ANTENNA DESIGN STRATEGY AND DEMONSTRATION FOR SOFTWARE-DEFINED RADIO

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ABSTRACT

Antennas are a key enabling technology for SDR, because although software is extremely flexible, SDR's potential is limited by antenna size and performance. In this paper, we review typical antenna miniaturization techniques and fundamental theories that limit antenna size and performance including operational bandwidth, gain (or range), and radiation pattern. Possible antenna design strategies are discussed to meet the desired specifications in software-defined radios based on observations on the limit theories. The application of strategies to enable multiband (resonant), continuous multiband (frequency independent), and instantaneous, ultra-wideband antennas will be discussed. Advantages, disadvantages, and design trade-off strategies for different types of antennas are compared from a system level perspective. A design example of a compact ultra-wideband (UWB) antenna is presented for a software-defined platform. The example involves a direct conversion radio board developed in Wireless@VT that uses a Motorola RFIC having a 100 MHz - 4 GHz operational frequency range with a 9 kHz to 20 MHz channel bandwidth. The example antenna covers frequencies from 450 MHz to 6 GHz instantaneously with approximately 5-dBi realized gain over a ground plane, including return loss and omni-directional coverage.

1. INTRODUCTION

Software-defined radios (SDR) offer opportunities for a variety of applications in consumer electronics, public safety, and military. However, there are practical design issues because of the required wide operating frequency range from HF to C-band and beyond. The required operational bandwidth should be considered for analog functions (antennas and RF front ends), digital operations (baseband and software), and transition domains (ADC/DAC) during the implementation of a software-defined radio. Software-defined radios may be configured in various architectures to sustain the frequency-agile capability in a wide operational band, but the common bottleneck of the various architectures is the antenna. The stated wide-operating frequency range need not be covered instantaneously for some applications, but it is still very challenging to design a simple, rugged, highly-efficient broadband antenna with a compact footprint. Achieving ideal antenna performance is limited by radiation physics principles, not technology. Therefore, an important key to successfully developing high-performance, compact antennas for software-defined radios is to understand antenna radiation physics and apply the associated physical-limit constraints (fundamental limit theory) from the start of the system design process.

In this paper, we first overview typical antenna miniaturization techniques to obtain an idea about the practical aspects of the antenna size reduction. The review of the classic fundamental-limit theory on antenna size and performance leads to a better understanding of the trade-off relationship on antenna size and performance. Based on these reviews, we discuss possible antenna design strategies for software-defined radios. A compact, ultra-wideband antenna is introduced as a design example.

2. ANTENNA MINIATURIZATION TECHNIQUES

Many antenna designs have been introduced over the years, but most of them are a variation of, or a combination of, well-known canonical antennas for specific needs. If these antennas meet the required operational bandwidth for software-defined radios, one can apply antenna miniaturization techniques to satisfy the antenna size specification.

Some typical antenna miniaturization techniques are illustrated in Figure 1. Antenna size can be reduced by impedance-loading (R, L, and C) and/or by slow-wave structures (e.g. zig-zag, meander lines, etc.). The loading enables the antenna to be tuned to lower operating frequencies, but typically gives the antenna a more narrow impedance bandwidth. Resistive loading is effective at increasing the impedance bandwidth, but sacrifices radiation efficiency. Thus, resistive loading results in reduced gain and ohmic heating. Magnetic-material loading tends to be lossy, heavy, and typically readily available only for frequencies below 1 GHz. Loading with high dielectric constant materials, such as low-temperature co-fired ceramics (LTCC), leads to substantially reduced impedance bandwidths. Magneto-dielectric material loading to reduce the antenna size and the reflections from the material-to-air boundary is a straightforward technique to miniaturize antennas, but high magneto-dielectric materials ($\varepsilon_r > 10$ and $\mu_r > 10$) are not readily available on the market. Slow-wave structures such as fractals and meandering lines can reduce the size of antennas, but sacrifice gain due to the cancellation of currents in the far field.

Recently, metamaterials have been heavily explored as a means to produce miniaturized, high-performance antennas [2]. Metamaterials are composite structures with physical features engineered to give them properties that cannot be found in natural materials, like double negative materials (DNG, $\varepsilon_r<0$ and $\mu_r<0$). In some cases, metamaterials have been shown to reduce the electrical size of antennas, improve the front-back ratio of antenna patterns, and prevent the generation of surface waves to improve gain. DNG materials have been used to mitigate scan blindness of array antennas. Metamaterials, however, are most often composed of periodic and inefficient metallic resonator structures that store electric and magnetic energy at the desired frequency. The excessive use of these structures makes the antenna inefficient due to ohmic losses in the conductors storing the energy. In addition, DNG materials only provide their novel properties over narrow frequency bands and are highly dispersive, with frequency-dependent delay that is unsuitable for wideband signals.

Negative-impedance converters (NIC) [3] can be employed to operate antennas below their intended original operating frequency range. However, because active devices are used to emulate non-physical passive components, negative-impedance converters often suffer from instability issues.

The above mentioned techniques can be effective for a limited operational frequency range. However, extreme size reduction using any of these techniques will result in decreased efficiency and/or reduced bandwidth, which corresponds to a trade-off relationship in the fundamental-limits on antenna size and performance.

3. FUNDAMENTAL-LIMIT THEORY AND TRADE-OFFS ON ANTENNA SIZE AND PERFORMANCE

Wheeler [4] first introduced the concept of the fundamental-limit theory on antenna size and performance. A year later, Chu [5] proposed a modern form of the theory. Chu used radiation Q as a figure of merit, defining Q by [5]

$$Q_{rad} = e_r \omega \left[W_{non-rad} \right]_{peak} / \left\langle P_{rad} \right\rangle \tag{1}$$

where e_r is the radiation efficiency (= P_{rad} / P_{in}), ω is the angular frequency, $W_{non\text{-}rad}$ is the non-radiating energy, and $\langle P_{rad} \rangle$ is the average radiated power of an antenna. It is well known that the radiation Q is inversely proportional to 3-dB fractional, instantaneous impedance bandwidth for single-resonant antennas. Particularly, for a high Q ($Q > 10$) or an electrically-small antenna case, the radiation Q can be evaluated from the fractional impedance bandwidth, i.e.

$$Q_{rad} \simeq f_c / BW_{3dB} \tag{2}$$

where f_c is the center frequency. Therefore, the radiation-Q for a given antenna size is related to impedance bandwidth and radiation efficiency (or radiation gain).

For example, Chu's minimum radiation Q for the fundamental spherical mode (TM_{01}, dipole mode) is given as

$$Q_{rad,\,Chu}^{\min} = e_r \left(1 + 2k^2a^2\right) / \left[\left(k^3a^3\right)\left(1 + k^2a^2\right) \right] \tag{3}$$

where k is the wave number (= 2π / λ) and a is a radius of the sphere just enclosing the antenna (*antenna sphere*). Note that the radiation-Q of higher-order spherical modes is higher than that of the fundamental mode. Thus, the limit of radiation-Q for the spherical TM_{01} mode is the ultimate lower-bound. Chu used equivalent circuit models of the wave impedances of the spherical TM modes in his derivation of the minimum radiation-Q. As Eq. (3) implies, radiation-Q cannot be zero unless the radiation efficiency becomes zero or antenna size (a) is infinite. Thus, there must be a minimum non-radiating energy inside or around the antenna sphere in order for the antenna to radiate, which is governed by law of physics, not advances in technology. As a matter of fact, it can be shown that the minimum radiation-Q can be derived from the condition that the energy associated with antenna radiation phenomena is equal to or greater than zero at any given time. In addition, the limit of minimum radiation-Q for an electrically-small, single-resonant antenna is equivalent to the limit of maximum impedance bandwidth to a first-order approximation as indicated in Eq. (2).

Since Chu's early contributions, many researchers have investigated the antenna size-and-performance limit. However, it turned out that all previous developments, including Chu, were in error due to the wrong implicit assumption for the speed of the radial energy velocity [6]. Based on this observation, Davis *et al*. proposed a new minimum radiation Q as [7]

$$Q_{rad,\,VTAG}^{\min} = e_r / \left(k^3a^3\right) \tag{4}$$

which is slightly lower than Chu's result except for $ka << 1$. Eq. (4) appears the same as Wheeler's minimum radiation-Q formula in [4]. However, Wheeler's minimum radiation-Q was developed with the assumption of $ka << 1$, while Eq. (4) is valid for any antenna size.

The minimum radiation-Q curves, with the assumption of 100% radiation efficiency, are shown in Figure 2, along with the typical radiation Q of various antenna types. Clearly, the limit curve shows that the radiation Q should increase if antenna size (ka) decreases. If one wants to keep the impedance bandwidth for size miniaturization, the radiation efficiency must be decreased. This is the trade-off that the classic fundamental-limit theory suggests, i.e. only two of the three parameters of antenna size, radiation efficiency (or gain), and bandwidth can be optimized close to the theoretical limit curve.

Notice that the typical radiation Q of the antennas in Figure 2 is not even close to the theoretical limit curve. Especially, the legacy performance line connecting from a dipole to a spiral antenna appears as a simple shift of the limit curve, i.e. resulting in a higher radiation Q or narrower impedance bandwidth. The shift occurs because those antennas do not use the volume of the antenna sphere efficiently or integrate wideband impedance-matching topology into the antenna, compared to the folded hemisphere and Goubau antennas.

Typically, a single antenna problem is treated as a one-port problem at the antenna terminal, which is useful for evaluating the return loss of the antenna or the delivered power to the antenna. The other approach would be to consider the antenna as two-port problem, i.e. port 1 is at the antenna terminal and port 2 is the virtual sphere at a far-field distance. The transmission response from the port 1 to port 2 represents the power that can be delivered to the far-field region relative to the input power, i.e. gain. In this sense, an antenna design can be treated as a 2-port, spatial-filter problem. Yang *et al*. [8] elaborated on this approach for the classic fundamental-limit problem. They observed that an ideal antenna meeting the size and performance of the fundamental limit theory has a high-pass-filter-like gain performance. The ideal antenna has a cut-off frequency around $ka = n$ for the spherical TM_{0n} mode ($n = 1, 2, 3, \ldots$). Above the cut-off frequency, the ideal antenna has almost constant gain. Therefore, the ideal antenna shown in the classic fundamental-limit theory is an ideal ultra-wideband antenna with a constant group delay over entire operational frequency range. The cut-off frequency results from the impedance mismatch to the spherical-mode wave impedance. The ideal antenna can be tuned with broadband matching techniques below the cut-off frequency to achieve operation as done with the folded hemisphere and Goubau antennas, achieving a lower radiation-Q in Figure 2. Many antenna designs shown in the literature considered resonant antennas to make the antenna close to the size and performance of the limit theory. However, the resulting radiation-Q will be higher than that of the ultra-wideband ideal antenna due to the Q for each of the resonances. Therefore, in order to not sacrifice the ideal instantaneous impedance bandwidth and the constant gain with 100% radiation efficiency above the cut-off frequency, the optimum antenna size needs to be approximately $a = n / k$. As implied in the previous section on antenna miniaturization techniques, the lowest operational frequency limit can be lowered by reducing radiation efficiency. If antenna size (a) is smaller than n / k, a wideband impedance matching circuit or structure is needed. Therefore, an antenna with $a < n / k$ is electrically small relative to the nth order mode, though the condition of $a < 0.1$ wavelength at the lowest operational frequency is widely accepted as a criteria for electrically-small antenna classification.

The reviewed classic fundamental-limit theory on antennas provides a useful trade-off relationship between size, efficiency, and bandwidth, allowing antenna designers to avoid unrealizable antennas design specifications. RF system designers can use the limit curve with specific radiation efficiency for their link-budget calculations. Particularly, an antenna size and performance specification located between the theoretical and the legacy performance curves would be a challenging, but feasible specification.

3. SDR ANTENNA DESIGN STRATEGY

Three types of antennas are useful for consideration with software-defined radios: resonant, frequency-independent, and ultra-wideband (UWB) antennas.

Resonant antennas are attractive due to their compact antenna footprint. However, their intrinsic impedance bandwidth is limited. Presently most software-defined radios use a limited channel bandwidth. Often, the impedance bandwidth of a resonant antenna with minor resistive loading is enough to support the channel bandwidth rather than applying complicated broad-banding techniques that ultimately introduce a loss anyway and/or increase sensitivity due to platform or environmental change. An automatic tuner can be considered to provide a dynamic frequency-agile capability. However, it is challenging to design a fast, automated tuner with an extremely-wide tuning range.

If the required sub-bands are known, a multi-band resonant antenna can be designed by using parasitic elements or integrating other types of resonant antennas into the original structure. If the required number of sub-bands increases, the resulting multi-band resonant antenna does not necessarily have a simple, rugged, compact form factor. An alternative approach would be to use the canonical form of the resonant antenna with additional impedance matching circuits. The circuit can be obtained from the simplified real-frequency technique proposed by Yarman [9] that provides a systematic impedance-matching topology close to the theoretical limit, based on the antenna input impedance.

Both the automated tuner and additional impedance circuit approaches do not change the effective shape/structure of the antenna. If the antenna is tuned above the fundamental resonant frequency of the antenna, the radiation pattern of the antenna will change. In a severe situation, a null can be located at the desired coverage angle in the radiation pattern. In order to mitigate this pattern change issue, a reconfigurable antenna may be considered. However, the complexity of the switching circuits on the antenna structure becomes an issue. Alternatively, trap circuits can replace the switches to change the effective antenna height by stopping current flow at desired frequencies, which is a general form of an impedance-loaded antenna. If a wideband matching network is added to the impedance-loaded antenna, the resulting antenna will support an extremely large impedance bandwidth in a small antenna footprint, as demonstrated in [10, 11]. However, the realized gain of the antenna will fluctuate over the operating frequency. In addition, the maximum achievable gain is still governed by the fundamental-limit theory. The resonant antenna using impedance loading and additional impedance matching circuits would be the best choice for a handheld software-defined radio.

Unlike the resonant antennas, frequency-independent antennas, including log-periodic dipoles and equiangular spirals, have a very large impedance bandwidth. Typically, the lowest operational frequency is limited by the size of the antenna while the highest operational frequency is limited by the fineness of mechanical construction around the feed region. The typical radiation pattern of the frequency-independent antennas is either directional (log-periodic dipoles and conical log spirals) or bi-directional (equiangular spirals). Particularly, cavity-backed equiangular spirals are attractive due to the low-profile form factor. The potential issue of the frequency independent antenna is that the group delay over a wide operational band is not constant. That is because each part of the antenna structure radiates actively at a different frequency with a different delay. Therefore, the extremely-wide operational bandwidth of the frequency-independent antenna cannot be used instantaneously. However, the local phase response would be linear over a typically-required channel bandwidth, allowing the use for many SDR applications. If size is of concern, inductive or material loadings [12, 13] can be applied. For the case of equiangular or conical-log spirals with strong loading, the type (linear, circular, or elliptical) or sense (left or right handed) of the polarization may change over the operational frequency range, resulting in an additional polarization mismatch loss. The loaded equiangular spiral may be the best choice if a directional, planar form factor is required for software-defined radio.

If a large instantaneous bandwidth is necessary, ultra-wideband antennas can be employed, such as the bicone (omni-directional) and Vivaldi (directional exponentially-tapered slot) antennas. Compared to frequency-independent antennas, the phase response of ultra-wideband antennas is linear over the entire operational bandwidth (constant group delay). Most ultra-wideband antennas include a smoothly-tapered structure. The tapered structure acts as a wideband impedance transformer and a radiator at the same time. The typical size of ultra-wideband antennas are approximately a quarter wavelength at the lowest operational bandwidth. Without sacrificing gain or phase linearity, it is very challenging to obtain electrically-small, ultra-wideband antennas.

As we explained above, there are many choices for modifying an antenna for software-defined radios, but there is a general strategy based on the observations from the classic fundamental-limit theory. Considering only the operational bandwidth, one can choose any of the described antennas for the desired channel bandwidth and angular coverage. However, if the size of the antenna is the biggest concern in the system design, then resonant antennas with multi-banding and broadbanding techniques would be prime candidates.

On the other hand, if the gain of the system is the most important factor in the design, either ultra-wideband (directional or omni-directional) or frequency independent antennas (directional) can be good starting points. In this case, the minimum antenna size that can be achieved without sacrificing gain will be approximately between $\lambda/(2\pi)$ and $\lambda/10$.

Though purity of polarization is not a big issue for mobile applications, some software-defined radios require covering both horizontal and near-vertical angles. This coverage is very challenging to obtain with an extremely low-profile antenna due to the cancellation of the horizontal current distribution on the antenna by the image current in the ground plane. In this case, the additional increase of antenna size needed for both horizontal and near-vertical angle coverage should be considered at the initial stage of the system design.

4. AN EXAMPLE DESIGN: COMPACT MULTI-FUNCTIONAL ULTRA-WIDEBAND ANTENNA

The direct conversion radio with the flexible RF front end designed by Wireless@Virginia Tech provides an example of a software-defined platform to demonstrate the antenna design strategy. The RF front uses a Motorola RFIC supporting a 100 MHz - 4 GHz operational frequency range with a 9 kHz to 20 MHz channel bandwidth. Since a maximum instantaneous bandwidth and a constant gain are of interest to maximize the frequency-agile capability of the software-defined radio, a compact ultra-wideband antenna (CUA) [14, 15] was considered as a candidate antenna. The CUA has a hemispherical form factor. It comprises folded hemispherical helices surrounding a mono-cone structure that acts as an impedance transformer as well as a radiator. The CUA is fed from the bottom of the mono-cone structure. The surrounding folded hemispherical helices act as a distributed impedance matching structure. The height of the CUA is approximately 0.1 λ at the lowest operational frequency. The upper limit of the operational frequency is limited by the fine mechanical construction of the feed region. If the CUA design is optimized, the CUA has an almost 5 dBi realized gain over the operational frequency range with vertical polarization (dominant spherical TM_{01} mode).

The desired antenna height including a radome was 3" to cover the frequency range of 450 MHz - 6 GHz. A hemispherical acrylic shell with 1/8" thickness was chosen. The radome material was characterized (ε_r = 2.53 and tanδ = 0.01) with a reflection and transmission coefficient approach [16, 17] by using a 7mm coaxial air line. In Figure 3, the initial design is shown. The folded hemi-spherical helices were printed on the inner surface of the radome. The slight loading effect of the radome could be achieved by increasing the number of turns for the helical structure.

The initial antenna design was modeled and simulated in a commercial hybrid code (method of moment + finite element method) [18]. The metallic structures in the model were assumed as a copper (σ = 5.8e7 S/m). The computed VSWR (referenced to 50 Ω) and realized gain including the return loss are shown in Figure 4 and Figure 5 respectively. The initial design shows a good impedance matching (VSWR ~2:1 or less) from 450 MHz to 6 GHz. The realized gain fluctuates slightly around 5 dBi, probably due to the excitation of higher-order spherical modes. The gain performance of the initial CUA design at the lower operating frequencies can be further improved by optimizing the number of turns and the width of the strip in the folded hemispherical structure. In actual fabrication, a tube structure with a low dielectric constant can be added to support the mono-cone structure.

5. SUMMARY AND CONCLUSION

In this paper, an effective, theoretically based antenna design strategy for wideband, size-constrained software-defined radios was discussed. Typical miniaturization techniques were reviewed and indicated that extreme size reduction using any of several miniaturization techniques will result in decreased radiation efficiency and/or reduced bandwidth. This trade-off relationship between antenna size and performance, including the impedance bandwidth and gain (or radiation efficiency), was explained with the classic fundamental-limit theory. The possible design-strategy study suggested that resonant antennas with impedance loading and wideband impedance-matching circuits are a good candidate for size-constrained or hand-held applications. On the other hand, frequency-independent and ultra-wideband antennas are more suitable to obtain a higher system gain. The minimum antenna size in order not to sacrifice both radiation efficiency or impedance bandwidth is in between $\lambda /(2\pi)$ and $\lambda /10$ at the lowest operational frequency. The design strategy was demonstrated with a compact ultra-wideband antenna for a direct-conversion software-defined radio.

The discussed antenna miniaturization techniques, the classic fundamental limit theory, and the antenna design strategy do not address a specific system, but these provide enough background knowledge in order to avoid wasting time with non-realizable system specifications. Particularly, the legacy radiation-Q curve helps to estimate the gap between the limit theory and the practice.

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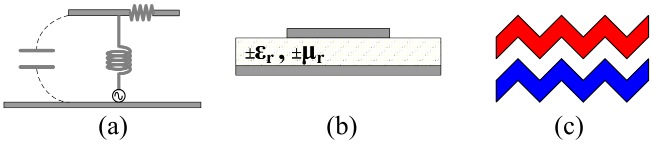

Figure 1. Various antenna miniaturization techniques: (a) capacitive, inductive, and resistive loading; (b) Material loading; and (c) Slow-wave structures [1].

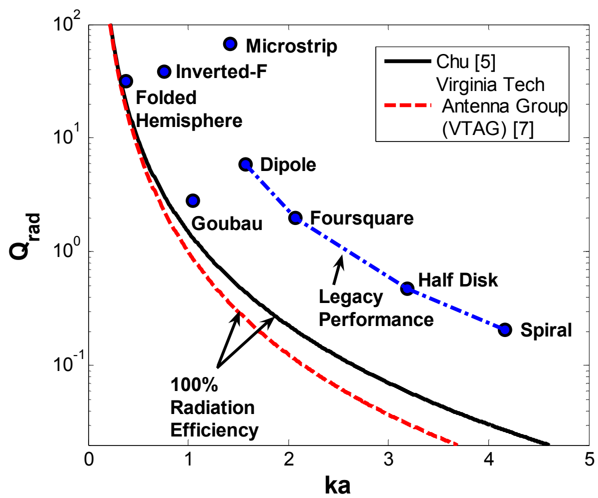

Figure 2. Comparison between theoretical radiation Q limit curve and radiation Q of various antennas [1].

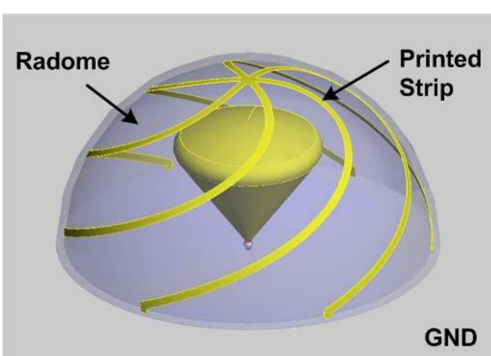

Figure 3. Designed compact ultra-wideband antenna inside hemispherical radome with a 3" radius [14].

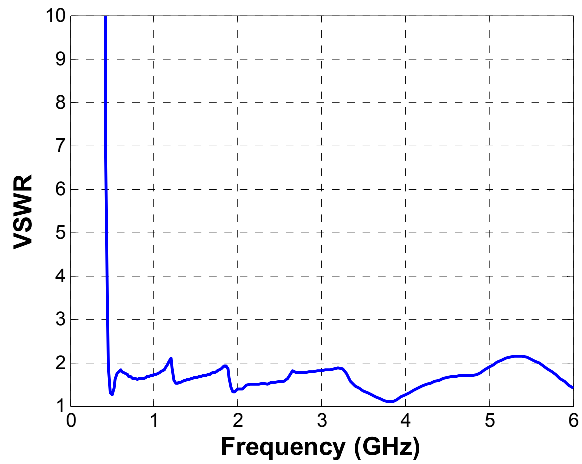

Figure 4. Computed VSWR versus frequency for the initial CUA design ($Z_0 = 50\Omega$).

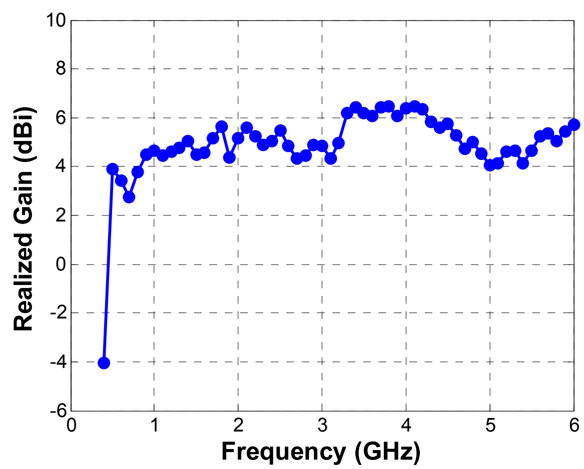

Figure 5. Computed realized gain versus frequency for the initial CUA design.