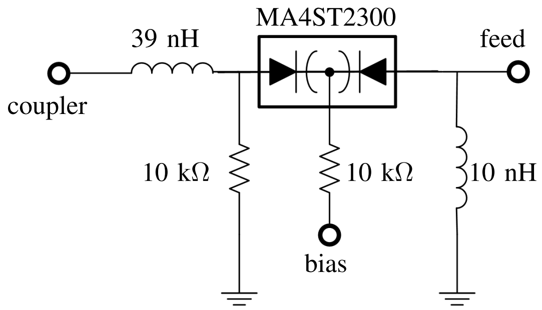


Fig. 3. Schematic of the tunable matching circuit for the 1st prototype tunable DVB-H antenna.

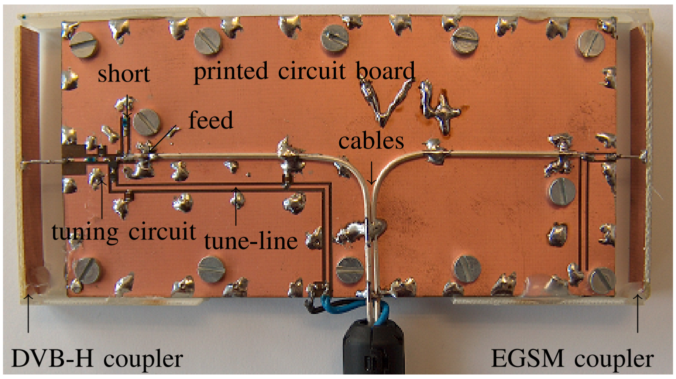


Fig. 4. Photo of the 1st prototype tunable DVB-H antenna, together with an EGSM antenna attached to a 110 mm ×55 mm printed circuit board.

The tunable inductor is approximated by a varactor in series with an inductor. The series inductance $L_0$ is chosen to be 39 nH. By Equ. 1, $C_{\text{min}} = 1.7\,\text{pF}$ and $C_{\text{max}} = 13\,\text{pF}$. The ASVP (anti-series varactor pair) MA4ST2300-CK by MACOM which can cover this capacitance range is selected. The structure of ASVP can suppress the harmonics. The tunable matching circuit is shown in Fig. 3. The top and bottom layers of the printed circuit board are connected by vias for unique definition of the ground plane. The photo of the first tunable antenna prototype is shown in Fig. 4.

## V. Measured Result of the 1st Prototype

Fig. 5 shows that the tunable DVB-H antenna covers the frequency range from 442 to 758 MHz (55% fractional bandwidth) with maximum −7 dB reflection magnitude, for the tuning voltage in the range from 0 to 5 volts. The instantaneous bandwidth is 26 MHz centered at 450 MHz, and 50 MHz centered at 650 MHz and above. The measured radiation efficiency by Wheeler cap is 25% at 470 MHz and 65% at 710 MHz. EGSM 900 is covered with maximum −7 dB reflection magnitude. The isolation between the ports of the two antennas is over 17 dB.

The coexistence of tunable DVB-H antenna and EGSM transmitter is important. As the highly non-linear varactor diodes are introduced, the spectrum of EGSM TX with the peak power of 33 dBm will be distorted, harmonics will be generated. The requirements on the in-band output spectrum

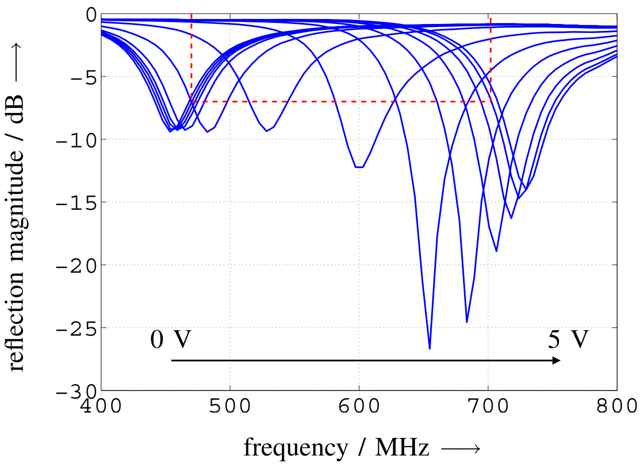


Fig. 5. Measured reflection magnitude over frequency of the 1st prototype tunable DVB-H antenna for tuning voltage in the range from 0 to 5 V. The dashed line denotes the target 7 dB return loss in the DVB-H band.

and out-of-band spurious emission are given in [6]. In practice, spurious emission (harmonics radiation) is the most critical issue. The harmonics of the antenna is measured by feeding 33 dBm CW signal at 903 MHz (center channel of EGSM 900 TX) to the EGSM port, with DVB-H port terminated by a 50 Ω load. The harmonics generated by the antenna was measured by a receiving antenna. The radiated harmonics power was calculated based on the assumption that the antenna radiates the harmonics isotropically. The measured maximum harmonics exceeds −30 dBm requirement by less than 1.5 dB, when the antenna is tuned above 650 MHz.

## VI. Harmonics Suppression Methods

The harmonics radiation of the tunable DVB-H antenna can be suppressed by various methods shown in Fig. 6. Several modules are introduced into the tunable matching circuit, which are: a filter between the coupler and the ASVP to block the EGSM TX from entering the ASVP (module a); a passive (LC) circuit in parallel with the ASVP to shunt the EGSM TX current (module b); a passive circuit in series with the ASVP to divide the EGSM TX voltage over the ASVP (module c). Module c can contain a second tuning device to maintain the coverage of the whole band.

Module a is chosen to design the second prototype tunable DVB-H antenna whose tunable matching circuit is presented in Fig. 7. A third-order Chebychev bandstop filter for the EGSM-TX (over 70 dB simulated attenuation) is put directly after the DVB-H coupler. In tunable antennas bandpass and lowpass filters can not be used for the DVB-H signal.

## VII. Measured Result of the 2nd Prototype

Fig. 8 shows that the 2nd tunable DVB-H prototype antenna covers the frequency range from 462 to 696 MHz (41% fractional bandwidth) with minimum 7 dB return loss, for the tuning voltage in the range from 0 to 2.2 volts. The dashed line denotes the target 7 dB return loss in the DVB-H band.

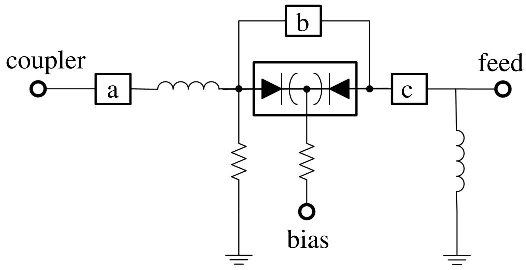


Fig. 6. Schematic of the tunable matching circuit with harmonics suppression modules, with a, the filter to block EGSM TX from entering the ASVP; b, the EGSM TX current shunt module; c, the EGSM TX voltage dividing module.

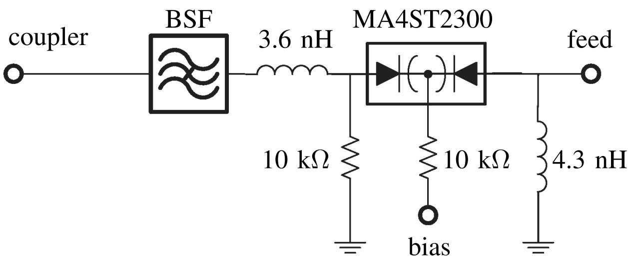


Fig. 7. Schematic of the tunable matching circuit for the 2nd prototype DVB-H antenna.

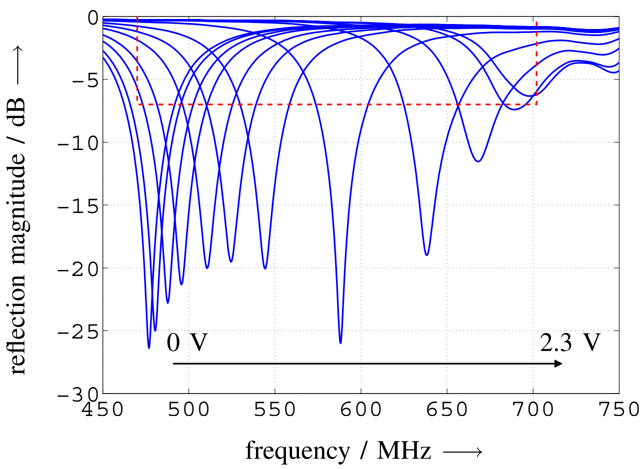


Fig. 8. Measured reflection magnitude over frequency of the 2nd prototype DVB-H coupler for tuning voltage in the range from 0 to 2.3 V. The dashed line denotes the target 7-dB return loss in the DVB-H band.

The instantaneous bandwidth is larger than 10 MHz. Further optimization of the components of the bandstop filter can increase the instantaneous bandwidth at 2.2 V, and make the antenna cover the DVB-H band. The EGSM antenna shows over 9 dB return loss in EGSM band. The reflection magnitude is slightly affected by the change of the tuning voltage.

For the harmonics radiation measurement, result is given in Tab. I. The measured harmonics levels are over 20 dB lower than what is required by standard [6].

Compare to the 1st prototype, the isolation of the two ports in EGSM band increases to 46 dB by 29 dB, which greatly alleviates the design of the bandpass filter before the DVB-H receiver. The bandpass filter can be designed with lower order which leads to lower insertion loss. Thus, the loss introduced by the bandstop filter can be compensated by this bandpass filter simplification.

TABLE I

THE HARMONICS RADIATION LEVELS OF 2ND PROTOTYPE DVB-H TUNABLE ANTENNA AT DIFFERENT TUNING VOLTAGES.

| tuning voltage / V | 0.0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.3 |
|---|---|---|---|---|---|---|
| center frequency / MHz | 477 | 496 | 524 | 589 | 669 | 697 |
| 2nd harmonic / dBm | -56.6 | -56.6 | -57.0 | -56.5 | -57.1 | -57.0 |
| 3rd harmonic / dBm | -52.7 | -51.8 | -52.7 | -52.8 | -52.8 | -53.0 |

## VIII. Conclusion

A design procedure for tunable DVB-H antennas for mobile applications is presented. Two antenna prototypes are designed and fabricated on short printed circuit boards, covering the DVB-H band well matched. Both of them feature simple structures and easy control.

Harmonics radiation is critical when the DVB-H tunable antenna is required to coexist with the EGSM transmitter in the same mobile phone. Methods to suppress the harmonics radiation are shown. By utilizing the suppression method, the second designed antenna shows great improvement on linearity over the designed one. This suppression method also leads to greatly improved isolation between EGSM and DVB-H ports, which reduces the demands to the bandpass filter before the DVB-H receiver. Thus, the loss introduce by the harmonics suppression method can be compensated.

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