

On the Practical Design of Small Terminal Antennas for Mobile Applications

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SUMMARY Mobile communication have become an important part of telecommunications. Original applications like paging, mobile phones or GPS have shown a tremendous growth, and new applications are emerging every day: tagging, wireless computer links, wireless microphones, remote control, wireless multimedia links, satellite mobile phones, wireless internet. Mobile means light, small, with low energy consumption and appealing designs. Technology has evolved very fast to satisfy these needs in rapidly growing markets: chips are becoming smaller, consume less current, are more efficient and perform more complex operations. The antennas however have not experienced the same evolution, as the size of an antenna is mainly dictated by the frequency band it has to transmit or receive. Thus, the art of antenna miniaturization is an art of compromise: one has to design the smallest possible antenna, which is still suitable for a given application regarding its radiation characteristics. Or in other words, one looks for the best compromise between volume, bandwidth and efficiency. In this paper, we will go through classical design techniques, starting from ultra small antennas and going UWB antennas over multiband designs.

key words: *small terminal antennas, miniaturization, multifrequency antennas, ultra WideBand*

1. Introduction

The need for small terminal antennas designed to fulfill the specific need of mobile communications started roughly 25 years ago with the apparition of the 1st generation of mobile phones. Indeed, the mobile phone service had new and stringent requirements for antennas, which differed from the portable radio link systems which were anterior to them. These new requirements were linked to the fact that this new communication service targeted a broad market. Thus, the handheld had to be small enough to be easily carried, of reasonable weight and low cost to manufacture. The initially selected relative low frequencies gave few degrees of freedom to the antenna designer and the only practical solution was a whip where the handheld itself acted as the ground. The strong development of the second generation of mobile phones in the last decade induced an increase of the carrier frequency, giving thus a little more freedom in the antenna design. New mobile services like high speed data transfer (WLAN), Bluetooth, ad hoc networks, mobile peer to peer transfer, as well as the competition for the available frequency spectrum have broadened the range of requirements for the antennas which are used on the mobile termi-

nals. These requirements include typical “user defined requirements” like 1) small dimensions; 2) low weight; 3) low induced SAR; 4) low cost. But also requirements that are defined by the service provider or by the network, like 5) high efficiency; 6) capability to handle multiple frequency bands; 7) broadband; 8) robust to changes in the environment; and 9) optimized use of the available channel capacity.

Of course, depending on the considered service, the relative importance of all these requirements will quickly change. For instance, size is far less critical for WLAN system located in a laptop than for a DCS phone. Bandwidth and capacity, however, will be far more critical in the former example.

Considering this, the design of terminal antennas is more than ever the art of defining the right compromise between all the requirements for a specific application. In this paper, we will show some design examples for specific situations and will propose some solutions to meet the design requirements listed above.

We start with the so-called ultra-small antennas, we will address then the multifrequency problem for both classic and new applications and we will end with some considerations about ultra wide band antennas.

2. Ultra Small Antennas

We can define ultra-small antennas as those having linear dimensions not exceeding a tenth of the free space wavelength. With a diameter typically smaller than 40 millimeter, the conventional wrist watch provides an environment where many commercial services up to 2.5 GHz require ultra small antennas. No wonder that this has been a typical research subject in countries like Switzerland. The selected two examples here below are concerned with inclusion of GPS and Bluetooth services in a wristwatch.

2.1 GPS Integrated in a Wristwatch

The first design example is an antenna for a GPS receiver integrated in a wristwatch. The overall dimension of the watch is a cylinder of 35 mm of diameter and 8 mm high. The GPS bandwidth being very small, the main problem in this design was to achieve a sufficiently high gain: The minimum to achieve the link was -6 dBi, while the maximum achievable gain after Harrington [1] is 0 dBi. This gave us a margin of 6 dB, which was used in order to obtain circular polarization. Indeed, the requirement for circular polariza-

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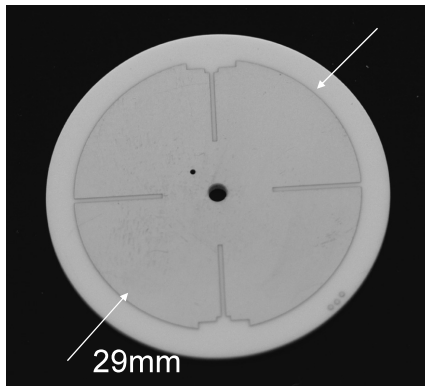


Fig. 1 GPS antenna for a wristwatch.

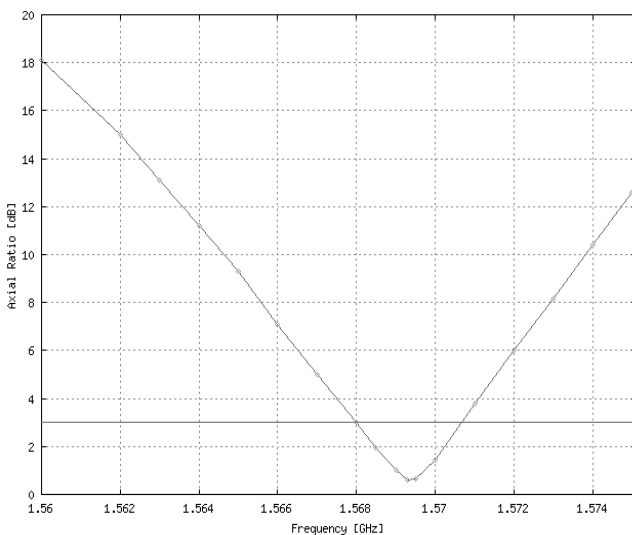


Fig. 2 Measured axial ratio of the wristwatch GPS antenna.

tion severely limits the choice of possible antennas, and high efficiency antennas like PIFAs cannot be considered. This, along with the space requirements in the watch led us to select a circular patch antenna, placed under the hands of the watch [2]. The antenna is illustrated in Fig. 1. The patch is etched on a Rogers TMM10 substrate, having $\epsilon_r = 9.8 \pm 0.245$ and $h = 1$ mm. As this permittivity is not high enough to achieve the GPS resonance within the allotted space, four deep slots were etched on the circular patch's edge in order to further decrease the frequency, with a rate of 80 MHz per mm of slot. Finally, the slots' openings were widened in two opposite slots (Fig. 1). This carefully controlled asymmetry between the two pairs of slots yields the circular polarization.

The impedance bandwidth of this antenna defined at -10 dB is of 0.6%. As shown in Fig. 2, the measured axial ratio bandwidth at -3 dB is very narrow (0.2%), but adequate for a GPS application. It was however necessary to use a temperature stabilized substrate like Rogers' TMM, in order to avoid to slide out of band due to temperature shifts.

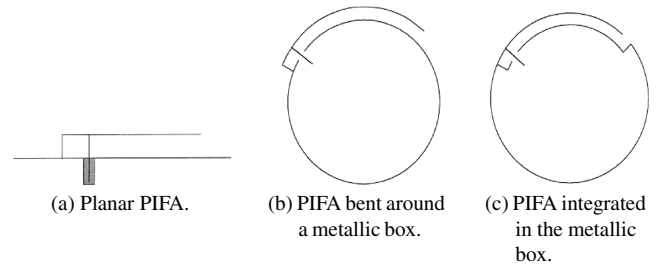


Fig. 3 Principle of the SMILA.



Fig. 4 Realized SMILA.

2.2 Bluetooth Integrated in a Wristwatch

The second example of an electrically very small antenna design is linked to a Bluetooth transceiver integrated in a wristwatch. The overall dimensions of the watch are given by a cylinder of 35 mm of diameter and 10 mm high. In this case, there is no requirement about the polarization, as we target an indoor application, so depolarization will occur anyway due to multiple reflections and movement. The critical requirement in this case is to achieve the required bandwidth.

The first design antenna was a so called "Smart Integrated L Antenna" (SMILA) integrated around the watch casing. The principle of this antenna is shown in Fig. 3, and the final device in Fig. 4. A classical Planar Inverted F-antenna (PIFA) is considered as starting point (Fig. 3(a)). Then this PIFA is conformed around a cylindrical watch case geometry (Fig. 3(b)) and made flush with the external edge to yield the final SMILA configuration (Fig. 3(c)). The overall diameter of the casing is 35 mm ($\lambda/7$), the height of the casing 10 mm ($\lambda/12$) and the distance between the PIFA arm and the ground 3 mm ($\lambda/40$).

This antenna being electrically very small, it was measured and characterized directly in its final setup, powering it from a VCO inside the casing, thus avoiding all cables. The measurement procedure is described in detail in [3]. The obtained gain was 0.5 dBi, and the bandwidth was 4% at -10 dB.

This Bluetooth transceiver being integrated in a wristwatch, it is important that the antenna characteristic do not deteriorate when the watch is close to a human arm. In order to test this, the antenna was characterized again, but placed at different distances from a "lossy cylinder" (actually a

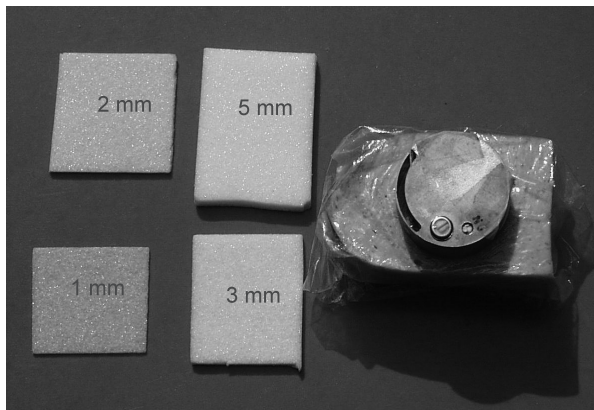


Fig. 5 SMILA on human arm phantom.

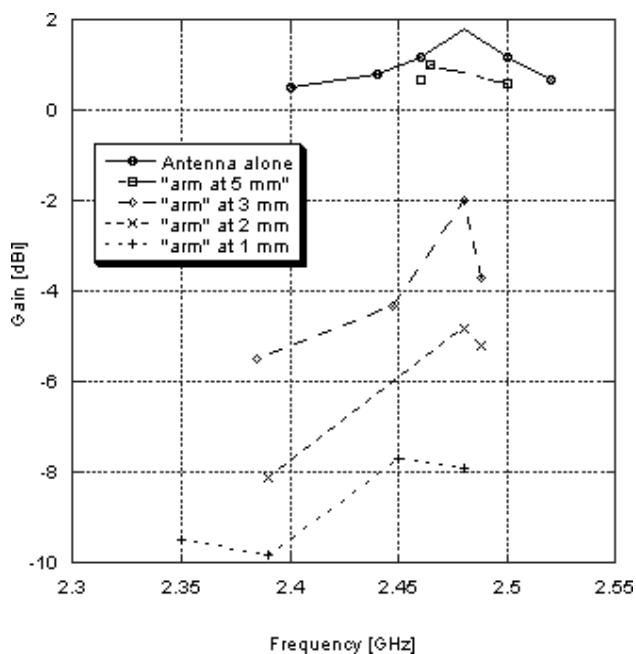


Fig. 6 Measured gain of the SMILA in presence of the "arm phantom."

piece of sausage!), the latter acting as a phantom for the arm. The spacing between the watch and the "arm" was controlled using Rohacell foams of different thicknesses. The overall setup is depicted in Fig. 5.

The measured gains for the different distances are depicted in Fig. 6. We see that the antenna radiating performances deteriorate rapidly as the watch is set nearer to the arm. Indeed, the presence of a lossy medium close to the antenna short circuits the fields of the PIFA, and dramatically reduces the efficiency of the antenna.

In order to alleviate this problem, a new design was performed with the antenna integrated on the top of the watch. This new design is illustrated in Fig. 7, where now the SMILA with slots in both top and lateral surfaces looks like a curved PIFA with its classical coax-fed excitation near the short circuited edge. This novel geometry dramatically reduced the sensitivity of the performances to the presence

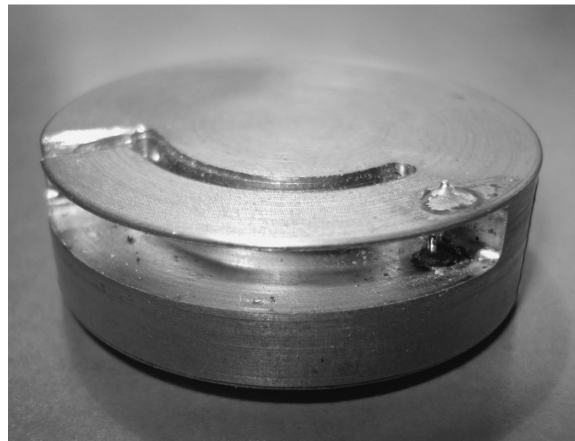


Fig. 7 New design, with antenna integrated on the top of the watch.

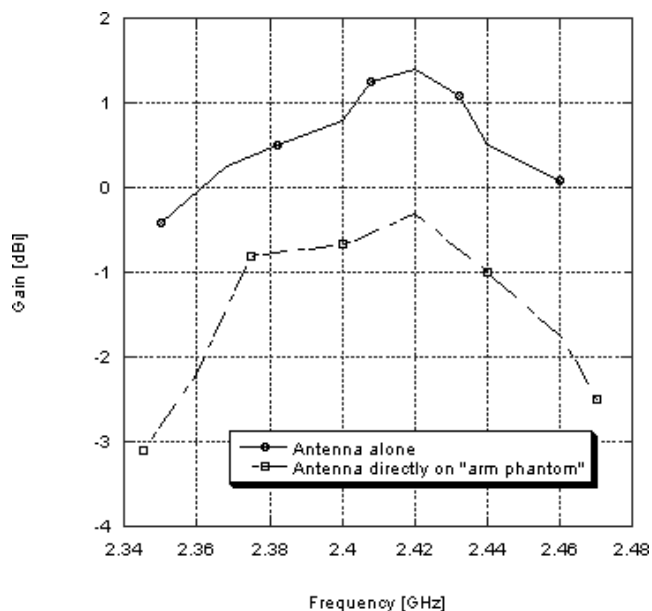


Fig. 8 Measured gain of the new antenna, with and without the "arm" phantom.

of the arm, as is shown by the measured results depicted in Fig. 8. The gain deterioration was now of only -2 dB in the most critical situation, to be compared with -10 dB in the previous design.

The efficiency was measured with and without the "arm phantom." The efficiency over the Bluetooth band was above 95% in the former case, and still around 75% in the latter one.

3. Classical Multifrequency Antennas

The venue of new generations of voice services (DCS and UMTS to GSM for instance), and the offer of new services incorporated in phone terminals (like Bluetooth and GPS) require antennas which provide multiband possibilities. Indeed, a multiband antenna solution is often smaller and less costly than a solution with a distinct antenna for each fre-

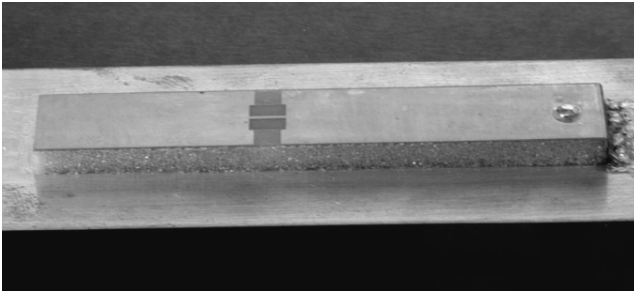


Fig. 9 Dual band PIFA antenna (GSM/DCS).

quency band. Typically, a distinction can be established between single and multiple feed (port) multiband antennas.

3.1 Multiband Single Feed Antennas

The big advantage of having a common feed point for all the bands is that we do not need to care about mutual coupling problems. The drawback is that the radio front end has to discriminate the signal belonging to different services. Single feed is the usual choice for dualband mobile phone handset antennas. An example of this kind of antenna [4] is shown in Fig. 9. This is again a PIFA geometry with the single coaxial feed easily recognizable in the right side, close to the short circuit end.

The full strip length is resonating at the lower frequency. However, at a higher frequency, the LC circuit etched in series in the middle of the strip prevents the current to enter the left-hand side part of the strip. Hence the upper resonance is determined by the strip length at the right of the blocking LC circuit.

The design of a multiband printed antenna usually starts by combining several resonant structures in a single antenna, with a common feeding point. Typically, slots and patches resonances are combined to obtain several bands of operation. Optimization combining an accurate analysis technique (for instance IE-MoM or FDTD) with a fast optimizer (genetic algorithm) is essential here. With proper tuning, four or even five bands can be obtained, keeping essentially the same surface and volume needed for a single band patch and achieving good performances in terms of matching and efficiency. Figure 10 shows a quad-band antenna for mobile phone applications (GSM 900/1800/1900 +UMTS) combining a parasitic element and a $\lambda/2$ slot (at the UMTS frequency) etched in the main patch [5].

The antenna design consists of a folded, probe-fed metal plate with a shorting pin, which provides a double resonance around 900 MHz and 1800 MHz. The shorted patch was designed for a resonant frequency of 1800 MHz. A spur-line filter embedded in its perimeter introduces a new resonant mode at 925 MHz. This technique allows a dual-band operation without incrementing the total size of the antenna. Since the spur-line is made parallel to the patch edges, its influence upon the fundamental mode TM₁₀ of the patch is not significant, while the new generated mode has similar characteristics to those of the main mode. Then,

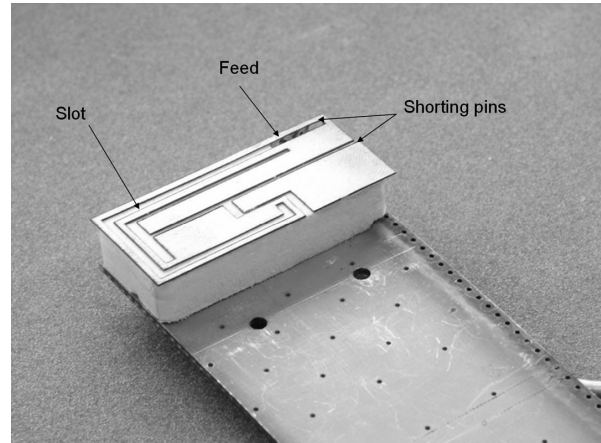


Fig. 10 Quadband patch antenna for mobile telephones.

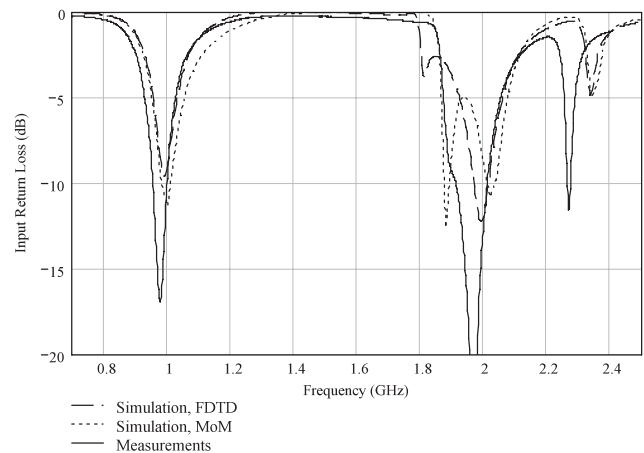


Fig. 11 Simulated and measured input return loss of the quadband antenna.

a shorted parasitic plate, capacitively coupled to the main radiator, was used in order to introduce a new resonance in the upper band, allowing thus to cover both the DCS and PCS standards. Finally, a slot was etched within the perimeter of the main patch. The slot has a dimensions of $\lambda/2$ for the UMTS band and has a width of 0.5 mm, which does not disturb the GSM mode excited in this branch of the patch. This radiating element can in this way cover the frequency bands of four different standards, namely GSM 900, GSM 1800, PCS and UMTS (FDD), without increasing the overall size of the structure. For UMTS, only the downlink frequency band was considered, as the uplink band overlaps with the PCS band.

Figure 11 shows a comparison of the input return loss obtained by simulation using two different codes (FDTD and Method of Moments), and the measurements. A reasonably good prediction of the resonant frequency was achieved for the three first frequency bands. Yet, a frequency shift can be observed in the fourth band, which corresponds to the slot mode. This is probably due to two different reasons: first, the discretization of the structure, was fine enough to give an approximate estimation of the behaviour of the slot

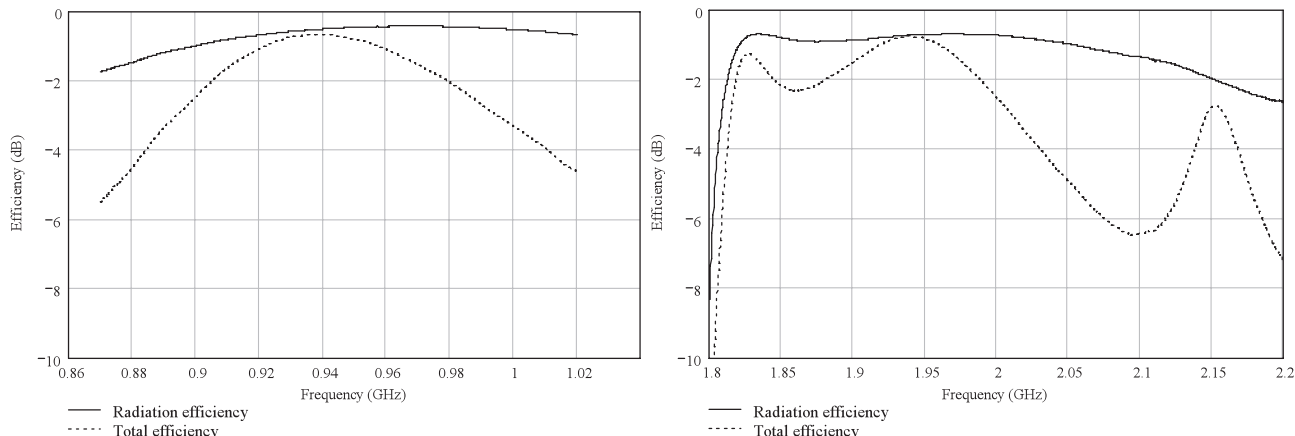


Fig. 12 Simulated and measured input return loss of the quadband antenna.

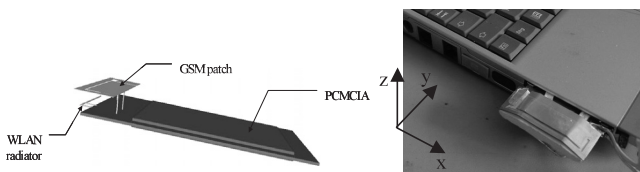


Fig. 13 Multiband antenna for PCMCIA.

mode, but not sufficient as to predict the exact resonance frequency; and second: Perfectly Matched Layer (PML) boundaries where used in FDTD, which have a stronger influence on the slot mode than on the others.

The measured efficiency of the quadband antenna is presented in Fig. 12. In the GSM, DCS and PCS frequency bands, the total efficiency remains over -5 dB in the GSM, DCS and PCS bands, which correspond to the patch operating modes.

3.2 Multiband Multiple Feed Antennas

In some applications, multifeed antennas with a feed per frequency band are frequently needed. The drawback is that the mutual coupling between the feed points can be high. This can degrade the overall performances. However, each service is decoupled already at the antenna stage. This option is usually chosen when the two offered services are uncorrelated (voice and GSM for instance). This can also be a good choice for frequency bands which are far apart.

For instance, to implement a multi-standard PCMCIA antenna system that covers simultaneously the frequency bands of the GSM family (namely, GSM 900, GSM 1800 and GSM 1900) and WLAN, two feeding ports are usually necessary, in order to comply with the current requirements of hardware manufacturers, who can thus use cost-performant circuitry. An example of multiband antenna for PCMCIA [6] is presented in Fig. 13. Two separate radiating structures were integrated into the available volume. A PIFA was chosen to cover the GSM bands. It provides two separate resonances for the GSM 900 and the GSM 1800/1900, respectively. In this case, a single mode was enough to cover

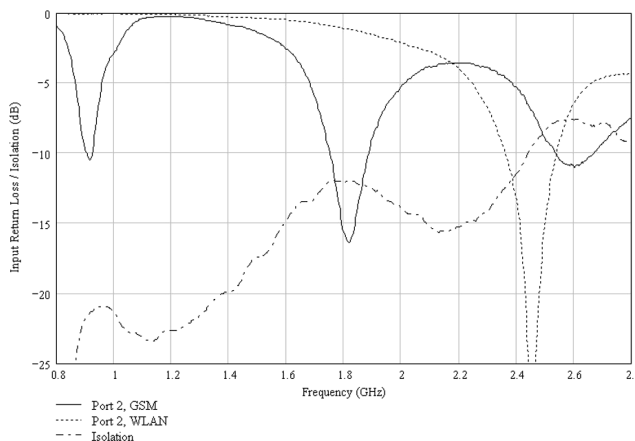


Fig. 14 Multiband antenna for PCMCIA.

these two overlapping bands. Also, an Inverted-F antenna (IFA) was added, to ensure the access to WLAN. It consists of a shorted wire printed onto a non-metallized area of the PCB board. The overall size of the PCMCIA board is $54\text{ mm} \times 110\text{ mm}$. For this kind of antenna, computer optimization is needed to only for achieve a good matching but also to obtain a good decoupling between ports.

The antenna was measured in its intended operation configuration, that is, mounted on a PCMCIA card, which was in turn inserted into the corresponding slot of a notebook. The antenna displays good matching performances in all the frequency bands of interest, as shown in Fig. 14. A matching better than -6 dB is achieved even in the band limits for GSM 1800, GSM 1900 and WLAN. As for GSM 900, the -6 dB matching level for the lower limit of the GSM 900 band should be easily achieved through a slight tuning of the resonant frequency.

3.3 Multiband Antennas with Reduced Feeds

Using less feeds than bands is a solution often introduced to cope with the evolution of one type of service. For mobile voice in Europe for instance, one could use a multi band an-

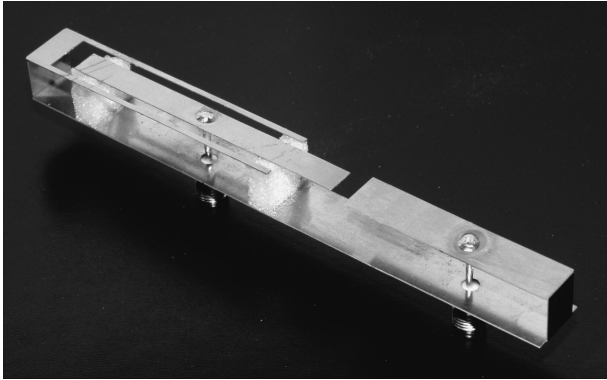


Fig. 15 Double PIFA for GSM/DCS (feed point to the left) and UMTS bands.

tenna with two feed points, one for the GSM/DCS bands and a second for UMTS. An example covering GSM/DCS on one port and UMTS on the other is shown in Fig. 15. A PIFA antenna in the right hand side of Fig. 15 provides UMTS operation, where a elongated patch surrounded by a slot and fed by a second coaxial probe (lft hand side of Fig. 15) is responsible for GSM/DCS frequencies. See Ref. [7] for additional informations.

4. Multifrequency Antennas for Applications beyond 3G

Mobile services beyond 3rd generation will imply the use of much higher frequency bands. In an initial stage, these new service will have to appear along the existing ones. This means that there will be a market for antennas being able to work both in the actual wireless frequencies (1–5 GHz) and in the Ku band. The size of the low band antenna will be much large that the size of the high band antenna, and will set the overall size of the radiating part of the system.

The difference between the required sizes for both bands can be used to add some “smart” features to the high band part of the antenna. An example is sketched in Fig. 16. The radiating structures (in this case patches) are made of an array of elements resonating in the higher band, connected by filters, switches, or other circuit elements. For the lower frequency band, the entire structure will be considered as one single radiating element. In this case, it is conceptually possible to use the feed of any individual patch as antenna feed. This provides interesting matching possibilities For the higher frequency band, the structure can be considered as an array antenna, whose features (beam steability, tunability of the matching, etc.) will be determined by the nature of the connecting circuit elements, and by the feeding network.

5. UWB Antennas for Handheld Terminals

Mobile communication is a rapidly expanding market, with strong influence in the RF and microwave areas. UWB communications can be used for indoor and outdoor short-

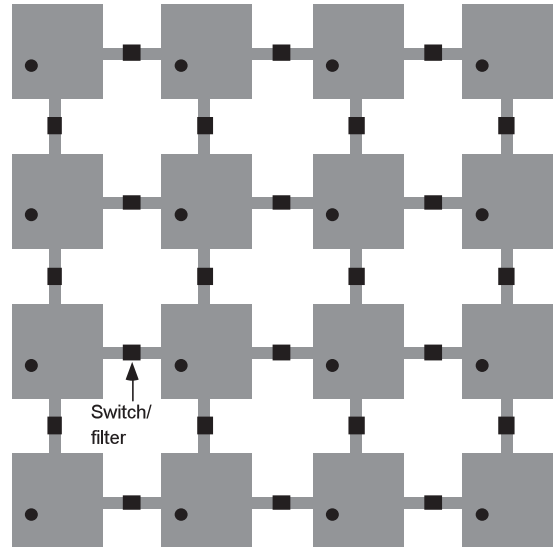


Fig. 16 KU band array working as a single element in 2G or 3G bands.

range communications, and are seen as a means to overcome the intrinsic problems of multipath environments. Besides a high radiation efficiency, two antenna characteristics are most desirable for UWB radio systems: 1) a wide impedance bandwidth with good matching, to minimize reflection loss and to avoid pulse distortion; 2) a phase centre fixed over frequency, to avoid pulse dispersion. To put into service an UWB communications system, different kind of devices, both desktop and handheld, must be considered. Some standard antenna solutions, like Vivaldi or bowtie antennas, show a good behavior for common household devices such as TV-sets or DVD players. However, they are too cumbersome to be integrated into smaller, portable terminals. In this case, smaller and higher-performance solutions are needed. Figure 17(a) shows a small UWB antenna for handheld terminals [8]. The design is based on a planar version of the monopole antenna, with a size of 20 mm × 18 mm. The handset was modeled as a 120 mm-in-length, 80 mm-in-width PCB, which is a normal size for multimedia devices to be used in an UWB environment. Some components of the device have also been considered, namely the RF-shielding, the battery, the display, the vibration motor and the loudspeaker. They all were modeled as metallic elements connected to the PCB. The final structure is displayed in Fig. 17(b). In order to improve the performance of the antenna, a horizontal metallic strip can be added, as shown in Fig. 17(c), which will act as a small ground plane for the antenna. The size of this strip is 11 mm × 80 mm. The simulated input return loss results of the antenna are depicted in Fig. 18.

Three cases were considered: the antenna over an ideal infinite ground plane, or integrated in both handset models.

The antenna shows good matching performances from 3 to 10 GHz when an infinite ground plane is considered. Once the antenna is integrated into the handset, the matching is shifted to lower frequencies, whereas the overall level is

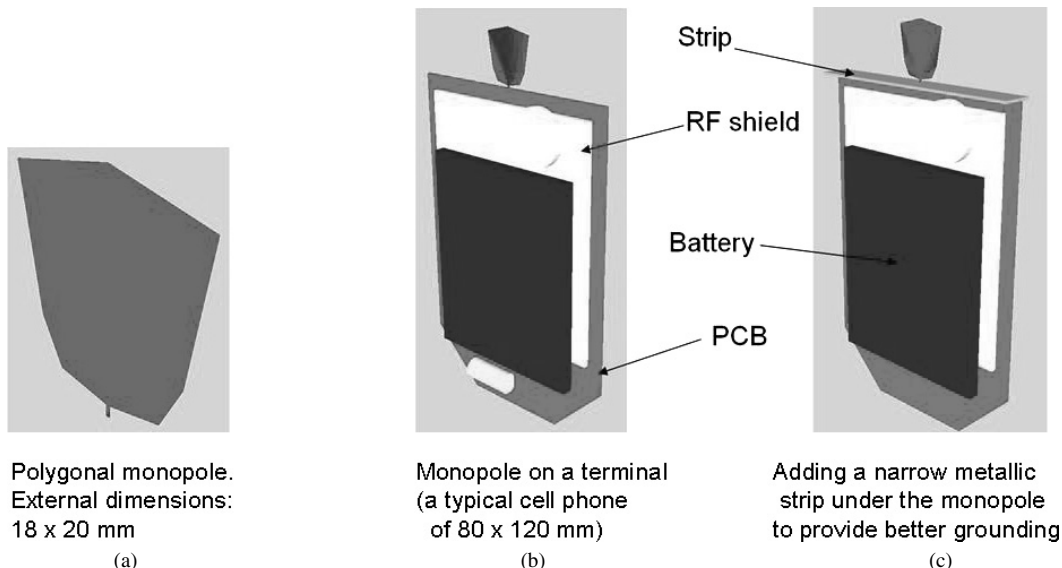


Fig. 17 Small UWB antenna.

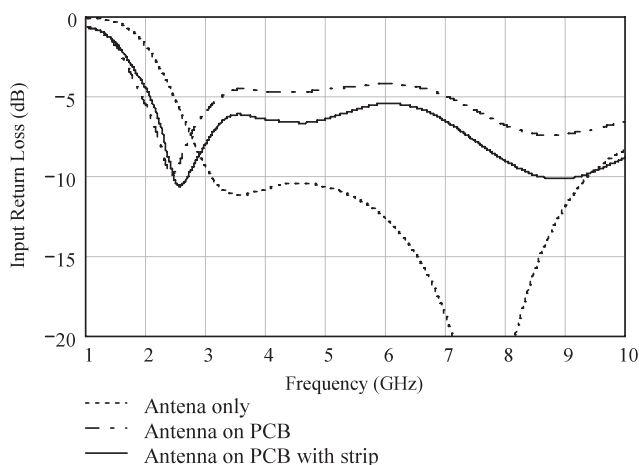


Fig. 18 Simulated input return loss of the UWB antenna with infinite ground plane, and integrated into the terminal.

deteriorated. Adding the thin metal strip at the top of the device allows a 2 to 4 dB improvement of the input return loss, as the strip acts as a small ground plane, especially for the higher frequencies.

6. Conclusion

This paper has presented several examples of small terminal antennas successfully meeting the specifications in several commercial services and different frequency bands. In every case, success was obtained thanks to a well balanced blend of numerical simulations and empirical, well seasoned design concepts. This combination has in turn created new design rules for innovative advanced small antennas.

There a still lot of work to do in the novel field of small terminal antennas. Besides traditional fields of research, like the development of more efficient full wave simulation tools

and pure electromagnetic-based design, new challenges appear in the form of transdisciplinary research. Indeed, beside antenna and electromagnetic theory, the designer of efficient future terminal antennas will have to develop skills in areas like materials science, MEMS technology, signal processing and MIMO channels, probability & statistics and optimization theory, as terminal antennas will migrate more and more from a component to a subsystem or even system level.

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