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A Reconfigurable High-Q Antenna for Automotive Applications

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***Abstract*—This paper is a review of the way in which the high-quality factor antennas can be used to integrate the VHF and HF car's antennas in one device. The usage of the citizen band (CB) antennas in an HF band extends the environmental awareness of the driver and could increase the safety of the traffic. Usually, the citizen band transceiver with its antenna isn't installed in a brand new car but the FM radio receiver it is. The main constraints that are related to the size difference between the two antennas (in FM and CB) make the main car manufacturers let the matter regarding the CB usage, open, at the choice of the buyer. The paper analyzes the technological advancements in the field and investigates some alternatives to the issue that will allow an opening through a single antenna usage for both radio bands.**

Keywords—reconfigurable antenna, automotive, citizen band

I. INTRODUCTION

A super-antenna is the one that is pushing its parameters near the limit in order to offer a good reception. These limits of antennas are identified by R. C. Hansen in [1]: the shortening, the resolution, the super-gain, and the super-directivity in this order. This paper is a review of the first limitation, which is the main concern for car operators, especially in urban locations but also on the roads, far away from urban radio spots. The most important question the paper is trying to answer is, in fact, how short an antenna could be cut and still operate acceptably in a car. In the literature are a lot of ideas about how we can cut short an antenna and still radiates or, at least, resonate at the working frequency. One shortened antenna is worth, to begin with, is being commercialized by *Heath Tech Inc.,* located near Sierra Nevada mountains [2]. The antenna is designed for working on mobile in all HF radio bands being designed to tune automatically with an actuator (DC motor with a reduction gear – see [3]). The owner applies the simple principle according to, any "wire" should be tuned, in fact, only using an antenna tuner (AT). This makes sense because the antenna is a resonator at any desired frequency if one uses an external LC circuit. Naturally, an antenna resonates itself at the frequency $f_0 = \frac{c}{\lambda} = \frac{c}{2l}$ where l is its length and c is the speed of light, roughly $c = 3 * 10^8 m/s$. The antenna *High Sierra Sidekick*, known as "*screw drive antenna*" has a DC motor at the base with a reduction gear which actuates a cursor that modifies the inductive value of the AT-coil. *High Sierra Sidekick* is actually a quarter wavelength antenna (a *Marconi* monopole) which uses the metal ceiling of the car as an electric ground to reduce its size to half. So the self-resonance of the antenna in the proximity of an ideal ground plane (as car's ceiling) is $f_0 = \frac{c}{\lambda} = \frac{c}{4l}$. That's why the producer warns the user of a bad mounting anywhere else. When the antenna is used without a ground plane or counterpoised (or radials) due to its inductive coil with high Q (a phenolic coil) the high voltage could cause damage to the AT or possibly to the transceiver itself. The usage of the high Q antenna is a dangerous process that could jeopardize the transmitter system, especially for high power use. That's why the power is limited to a maximum of 300 W for a good mounting. Periodically the verification of the connections especially to the ground is a must for reliable operation.

Fig 1. High Q antenna for HF radio bands (3-30 MHz) [2]

In the top, the antenna has a flexible wire (the whip) of roughly 0.9 meters made from steel. When fully retracted has 1.2 meters and 1.37 meters when fully extended. An extra detachable whip for better results in 80/40 meters of roughly 1.8 meters can be used instead of the shorter one of only 0.9 meters. There is also a US patent numbered 9,065,178 B2 belonging to Charles M. Gyenes in which the idea of the shortening with the help of the adjustable high Q inductor is claimed. Anybody can consult its claims at [3]. In figure 1 are some differences from the original patent as to replacing the stepper motor with a DC 8-24V motor with a reduction. The term used is the "*screw drive*" related to the actuation of the DC motor that allows the tuning in HF radio bands from 10 to 80 meters. The antenna is presented by its inventor as being the shortest antenna ever made. This may be true because as this review will present further, its size is near the Chu-Harrington limit. This could be a good start for a compromise between the two demands of CB antennas that are working in HF band and the VHF antenna for FM reception. The compromise is necessary here because of the size differences between the two and the need for a single integrated antenna (two in one), mounted over the car's ceiling.

II. Antenna Modeling

Modeling a shortened quarter-wave monopole that uses a perfect or a good ground is a straightforward task. The antenna is using two different wires, at the bottom, near the coil, we have a coper made and at the top, a flexible whip, made from steel. The most appropriate EM-simulator for wire antenna is NEC (Numeric Electromagnetic Code). This simulator is using the Method of Moments to analyze the antenna. The wire is cut into many segments that are at least ten times smaller than the wavelength. In the NEC2 is not a good idea to tap the wire using different diameters due to the limitations of the simulator. This yields inaccurate results by under-estimating the impedance which is unfortunate because we get very low input impedance value anyway. By under-estimating a low input impedance for a high Q antenna that could lead to erroneous results in terms of structure losses. Some corrections are made in NEC2 to overcome this problem but are not applicable for nonsymmetric elements like in the case of the monopoles. The Sidekick antenna is a quarter-wave, so the use of the mono-tapering wire is a must. The use of the mono-tapering would not lead to any problems related to the antenna bandwidth because in this case, the high Q antenna has a very narrow bandwidth which is upper bounded by the quality factor of the coil which is much higher than the quality factor of the wire alone anyway. So a small variation of the quality factor due to the effect of the variation of the wire's diameter is not an issue that should concern anymore. In Europe, the citizen's band assignment depicts 40 non-overlapped radio bands with a 10 KHz offset each. This offset allows the usage of the high Q antenna which has a small bandwidth too. The VHF antenna demands a higher offset, so the high Q antenna is not suitable for this type of approach at first glance. This restriction changes the way the antenna is operating in both bands. A combination of the high Q with a low Q antenna could be the best drawback the paper proposed here. Inside the citizen's band, the antenna will operate from 26.965 to 27.405 MHz, so the minimum wavelength is about 10 m. For twenty segments per wavelength, one gets 0.5 meters per segment. In this case, the overall length of the radiator must be smaller than 0.5 m, comparable in size with a common antenna used in an auto vehicle. This is comparable to the size of the segment also. The diminishing of the segment much more below 0.001λ increases the instability of the simulator and its convergence. Here a good compromise is to use eight segments for the overall length of 1.2 m which is only 0.15 m per segment with some drawbacks in terms of simulation resolution. The idea of the shortening is simple and remains the same here. That is to cancel the parasitic capacitance with an inductance in order to keep the electrical length constant at a quarter-wavelength for any physical length. A wire smaller than a half-wavelength will always exhibit a higher parasitic capacitance. When the wire is longer than a half wavelength will depict a higher parasitic inductance. A series capacitance will make antenna electrically shorter and a series inductance, electrically longer. Thanks to the reference [4] a Java-script code is allowing the series inductance calculation. Another reference source for a quarter-wave offloaded antenna calculation can be found in [5]. Figure 2 is the schematic of the antenna, modeled in 4NEC2. The ground ceiling of the car stands for the electric ground the antenna used in order to resonate at 26.99 Mhz. The feed point is located at 2.5 cm upon the ground plane and inductance L at 10 cm.

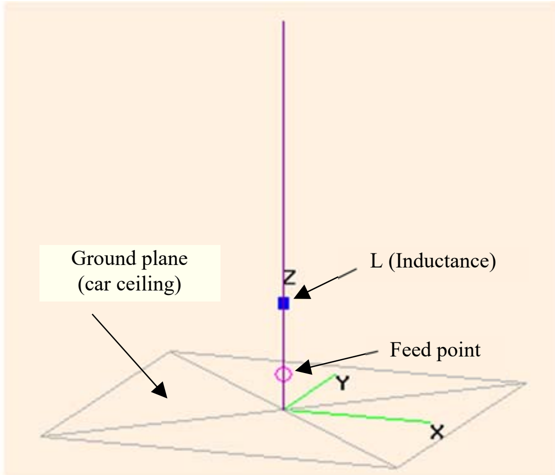


Fig. 2. High Q antenna in 4NEC2

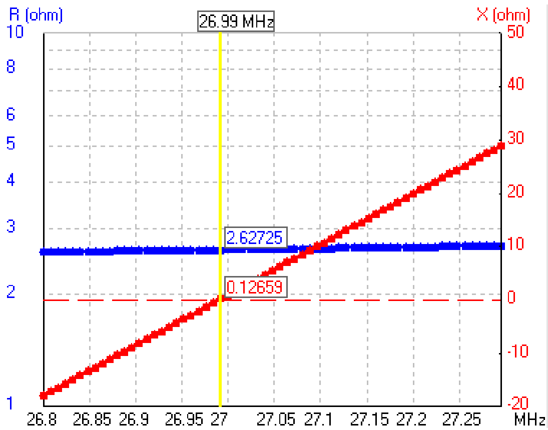
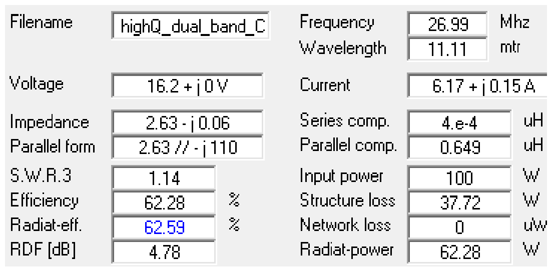


Fig. 3. Input impedance versus frequency



Filename	highQ_dual_band_C		Frequency	26.99	Mhz
			Wavelength	11.11	mtr
Voltage	16.2 + j 0 V		Current	6.17 + j 0.15 A	
Impedance	2.63 - j 0.06		Series comp.	4.e-4	uH
Parallel form	2.63 // - j 110		Parallel comp.	0.649	uH
S.W.R.3	1.14		Input power	100	W
Efficiency	62.28	%	Structure loss	37.72	W
Radiat-eff.	62.59	%	Network loss	0	uW
RDF [dB]	4.78		Radiat-power	62.28	W

Fig. 4. The 4NEC2 program interface with the signal parameters at 26.99 MHz

In figure 3 the input impedance exhibits low values near the RF ohmic resistance of the coil. This is going to alter the radiation efficiency of the antenna and also should be the price paid for the shortening. Figure 4 depicts program parameters at the working frequency. The efficiency of the antenna it drops to 62% as previously mentioned. The high current that is flying through the antenna increases loss and keeps the input impedance low. A balun (balance to unbalance device) must be taken into account to transform the impedance from 50 Ohms to 3 Ohms. The impedance transformer will keep the VSWR under 2:1 and will assure a good energy transfer from transmitter to the antenna.

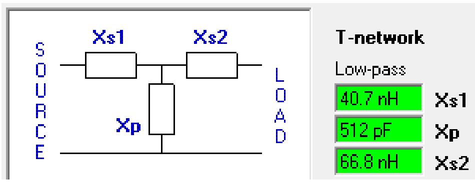


Fig. 5. The impedance transformer between load (antenna) and transmitter (source)

In figure 5 a T transformer is depicted. The low pass characteristic of the network is selecting the useful signal and cuts the VHF spurious components.

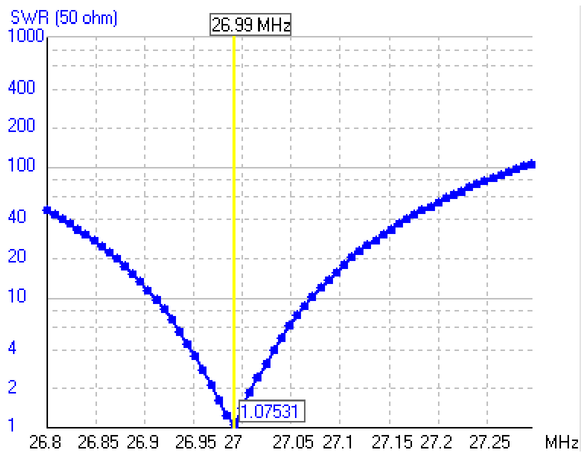


Fig. 6. The effect of the transformer over the VSWR (Voltage standing wave ratio)

TABLE I. INDUCTANCE AS A FUNCTION OF THE CB CHANNELS

Band index	Frequency [MHz]	Induct. L [μH]	VSWR X:1	RL [dB]
1,2,3	26.99	7.4	1.07:1	28.8
4,5,6	27.02	7.38	1.04:1	33
7,8,9	27.06	7.36	1.14:1	23
10,11,12	27.1	7.34	1.03:1	35

The effect of the impedance matching due to the use of the network from figure 5 is depicted in figure 6. The bandwidth limited by the VSWR at 2:1 is roughly 30 KHz, three times higher than the offset of the CB band plan. In table 1, column three the resulted inductance is depicted and is allowing the reception at the specified index. Every other three bands are selected with a small change of about 200 nH. This change can be implemented in practice if a relay switch by in a short circuit at the terminals at each 200 nH inductance in a series inductive array. The branch could be selected automatically when the working frequency is changed.

III. APPROACHING THE CHU-HARRINGTON LIMIT

L. J. Chu together with H. Wheeler between 1948 and 1960 and, later on, R. Harrington develop a theorem that defines the limit of the Q factor for a small radio antenna [6]. In their reviews, a small antenna is a device that can fit into a sphere with the diameter:

$$D = \frac{\lambda}{2\pi} \approx 0.16\lambda \,, \tag{1}$$

Chu established the limit of the quality factor Q for a lossless antenna, being greater or, at least, equal to the summation:

$$Q \geq \frac{1}{k^3a^3} + \frac{1}{ka} \,, \tag{2}$$

where:

k – is the phase constant of the wave $k = \frac{2\pi}{\lambda}$,

a – is the radius of the sphere that circumvents the antenna.

For a resonant device like the antenna the bandwidth will be:

$$BW \approx \frac{f_0}{Q} = \frac{c}{\left(\frac{1}{k^3a^3}+\frac{1}{ka}\right)\lambda} \,, \tag{3}$$

where:

c – is the speed of light in vacuum,

f_0 – is the resonant frequency of the device.

James s. McLean shows in his paper [7][8] that the power radiated for a spherical-mode (which is the propagation mode, specific just near the radiator device) is:

$$P_r\% = \frac{k^2a^2}{1+k^2a^2}100\% \,, \tag{4}$$

(an amount in % from the total injected power).

Let us remark that for the SideKick antenna $ka = \frac{2\pi}{\lambda}\frac{l}{2} = \frac{2\pi}{83m}\frac{1.5m}{2} \approx 0.0568$ then we get $\frac{1}{ka} \approx 17{,}60$ the second term of the Q formula (2), $\frac{1}{k^3a^3} \approx 5452$ the first term of the Q, equation 2.

As one can remark the first term is much higher than the second when ka is small (this is the case of shortened antennas with high Q like Sierra Sidekick). So in this particular case for the shake of simplicity we can consider the approximation of the Q factor:

$$Q \geq \frac{1}{k^3a^3} \,, \tag{5}$$

So we can imagine now, the effect of the high Q factor upon the normalized radiated power when we reconsider the McLean formula:

$$P_r = \frac{k^2a^2}{1+k^2a^2}Pin \leq \frac{1}{Qka+1}Pin, \tag{6}$$

So is obviously know that the higher the Q, the lower the radiation power will be. A high Q antenna is, in fact, the equivalent of a *bad radiator*. A contradiction in terms actually as long as the Q factor measures the efficiency of the power preserved inside an oscillator. In the case of an antenna we do not want to *preserve* the power inside the field zone but to radiate it through outside as much it gets. The preserved energy or non-propagating energy is:

$$W_E = \frac{QP_r}{4\pi f} \leq \frac{Q}{4\pi f}\frac{1}{Qka+1}P_{in} \approx \frac{ka}{4\pi f}P_{in}, \qquad (7).$$

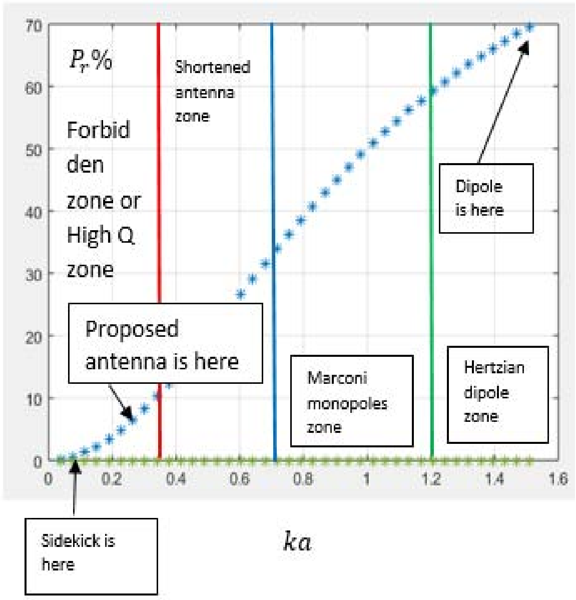


Fig. 6. Plotting the radiated power in percentages vs. *ka* using McLean formula (6)

In figure 6 the radiated power as a function of the ka terms is shown. As long the antenna is no longer than 0.75 m then the radius of the sphere that circumvents the antenna is smaller than 0.5 m. In such circumstances, the proposed antenna has a lower radiation efficiency in reality, yet a very small one in size. For a inserted power of about 100 W one can achieve the same radiated power as one could normally attend with a 1.5 m antenna with only 30 W. This is a good compromise that could be taken into account at the series vehicle production that can integrate it into the ceiling as it does ~~for~~ now for VHF antenna and to use its coil for other purposes [9].

IV. Conclusions

Pushing the antenna to the limit or even beyond is possible and has been an engineering debate for many years. More recently researchers in antennas show in scientific papers that this is possible without violation of the mathematical bound. For instance, we can keep the antenna wire at 0.2λ not to drop the Balanis limit from figure 6 but to meander the line to squeeze the antenna space (see figure 7). This is the basic idea of the meander-line antenna which stands just near the Chu limit. This antenna is used now in small devices like phones or tablets (see figure 7). Another way to push an antenna near the Chu limit is to use fractals to bend wisely a wire and to squeeze the antenna space. Even beyond the Chu limit is possible to design an antenna without any violation of the Chu law. This is possible for a circularly polarized antenna for which the Chu limit is twice higher than normal for a linearly polarized antenna [7]:

$$BW_{circularly\ polarized} \approx \frac{f_0}{Q} = \frac{2c}{\left(\frac{1}{k^3a^3}+\frac{1}{ka}\right)\lambda} = 2BW, \ (8).$$

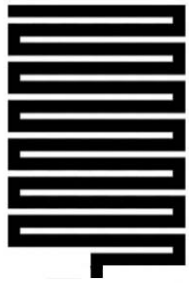


Fig. 7. Meandering antenna used in mobile devices like phones and tablets

The limitation is still there (see (8) and [8]), always exists and is not allowing us to exaggerate in the antenna shrinking or in designing some sort of magic punctiform antenna with the same performance as a YAGI array. The Chu limit warns as to the fact that an antenna is an interface between the electric world and the fields and this has a limit in terms of electrical/physical length ratio. If one would consider an analogy with a guitar cord that represents the antenna resonator, the instrument can still play when someone is shortening the guitar cord by keeping the device tuned upon the same tone, but the sound will vanish progressively until we can't hear it anymore. In the case of the FM usage a relay can short the inductance placed in series with the antenna whip wire to get the FM signal. In this case we get a one meter long wire which is enough for a good FM reception. Most FM antennas used on the auto vehicles are even smaller but in normal circumstances when the manufacturer offers a decent FM antenna this will be roughly 0.8 meters. In citizen band an antenna under one meter is diminishing drastically the radiation efficiency and is not a good choice. When we take into account the maximum power allowed by regulations for citizen band (up to 4 W) this will underline the need for an efficient antenna. Only an amplifier could compensate the shortening and its inefficiency. In some countries, it is allowed to use a co-phased array antenna that will double (at least) the efficiency of the same size.

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