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Mobile-Phone Antenna Design

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Abstract

This paper is a survey of internal antennas in mobile phones from 1997 to 2010. It covers almost 60 GSM and 3G handsets, ranging from the first GSM handset with an internal antenna to the current Nokia, Sony-Ericsson, Motorola, and Apple handsets. The paper discusses different types of mobile-phone antennas, feeding structures, active antennas, isolation, and antenna loading techniques. This paper examines different design techniques for mobile-phone antennas, and the limitations of antenna design due to manufacturing technologies and the effect of handset materials. Antenna performance parameters, including S parameters, radiation efficiency, SAR, and TRP/TIS are reported for the surveyed handsets. The effective antenna volume for every antenna is calculated, in order to determine the average volume/space required for each antenna type and the corresponding performance. Some of the handsets are further simulated using commercial electromagnetic simulators to illustrate the electromagnetic-field distributions. This paper summarizes the antenna design parameters as a function of handset performance, and presents a short summary of design procedure.

Keywords: PIFA; internal antenna; mobile phone; matching networks; manufacturing; TRP; TIS; SAR; GSM; 3G; 4G; land mobile radio equipment; land mobile radio cellular systems

1. Introduction

Prior to the mid 1990s, all GSM handsets had an external antenna that was one of the following three: a helix, a monopole (whip), or a helix-plus-whip combination. Internal antennas were gradually introduced into mobile phones to facilitate more flexibility in the industrial design, and SAR reduction.

The Hagenuk phone, produced by a Danish company in 1996, was the first mainstream GSM phone with an internal antenna (Figure 1). It resembled a curved television remote, and was often described as such. The antenna was a single-band (GSM900) slot antenna that was etched into the RF shielding using MID manufacturing technology. Since the antenna was a slot antenna with a large ground plane, it was very robust, and was not detuned as easily as the E-field internal antennas that became more popular.

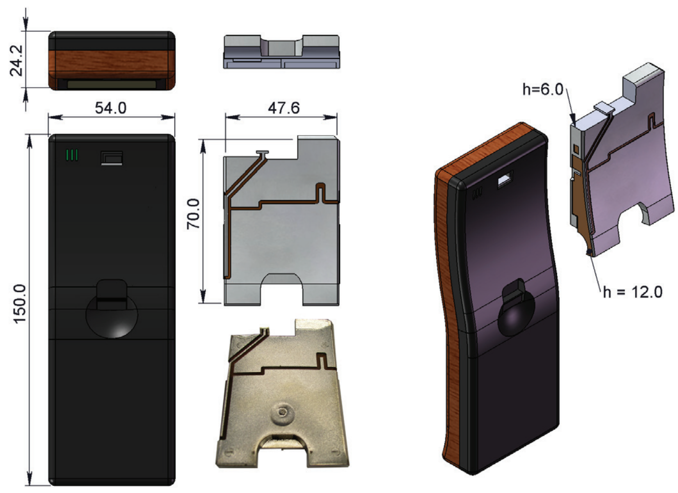


Figure 1. The first GSM phone with an internal antenna: Hagenuk Globalhandy (c. 1996); dimensions are in mm.

One year later, Nokia debuted the 8810, a small chrome-plated handset resembling a large cigarette lighter. Both the handset and the antenna were a fraction of the size of the Hagenuk, and the 8810 quickly became more popular. With the success of the 8810, Nokia began to produce more models with internal antennas in two separate market segments: the 88xx, with its metal covers for the high-end market; and the 3xxx, 6xxx, 7xxx, with plastic covers. By the early 2000s, the majority of phone models produced by Nokia had internal antennas. Given the sheer volume of the different models, Nokia used several types of internal antennas with many technology designs, such as capacitive feeding, parasitics, isolation technologies, active antennas, integrated ground planes, new manufacturing technologies, etc.

The other large manufacturers did not switch from external antennas to internal antennas until three to four years later. By that time, Nokia had already released over 10 models with internal antennas.

In the past two decades, there has been a wealth of papers on existing and new internal antenna innovations for mobile handset antennas with single-band PIFAs [1, 2], dual-band PIFAs [3], capacitive loading [4], shorting techniques [5], capacitive feeding [6], parasitic elements [7], combinations of different loading techniques [8], resonant slots [9, 10], and active antennas [11]. This paper builds upon a conference paper presented in 2006 at the IEEE International Symposium on Antennas and Propagation [12]. It further examines existing technology implemented in mobile phones, including some designs with newer antenna technologies not covered in the literature. The frequency bands analyzed in this paper are summarized in Table 1 [13, 14].

2. Methodology

2.1 Active Measurements

A Rodhe & Schwarz CMU200 with a Satimo Starlab system [15] were used to measure TRP and TIS for over-the-air (OTA) testing of the handset, as described in the CTIA setup for handset certification in North America [16], with a setup illustrated in Figure 2. TRP is the total radiated power, and is a measurement of the total radiated power compared to an isotropic antenna. The total radiated power is calculated by integrating the time-averaged radiated power (EiRP) across the spherical surface enclosing the handset. This is a measure of the RF transmitting performance of the handset:

$$TRP \cong \frac{1}{4\pi} \oint \left[EiRP_{\theta}(\theta,\phi) + EiRP_{\phi}(\theta,\phi) \right] \sin(\theta)\, d\phi\, d\theta$$

where $\oint$ is the volume integral over a sphere:

$$\oint \equiv \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} .$$

The effective isotropic sensitivity (EIS) is the power available from an ideal, isotropic antenna. TIS, the total isotropic sensitivity, quantifies the RF receiving performance of the handset, and is the antenna sensitivity integrated over a sphere:

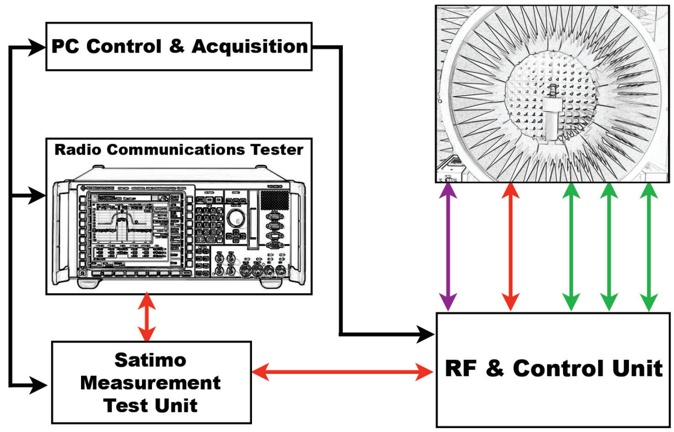


Figure 2. A TRP (total radiated power) and TIS (total isotropic sensitivity) measurement system. The PC controls the radio communications tester and the Satimo unit via a USB/GPIB interface (black arrows). The red arrows are the transmitting and receiving data streams. The purple arrow is for controlling the measurement probes. The green arrows control the positioner (azimuth, elevation, and end motions).

Table 1. The GSM and 3G (UMTS) frequency bands.

System	Uplink (MHz)	Downlink (MHz)	Region
GSM850	824-849	869-894	Americas
(E)-GSM900	880-914.8	925-959.8	Europe, Asia, Oceania
GSM1800	1710.2-1784.8	1805.2-1879.8	Europe, Asia, Oceania
GSM1900	1850-1910	1930-1990	Americas
UMTS Band I	1920-1980	2110-2170	Europe, Asia, Africa, Brazil, Oceania
UMTS Band II	1850-1910	1930-1990	Americas
UMTS Band V	824-849	869-894	Americas, Oceania

$$TIS = \frac{4\pi}{\oint \left[\frac{1}{EiS_\theta(\theta,\phi)} + \frac{1}{EiS_\phi(\theta,\phi)} \right] \sin(\theta)\, d\phi\, d\theta}.$$

2.2 Passive Measurements

For passive measurements, an RF cable was attached to an antenna feed between the RF module and the matching network. The cable was routed through the phone, and exited the phone in an area that caused the least disturbance to the EM field distribution of the antenna (typically, in the center of the handset, because the current distribution was often high at both ends of the handset). A Rohde & Schwarz ZVB vector network analyzer was used for the *S*-parameter measurements. A Satimo Starlab system was used to measure the three-dimensional radiation patterns, the antenna efficiency, and the antenna gain [15]. Since the presence of a cable changed the current distribution and required the removal of several components from the handset and PCB, the passive measurement results were different than the active measurement results, but are useful for characterizing general antenna behavior.

To measure the SAR, IndexSAR MapSAR equipment [17] was used because the sealed phantom had no evaporation and fluid maintenance. Since these measurements were performed over several years, a low-maintenance and accurate system was more suitable. The first measurement of the SAR measured at the earpiece was performed according to FCC regulations [18]. The second measurement was performed in the region of the handset with the highest current density, with the handset firmly pressed against the user's head. For planar monopole antennas located in the bottom of the handset, there was often a significant difference between the FCC measurement and the actual peak SAR near the mouthpiece.

2.3 Computer

The handsets were digitized using *Solidworks*, a three-dimensional CAD program [19], with separate components for the antenna, PCB, plastics, RF modules, LCD, speakers, microphones, etc.. These were saved as `SAT` files and imported into CST *Microwave Office* [20]. The material parameters (loss tangent and dielectric constant) were added into the simulations, and are listed in Table 2. The values for the hand and head were averages, since CST used a dispersion fitting to model the frequency-dependent RF properties of the tissue. After some adjustments to the components next to the antenna (especially to the grounding of various nearby components), antenna simulations were performed in order to calculate the electric and far-field distributions, and the effect of different components on the antenna's performance.

2.4 Hand Measurements

Hand effects for the total radiated power and efficiency were measured for some of the handsets. The hand phantom used was model IXB-060R from IndexSAR [17]. This had a loss difference of < 0.7 dB compared to a real hand between 800 MHz and 3000 MHz, and a repeatability of ± 0.1 dB. It was made of carbon fiber, carbon powder, and silicone rubber with similar conductivity and epsilon of a human hand at microwave frequencies: $\varepsilon = 16$ to 20, $\sigma = 0.05$ to 0.3.

2.5 Handsets

The mobile-phone handsets that were measured, analyzed, and imported into EM simulation platforms are listed in Table 3. There were a variety of form factors and antenna types, for handsets ranging from single band to penta-band. The work reported in this paper performed the following measurements:

- Active: total radiated power and total isotropic sensitivity
- Passive: SAR, three-dimensional efficiency, three-dimensional and two-dimensional radiation plots, S_{11}, VSWR, and detailed CAD drawings.

More information can be accessed at the Web site http://antennas.astri.org [21]. The effective volume was defined as the total antenna space minus all of the grounded components within that space (e.g., speakers, RF modules, connectors, etc.).

Table 2. The material parameters for the CST simulations.

Material	ε	Conductivity (S/m)	Loss Tangent
ABS-PC	2.5-3	NA	0.02-0.1
Chrome	1	8×10^6	NA
Metal	1	5.8×10^7	NA
Glass	4.82	NA	0.0054
Head (shell)	3.7	0.0016	NA
Head (fluid)	40	0.96	NA
Hand	20	1.18	NA

Table 3. Mobile phone handsets (all dimensions are in mm).

Model	Antenna	Length	Width	Height	Effective Volume (cc)	Form Factor	Frequency Bands
Apple iPhone 2G	Planar Monopole	55.6	22.8	10.4	6.9	Candybar	GSM850/900/1800/1900
Apple iPhone 3G	Planar Monopole	55	20	8.5	9.0	Candybar	GSM850/900/1800/1900+3G
Apple iPhone 4	Planar Monopole	58	14	6.1	4.8	Candybar	GSM850/900/1800/1900+3G
ASUS M307	Planar Monopole	35	24	0.2	1.6	Clamshell	GSM900/1800/1900
ASUS P525	PIFA	34	20	7.6	5.1	Candybar	GSM850/900/1800/1900
BenQ Siemens EF-71	Planar Monopole	38	10.1	5.3	2.0	Clamshell	GSM900/1800/1900
Blackberry 8100	Planar Monopole	42	9	6.7	7.7	Candybar	GSM850/900/1800/1900
Blu 233/Sendo M570	Planar Monopole	35	16.4	1.5	0.9	Clamshell	GSM900/1800
Geo GC688	PIFA	36.5	10.7	5.8	2.3	Slider	GSM850/900/1800/1900
Hagenuk	Slot	72.4	49.6	6.0	12.6	Candybar	GSM900
Motorola E398	PIFA	37.2	20.1	8.7	5.5	Candybar	GSM900/1800/1900
Motorola KRZR K1	Planar Monopole	37.5	7.6	7.0	2.4	Clamshell	GSM850/900/1800/1900
Motorola L2000/P7389	Helix	44.2	5	5.0	2.1	Candybar	GSM900/1800/1900
Motorola L6	Planar Monopole	36.1	7.5	7.0	1.9	Candybar	GSM900/1800/1900
Motorola T193	PIFA	27	17.8	8.1	2.9	Candybar	GSM1900
Motorola T720i	Helix	29	10	10	1.6	Clamshell	GSM900/1800
Motorola V690	PIFA	38	16.9	9.5	6.1	Clamshell	GSM900/1800/1900
Motorola W208	PIFA	35.6	24	6.5	2.1	Candybar	GSM900/1800
Nokia 2626	PIFA	38	22.3	7.7	3.0	Candybar	GSM900/1800
Nokia 2652	PIFA	41.4	18.6	6.6	5.1	Clamshell	GSM900/1800
Nokia 5210	PIFA	34	18	6.6	4.4	Candybar	GSM900/1800
Nokia 5300	Planar Monopole	36.5	8.4	9.3	2.8	Slider	GSM900/1800/1900
Nokia 5320	PIFA	42.6	28.5	8	6.4	Candybar	GSM850/900/1800/1900+3G
Nokia 5500	PIFA	34.4	38.8	8.5	10.5	Candybar	GSM900/1800/1900
Nokia 6030	PIFA	38	22.3	9.1	6.6	Candybar	GSM900/1800
Nokia 6100	PIFA	37.9	28.6	6.3	6.1	Candybar	GSM900/1800/1900
Nokia 6108	PIFA	37.9	28.6	5.6	5.5	Candybar/ Flip	GSM900/1800/1900
Nokia 6111	Planar Monopole	41.4	9.1	6.8	2.5	Slider	GSM900/1800/1900
Nokia 6210	PIFA	42.6	19.8	9.9	8.4	Candybar	GSM900/1800

Table 3. Mobile phone handsets (all dimensions are in mm) (continued).

Model	Antenna	Length	Width	Height	Effective Volume (cc)	Form-Factor	Frequency Bands
Nokia 6260	Planar Monopole	45	8.5	1.1	1.5	Clamshell	GSM900/1800/1900
Nokia 6270	PIFA	47.7	28.9	6	6.3	Slider	GSM850/900/1800/1900
Nokia 6300	PIFA	33	24.2	3.3	3.4	Candybar	GSM900/1800/1900
Nokia 6630	PIFA	33	34.4	6.5	7.0	Candybar	GSM850/900/1800/1900+3G
Nokia 6680	PIFA	28	34.8	10.6	10.0	Candybar	GSM850/900/1800/1900+3G
Nokia 6708	PIFA	33	28	11.1	9.0	Candybar	GSM900/1800/1900
Nokia 6800	PIFA	35.4	20.5	10.7	6.1	Candybar/ Flip	GSM900/1800
Nokia 7210	PIFA	38.3	32.9	8.1	8.8	Candybar	GSM900/1800/1900
Nokia 7270	PIFA	84	40	3.8	12.8	Clamshell	GSM900/1800/1900
Nokia 7280	PIFA	29.4	26	10.5	3.3	Candybar	GSM900/1800/1900
Nokia 7370	PIFA	40	28	7	8.2	Clamshell	GSM900/1800/1900
Nokia 8110	Helix	33	4.5	4.5	1.7	Candybar/ Slider	GSM900
Nokia 8210	PIFA	36	15.8	12.5	6.7	Candybar	GSM900/1800
Nokia 8850	PIFA	34.9	14.1	7.4	5.9	Candybar/ Slider	GSM900/1800
Nokia 9300	PIFA	43	23	7.2	7.1	Candybar/ Flip	GSM900/1800/1900
Nokia E60	PIFA	40	19.4	10.4	8.1	Candybar	GSM900/1800/1900 + 3G
Nokia N-Gage	PIFA	44.9	24.8	7.5	8.4	Candybar	GSM900/1800
Samsung P300/308	Planar Monopole	48.4	6.2	5	1.2	Candybar	GSM900/1800/1900
Samsung SGH-2200	Helix	38.5	5.1	5.1	1.4	Candybar/ Flip	GSM900/1800
Samsung SGH-C408	Planar Monopole	33.6	16	4	1.9	Clamshell	GSM900/1800/1900
Sony Ericsson J200i	PIFA	33	25.6	6.2	4.5	Candybar	GSM900/1800/1900
Sony Ericsson K660i	PIFA	40	22	8	6.2	Candybar	GSM850/900/1800/1900+3G
Sony Ericsson P910i	Planar Monopole	35	9.7	8.4	2.9	Candybar/ Flip	GSM900/1800/1900
Sony Ericsson W800i	PIFA	37.1	20	6.2	4.6	Candybar	GSM900/1800/1900
Sony Ericsson W850i	PIFA	33	31	7.5	5.4	Slider	GSM900/1800/1900 + 3G
Sony Ericsson Z200	Planar Monopole	32	28.8	0.3	0.8	Clamshell	GSM900/1800/1900
Sony Ericsson Z300i	PIFA	38.4	10	10.9	3.3	Clamshell	GSM900/1800
Sony Ericsson Z600	PIFA	43.6	39	4.4	7.5	Clamshell	GSM900/1800/1900
Toshiba TS30/ TS32	Planar Monopole	42.6	6.7	4.7	1.3	Candybar	GSM900/1800/1900

3 Mobile-Phone Antenna Designs and Manufacturing Technology

3.1 External Antennas

The first practical mobile phones for GSM used a quarter-wavelength monopole antenna (a whip antenna). A monopole antenna had excellent performance, especially when the main PCB of the handset was also a quarter-wavelength, forming a half-wavelength unbalanced dipole. These phones were quite large, with a total size of ~160-170 mm, corresponding to a half-wavelength at 800-900 MHz. In the early 1990s, handsets started using a dual-mode helix plus a whip antenna. The most common combination was a fixed helix antenna at the top of the handset, with a whip antenna that could be retracted into the handset and extended when in talk mode, as illustrated in Figure 3 [22]. The whip antenna was roughly a quarter-wavelength, with a section of plastic at the top to reduce the mutual coupling when the whip was retracted into the phone. The whip-plus-helix combination solved the portability challenge of the fixed monopole antennas. The helix could be made into a dual-band helix by adjusting the pitch of the helix, but the monopole antenna remained resonant at a single frequency (there were methods of making a monopole resonant at multiple frequencies, but manufacturing technology limited their deployment).

An external antenna generally has excellent bandwidth and efficiency performance, but has a high SAR (Specific Absorption Ratio). The SAR often exceeded the FCC limit of 1.6 mW/g (1 gram averaging) when moved closer to the user's head, as handsets became thinner in response to consumer demand. Moving a helix antenna 5 mm closer to the human head increased SAR by 40-50% when compared to the SAR in a thicker handset, as illustrated in Figure 4. In comparison, a microstrip antenna reduced the SAR by 40-60%. A monopole or helix antenna has a single polarization, with orthogonal polarizations inducing a 3 dB drop in received power. In contrast, the microstrip antenna can receive multiple polarizations, making it less susceptible to multipath fading in talk position (TP). In addition to the SAR and multipath considerations, an internal antenna gave the phone designers more design freedom.

The combination of whip and helix gradually became only a helix for tri-band and quad-band handsets. Although the helix was used by mobile phones for several years after the introduction of internal antennas in the market, they are no longer found in most handsets (c. 2011).

3.2 Internal Antennas

There are two types of internal antennas inside mobile phones: the PIFA/microstrip antenna and the ungrounded monopole type (referred to as a PMA, or planar monopole antenna, in this paper). These have different electrical-field distributions, as illustrated in Figure 5.

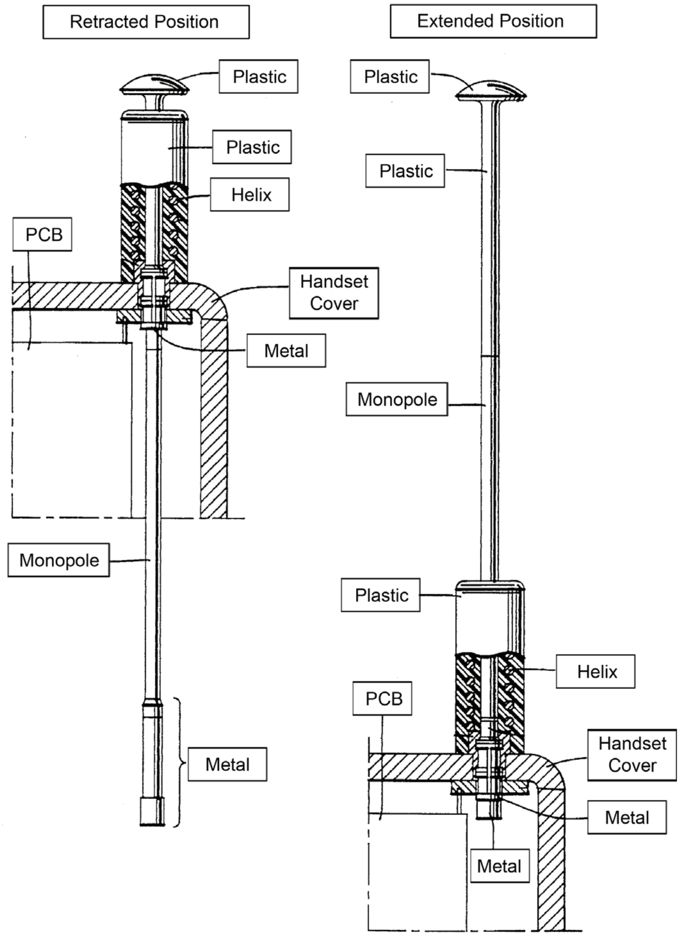


Figure 3. A monopole-plus-helix antenna: Allgon USA, US Patent 5,661,495.

3.2.1 PIFA

A PIFA (planar inverted-F antenna) is generally considered to be a microstrip antenna on a finite ground plane with a ground connection. For this paper, the PIFA is more strictly defined as a microstrip antenna with a ground connection, and contains a ground plane directly beneath the antenna and parallel to the main radiating surface (Figure 6). If the antenna is an inverted-F antenna with no ground plane parallel to the antenna, it is considered a planar monopole antenna (PMA).

The currents on a half-wave microstrip antenna are symmetric. Placing a connection to ground and using the principles of image theory forms a quarter-wavelength microstrip antenna. The size can be further reduced with appropriate loading in the form of dielectrics, inductive-slot loading, and capacitive loading. PIFAs can quite easily be made into multiband antennas by creating separate current paths on the antenna, through the use of slots and parasitics [4, 7-9].

While there are a large variety of possible patterns of the microstrip patch, the most popular patterns can be separated into three categories, as described in [12]: single slot, dual slot (Figure 8), and parasitics (Figure 9). The single slot creates two current paths and, consequently, two frequency reso-

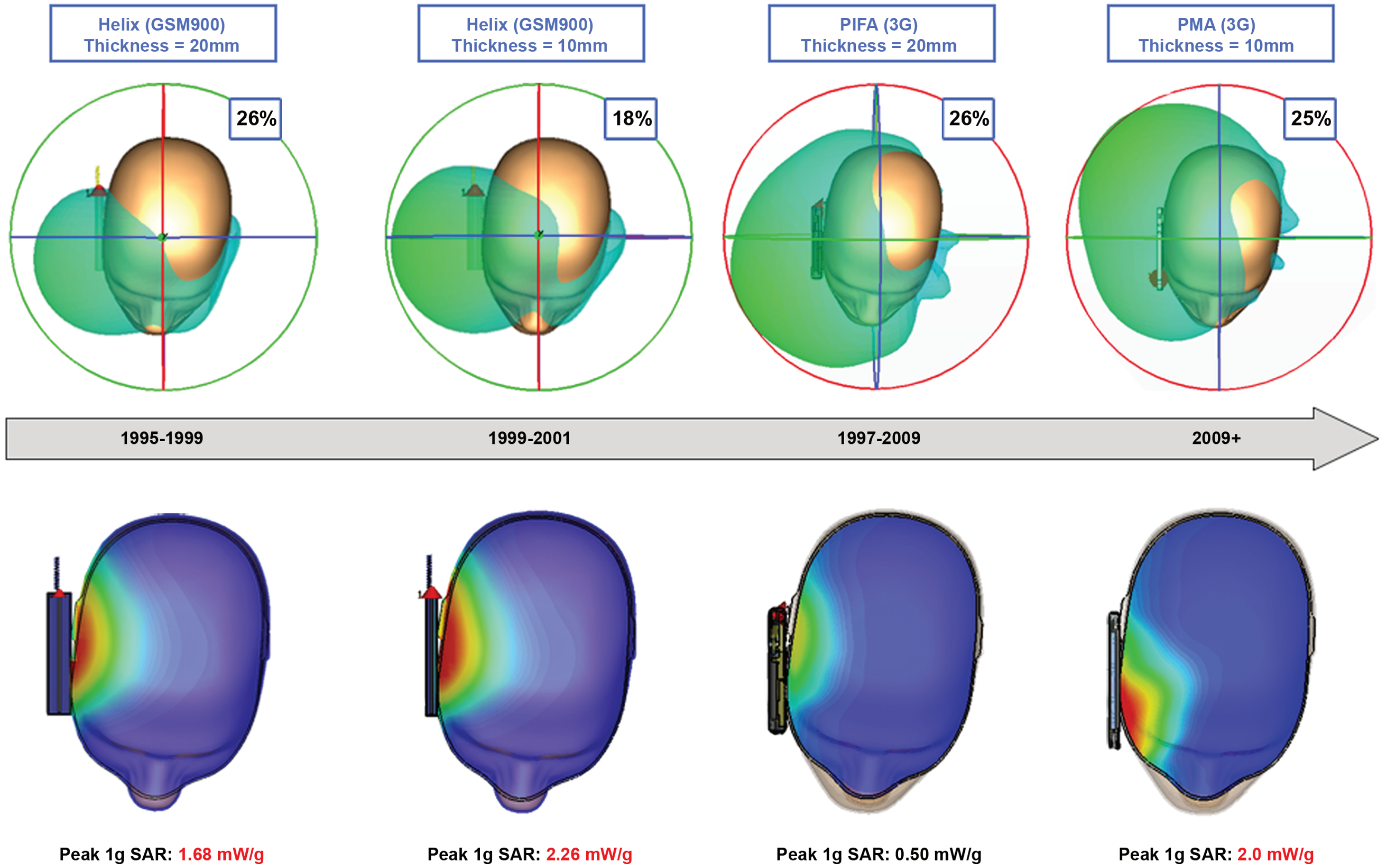


Figure 4. The evolution and performance of GSM antenna types from 1995 to 2011. As the thickness of the phone decreases, the helix antenna has poorer SAR and radiation efficiency. The PCB reduces the effect of the near fields for the PIFA, resulting in better SAR and radiation efficiency.

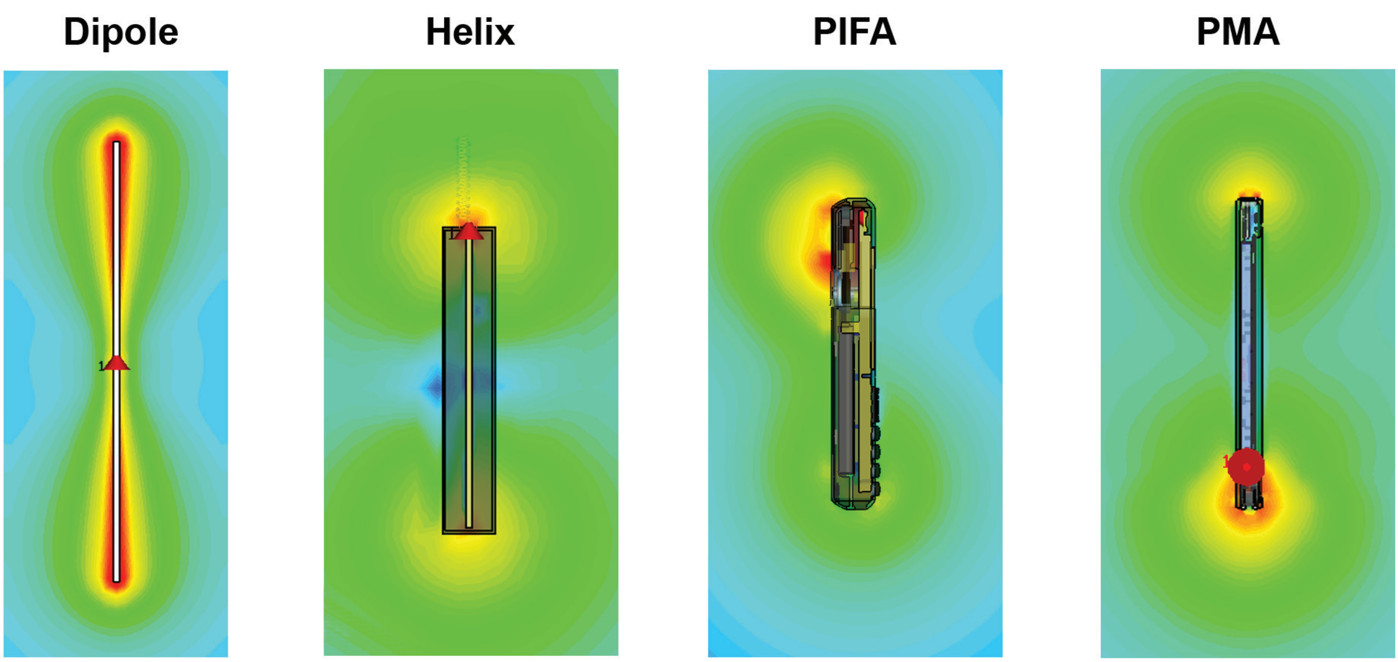


Figure 5. A comparison of the electric-field distributions: The PMA (planar monopole antenna) and the helix both have dipole-type electric-field distributions. The PIFA electric-field distribution is more similar to that of a microstrip antenna.

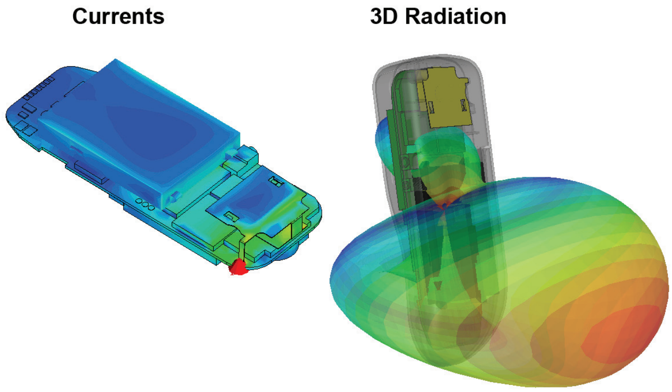


Figure 6. The current distribution and three-dimensional radiation pattern of a planar inverted-F antenna (1.8 GHz): Motorola T193. The current distribution showed that most of the currents were nearby the antenna, such that the PCB was not a main part of the radiator. The far-field radiation pattern was similar to a microstrip antenna with a single main lobe (the back lobe was due to the finite ground plane), but with a downward tilt due to the asymmetric ground plane.

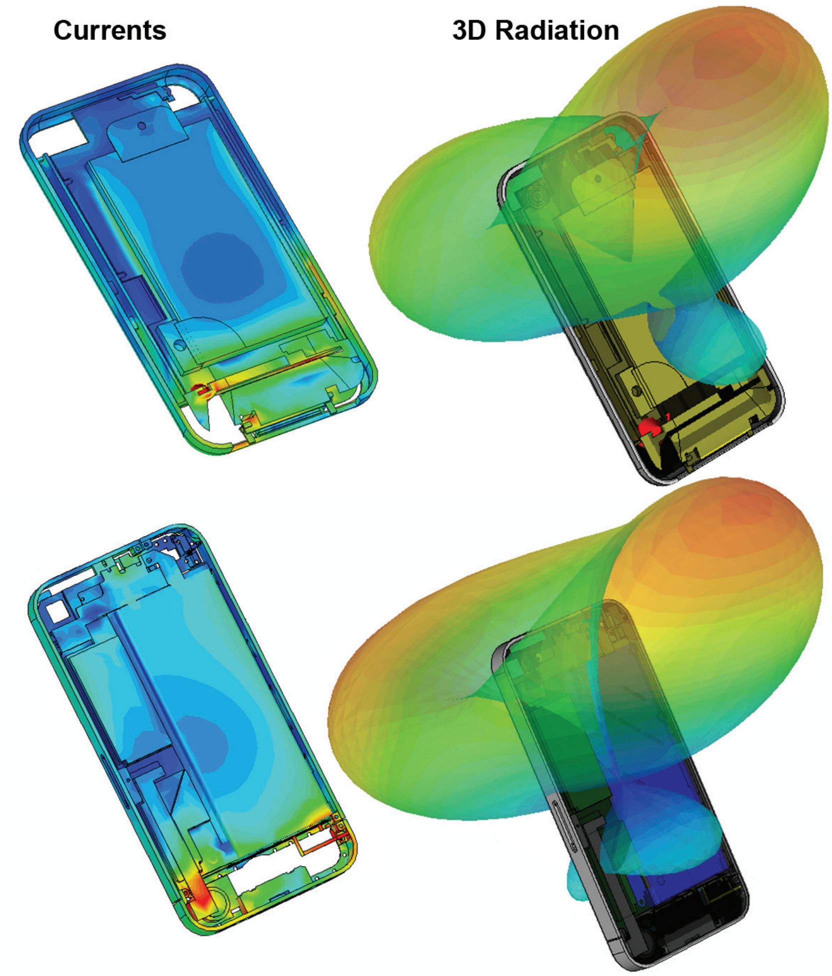


Figure 7. The surface-current distribution and three-dimensional radiation pattern of planar monopole antennas (1.9 GHz): the iPhone 3G on the top and the iPhone 4 on the bottom. The current distribution showed that most of the currents were nearby the antenna, but that there are some currents at the opposite end of the phone with a radiation pattern similar to a smaller helix-type antenna with two split lobes (a dipole with one short arm and one long, $\lambda/2$ arm). For the iPhone 3G, the antenna had a capacitive feed that coupled to the larger radiating element, which is grounded to the outer chrome ring via the external ground on the power connector. The iPhone 4 feed directly connected to the outer metal frame.

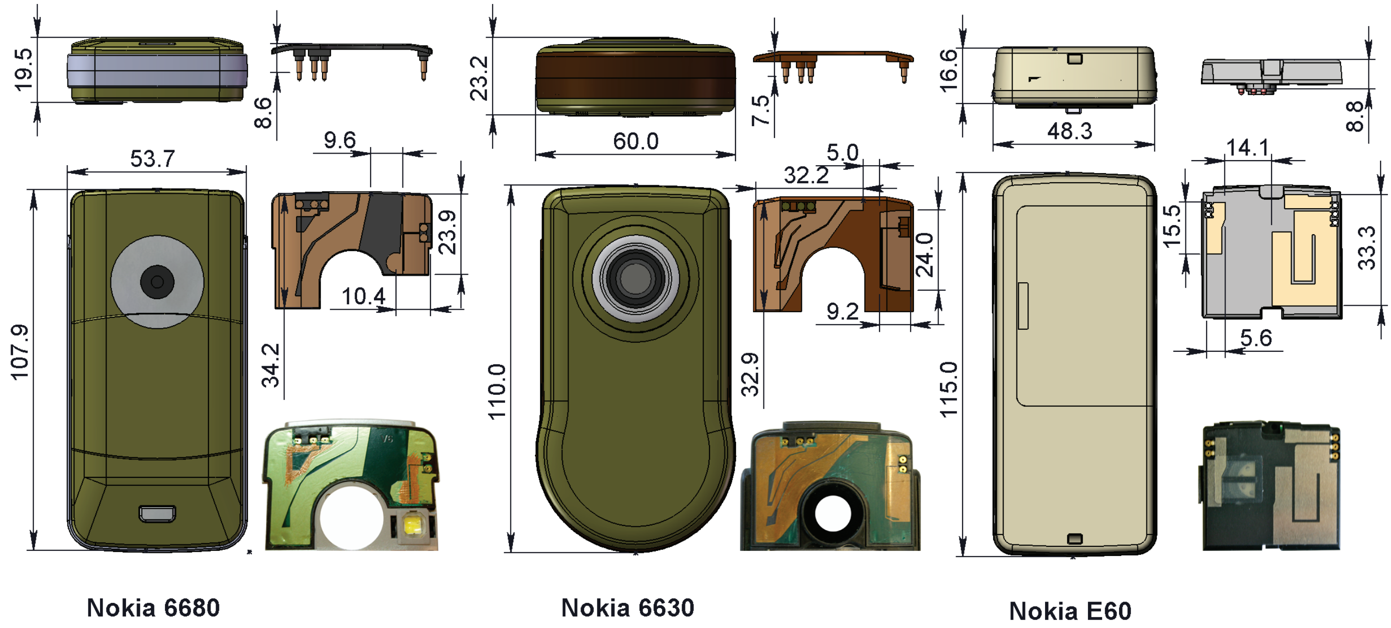


Figure 8. Multiple antennas: All three handsets were GSM + 3G. The first two handsets (Nokia 6680 and Nokia 6630) used multiple slots in the larger GSM antenna and a single slot in the smaller 3G antenna. The use of multiple slots allowed the antennas to be placed closer together (5.0-9.6 mm), as compared to the third handset (E60), with a 14 mm separation distance (dimensions are in mm).

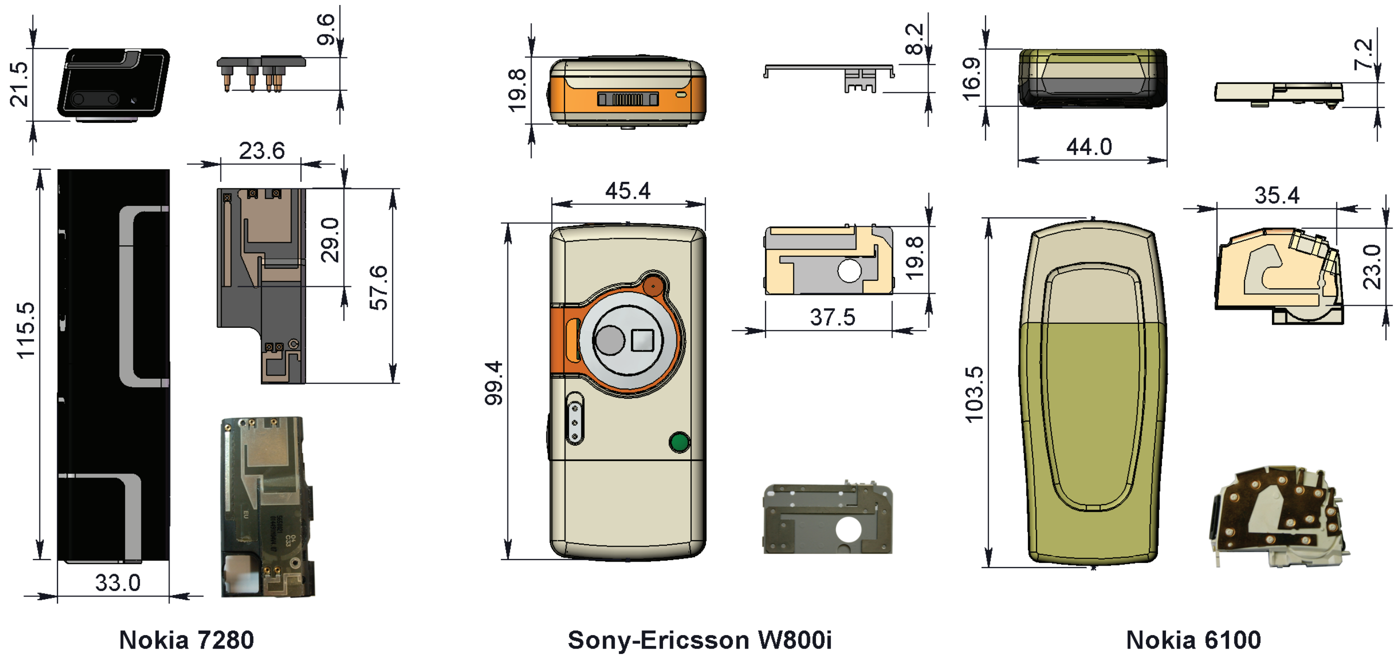


Figure 9. PIFAs with a parasitic element: In order to maximize the coupling, the parasitic element needs to be placed near the ground and feed for the main antenna, since this is the area with the highest currents. The Nokia 6100 also showed capacitive loading by bending the antenna closer to the ground (dimensions are in mm).

nances. The bandwidth of both resonances can be made wider by increasing the height between the antenna and the ground plane, transforming a dual-band (GSM900/1800) phone into a quad-band phone (GSM850/900/1800/1900). The second type is a dual-slot patch pattern, where the second slot is placed between the ground and the feed. This second slot can create a third resonance, or be used to reduce the mutual coupling between adjacent antennas (i.e., GSM and Bluetooth, or GSM and 3G).

The slot between the ground and the feed connections creates a band-stop filter at the higher frequencies, and consequently reduces the mutual coupling between the two antennas [23]. Additional antenna-isolation techniques include the use of a tuned parasitic, a neutralization line, or ground-plane modification to reduce the mutual coupling between the two antennas [24-26].

Another method to increase the number of resonances – in particular, for the higher frequency bands – is to use a grounded parasitic element that is placed in a region of high field strength to maximize coupling [27, 28]. The grounded parasitic element then forms a third resonance frequency that can broaden the higher frequency band. Because of the three resonances, this technology is often used in tri-band phones (GSM900/1800/1900).

The resonant and radiation characteristics of a microstrip antenna with a limited ground plane and a small height above a ground plane are similar to that of a resonator with a narrow bandwidth, high Q, concentrated current distributions, and multi-band resonances [29].

3.2.2 Monopole Antennas (PMA)

These antennas are typically classified as external antennas with the quarter-wavelength wire antenna (whip) or the helix antenna. In this paper, either an inverted-F antenna and or a monopole can be an internal antenna if it is an antenna without a ground plane directly underneath it. They are referred to as a planar monopole antenna, or PMA (Figure 10). Figures 6 and 7 compare the PIFA current distributions and three-dimensional radiation patterns at 1.8 GHz with two planar monopole antennas at 1.9 GHz.

Table 4 compares the different antenna types, and Table 5 summarizes the antenna performance as a function of the antenna.

3.3 Design Parameters

Designing a mobile-phone antenna consists of determining the right balance of compromises in order to minimize the antenna volume within the handset. The basic antenna parameters each have a different effect on one of the critical performance indicators of the mobile-phone antenna, and are summarized as follows (in order of decreasing importance):

1. Bandwidth: height (above ground), length, width

2. Gain/efficiency: length, height, width

3. SAR: length and height, width

4. Resonant frequencies: length and width, height

In addition to the basic antenna dimensions, there are several other factors that have various effects on the antenna's performance indicators, as described in the following sections.

3.4 Feeding Structures

There are two types of feeding structures: the capacitive feed, and the inductive feed. A capacitive feed couples the energy to the main radiating element [30], and can also be self-resonant at a high-frequency band, for matching purposes. It is either placed directly underneath the antenna, or adjacent to the main antenna. It is difficult to accurately manufacture capacitive feeds directly underneath the antenna, because the feeding is highly dependent on the separation between the main antenna and the capacitive feed (this separation acts as a matching network with variable serial-capacitance loading). An inductive feed is a wire/pogo pin with a direct electrical connection between the PCB and the antenna. By controlling the width and length of the feed connection, an engineer can fine-tune the antenna's matching, although this is difficult to utilize due to manufacturing and antenna-placement constraints.

3.5 Loading Structures

Antenna loading: In order to minimize the area occupied by an antenna, an engineer uses either a set of inductive or capacitive loads [31], or a matching network [32].

3.5.1 Matching Networks

A matching network is used to fine-tune the antenna's resonances. Typical matching-network configurations for multi-band antennas include the LC networks, Pi networks, and T networks with two to four components. Larger matching networks are rarely used, since they have greater sensitivity and induce higher losses.

3.5.2 Inductive Loads

An inductive load can be a slot, a meandering line, a notch, a choke, a corner, or any other pattern configuration that alters the current path. Inductive loading is the manipulation of the currents or H field of the antenna. Most PIFA antennas inside mobile phones use a slot as the inductive load, since a slot is easily tunable and can be used as a choke to allow relatively independent tuning of two different parts of the antenna (corresponding to two resonant frequencies). The inductive load is most effective in areas of high current density. For example, if a meandering line is used as the load, the load will require fewer meanders/turns if is placed close to the ground/feed than if it is placed at the end of the antenna with low currents. Figure 10 shows an example of inductive loading with a meander line.

3.5.3 Capacitive Loading

Similar to inductive loading serving as a means to manipulate the H field, capacitive loading is a way to manipulate the E field. The electrical-field distribution on a shorted microstrip antenna is near zero at the ground/feed locations, with a peak at the end of the antenna. A capacitive load therefore has the greatest effect near the ends of the antenna. Typical capacitive loads include bending the antenna closer to ground, and increasing the height or placing shielded components below the antenna, in order to increase the E-field density. Figure 9 shows an example of capacitive loading.

3.5.4 Feed and Ground-Connection Loading

By changing the size and placement of the feed and ground connections, the antenna's characteristics and matching can be fine-tuned. For the microstrip patch antennas, the optimal feed placement is along the side of the PCB. This allows for maximizing the physical length of the current path, and increases coupling to the PCB such that the PCB acts as a radiator, increasing the antenna's aperture size, and therefore its performance [33]. The separation between the ground and the feed affects the matching of the antenna. By changing the width of the ground connection, the resonant frequency can be increased by decreasing the width of the ground connection (at the expense of the antenna's bandwidth). In terms of matching, the ground connection can be modeled as a shunt inductance.

3.5.5 Parasitics

A parasitic is a piece of metal near the antenna where the parasitic can effectively couple to the electric and magnetic fields of the antenna, and this generates an additional resonance. If the parasitic is not connected to RF ground, it is called a "floating" parasitic. Metal handset covers or metal components nearby the antenna that are not grounded will act as parasitics. These will affect the antenna's performance in an adverse way (i.e., a user touching the floating metal covers will load the antenna with a random load, such that the antenna's resonance will also change in a random manner). Consequently, all metal covers and components nearby the antenna are grounded. If the metal parasitic is constructed to be a quarter-wavelength and placed in an area with the highest E field (near the end of the antenna) or the highest currents (near the feed and ground), then the parasitic will generate an additional resonance that can be controlled. This technique is often used for creating an additional resonance in the 1.7 to 2.1 GHz bands.

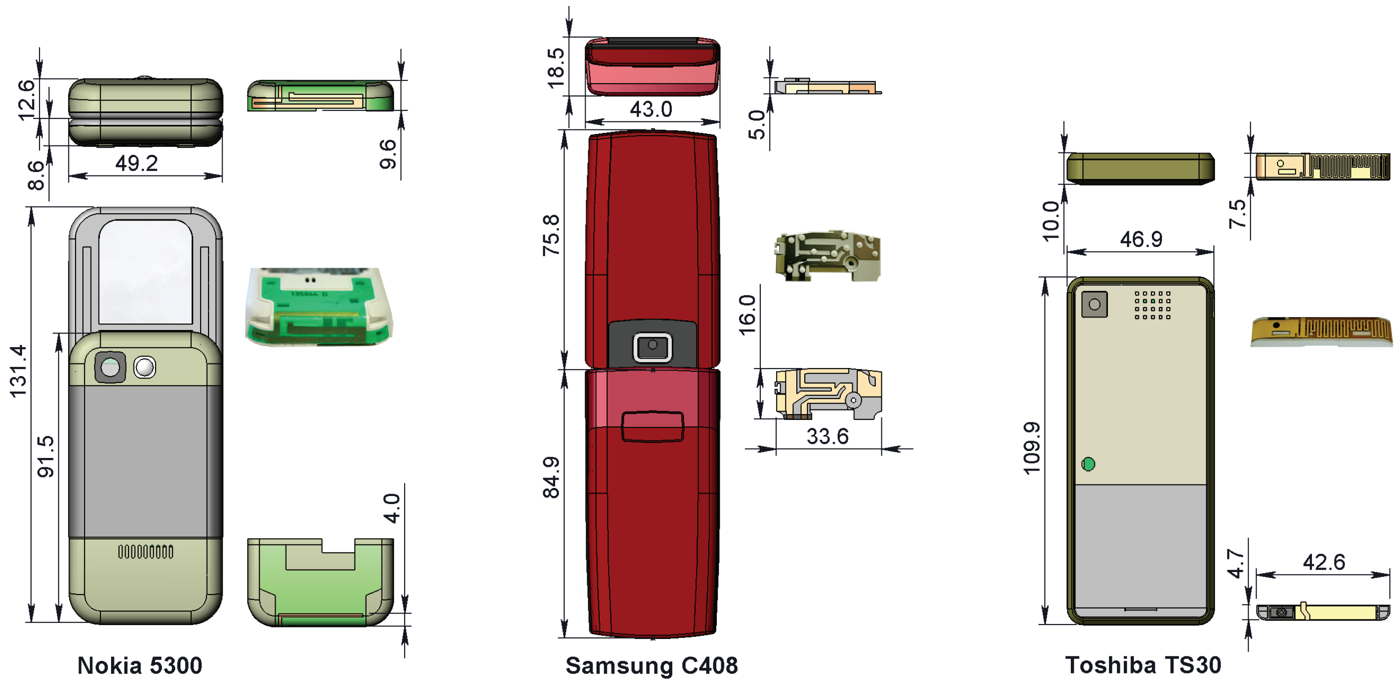


Figure 10. Planar monopole antennas (PMAs): The Nokia 5300 was a slider phone with a PMA at the bottom of the handset. The Samsung C408 was a clamshell phone with an inverted-F antenna in the middle of the phone (in the open position). Since there was no ground plane underneath this inverted-F antenna, it had antenna-performance characteristics similar to a helix or a monopole. The third handset is a Toshiba TS30 that also showed an example of inductive loading with a meandering line (dimensions are in mm).

Table 4. A comparison of mobile-phone antenna types.

Type	Theory	Advantages	Disadvantages
External Antennas			
Monopole (Whip)	$\lambda/4$ antenna, no loading	Excellent Gain & VSWR/ S11, easy to manufacture	Poor performance in paging mode when retracted, whip cannot be made easily into multi-band
Helix	$\lambda/8 \rightarrow \lambda/4$ inductively loaded monopole	Short size, reasonable efficiency, good bandwidth, easy to manufacture	Sticks out, high SAR: (helix > whip > PIFA), design limited
Whip + Helix	Retracted: $\lambda/4$ Extended: $\lambda/2$	Advantages of whip in extended position; advantages of helix in retracted position	Same disadvantages as helix antenna, whip cannot be easily made into multi-band
Internal Antennas			
Slot	$\lambda/2$ slot antenna, uses dielectric to decrease volume	Very low SAR, not sensitive to external disturbances (i.e. fingers)	Large Size (60×50×10 mm), single-band
Ceramic Antennas	$\lambda/4$ meandering antenna embedded in ceramic with $\varepsilon = 10 \rightarrow 30$	Small, easy to surface-mount	Low gain in talk position, very narrow bandwidth, heavy
PIFA (Planar Inverted-F Antenna)	$\lambda/4$ shorted microstrip antenna. Current peak near short.	Inside phone for more design freedom, control over current peak, lower SAR than helix, multi-band	Lower gain and bandwidth compared to external antennas, more production challenges with two contacts to PCB
PMA (Planar Monopole Antenna)	$\lambda/4 \rightarrow \lambda/2$ microstrip antenna without ground/PCB underneath antenna patch	Inside phone for more design freedom, can be made very thin, performance similar to helix	High SAR in regions close to antenna, requires longer handsets

Table 5. Antenna performance compared to antenna type: The values represent the average performance in all relevant frequency bands. The average effective volume is the total antenna volume minus grounded components underneath the antenna.

Types	Average Effective Volume (cc)	Average Low-Band BW (4:1)	Average Low-Band Efficiency	Average SAR (Earpiece)
Helix	1.7	24.73	44.95	1.8
PIFA	6.6	12.84	37.50	0.6
PMA	2.2	21.11	42.03	0.8
		Average High-Band BW (4:1)	**Average High-Band Efficiency**	**Average SAR (Peak)**
Helix		35.20	39.70	2.3
PIFA		19.86	38.18	0.9
PMA		20.16	46.67	2.8

3.5.6 Active/Passive Antennas

A passive antenna is an antenna (plus matching network) that does not have any intelligence or active components. In contrast, an active antenna will have switches to control the antenna's resonances. Examples include switched matching components, reconfigurable antennas, switched modes, switched parasitics, etc. [11, 34], with two circuits shown in Figure 11.

3.6 Multiple Antennas and Isolation

When 3G was first introduced into handsets, the RF chipsets were separate from the GSM chipsets, requiring two separate antennas (Figure 8). High isolation is critical for good antenna performance, since if the isolation is poor, the second antenna will absorb significant power from the first antenna (for example, an isolation of –3 dB means the second antenna would absorb 50% of the power radiated from the first antenna). The easiest method to increase the antennas' isolation is to separate the antennas. Since space is limited inside the handset, other techniques using slots and parasitics are used.

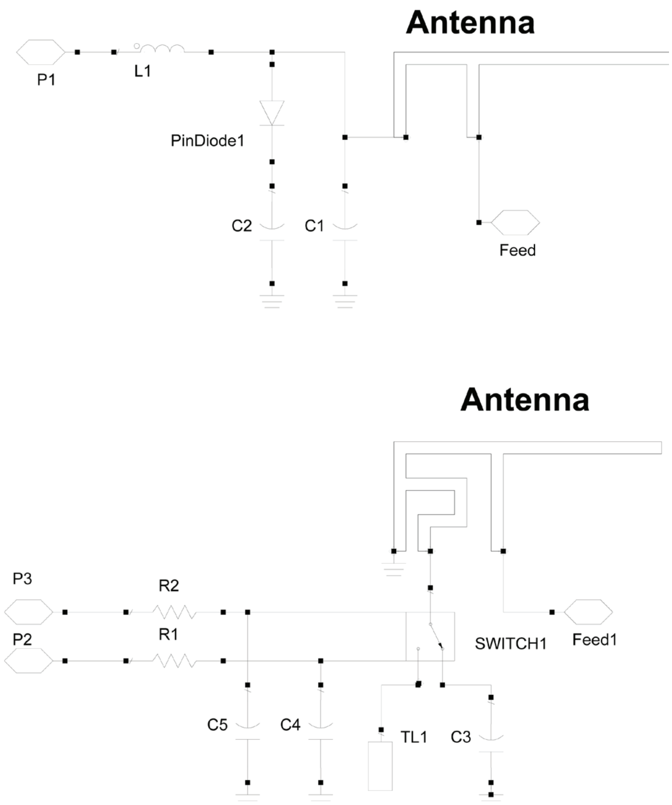


Figure 11. Active antennas: The upper circuit was for the Nokia 8810, a single-band GSM900 handset, using a diode to switch the matching between receiving and transmitting in GSM900. The lower circuit was for the Nokia 6270. This circuit is more complicated, switching between European mode (GSM900/1800) and Americas mode (GSM850/1900). The switch was a GaAs switch.

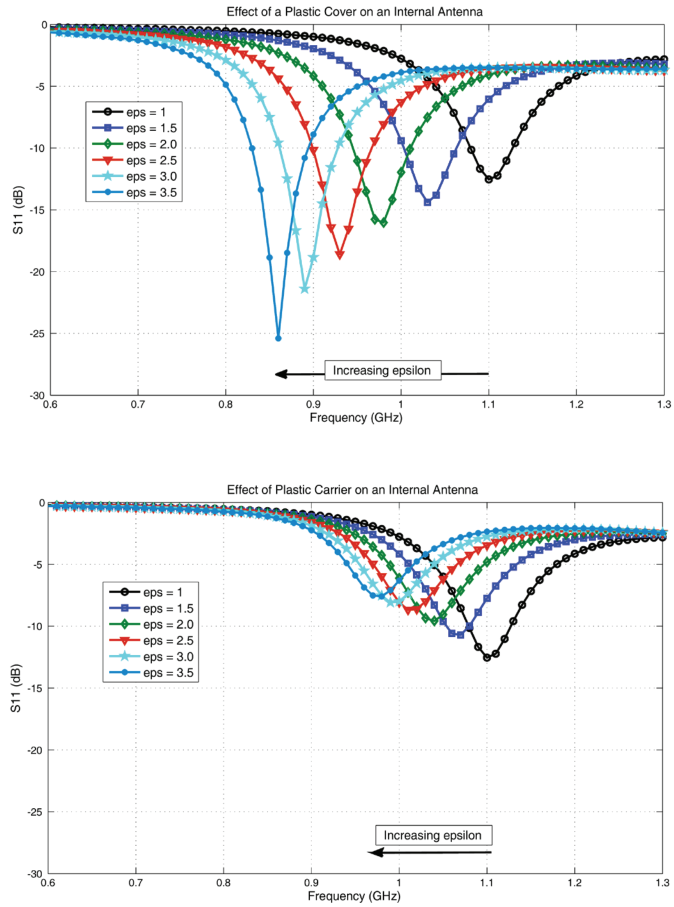


Figure 12. The effects of plastic on the performance of antennas: In the top graph, the dielectric constant was simulated between 1.0 and 3.5 for the plastic back cover of the iPhone 3G, while keeping the plastic antenna carrier constant at $\varepsilon = 1$. In the bottom graph, the dielectric constant was simulated between 1.0 and 3.5 for the antenna carrier, while keeping the back cover constant at $\varepsilon = 1$. Since the antenna was a PMA (planar monopole antenna) type, the plastic covers had a larger effect on the resonant frequency than the plastic carrier.

3.7 Handset Materials

3.7.1 Plastic Covers

Depending on the plastic material, the dielectric constant is between 2.5 and 3.5, with a loss tangent between 0.02 and 0.20. The plastic covers and plastic antenna carriers load the antenna, shifting the resonant frequencies lower (Figure 12).

3.7.2 Metal Covers

Metal covers increase the ground area around the antenna, and therefore increase the Q of the resonant structure. The bandwidth is inversely proportional to the Q of a resonator, so the antenna's bandwidth will decrease, as well. Since metal covers have high conductivity, there is little effect on the peak efficiency of the antenna.

3.7.3 Chrome Plating

Chrome plating is often used in handset design, but chrome's conductivity is one order of magnitude less than that of copper or aluminum. The increase in resistivity reduces the efficiency of the antenna, although the bandwidth will increase.

3.7.4 Lossy Ground Planes

Similarly to the antenna, the ground plane – especially the ground directly underneath a PIFA – must be a good ground: a ground with high conductivity that is connected and grounded to the main PCB ground. If the ground plane is made of lossy or resistive materials, then the bandwidth of the antenna will increase at the expense of radiation efficiency. Figure 13 shows two different handsets with lossy grounds: the Geo GC688 used the lossy ground to increase its bandwidth at the expense of radiation efficiency, and the Nokia 8850 integrated a more-conductive ground plane into the antenna to isolate the antenna from the lossy material in the middle portion of the handset (decreasing the bandwidth at the expense of increasing the radiation efficiency).

3.7.5 Plastic and Metal Cases

Users will often add a case to their mobile phone to express individualism, or to protect the phone. These have two basic form factors: one type covers the entire phone except for the display, and the other type only covers the outer ring of the handset. The cases use either plastic, chrome-plated plastic, or metal. Whereas the plastic cases have little effect on the antenna-efficiency performance, the user's hand absorbs less radiation. The metal and chrome-plated cases couple the currents more directly into the user's hand, and significantly reduce the antenna's performance. The best-performing cases were the two-layer ring cases that create an air gap between the handset and the plastic case, with a radiation-efficiency improvement when gripped by a user's hand. Results using CST simulations of different types of cases on the iPhone4, where the handset is gripped along the sides, are summarized in Table 6.

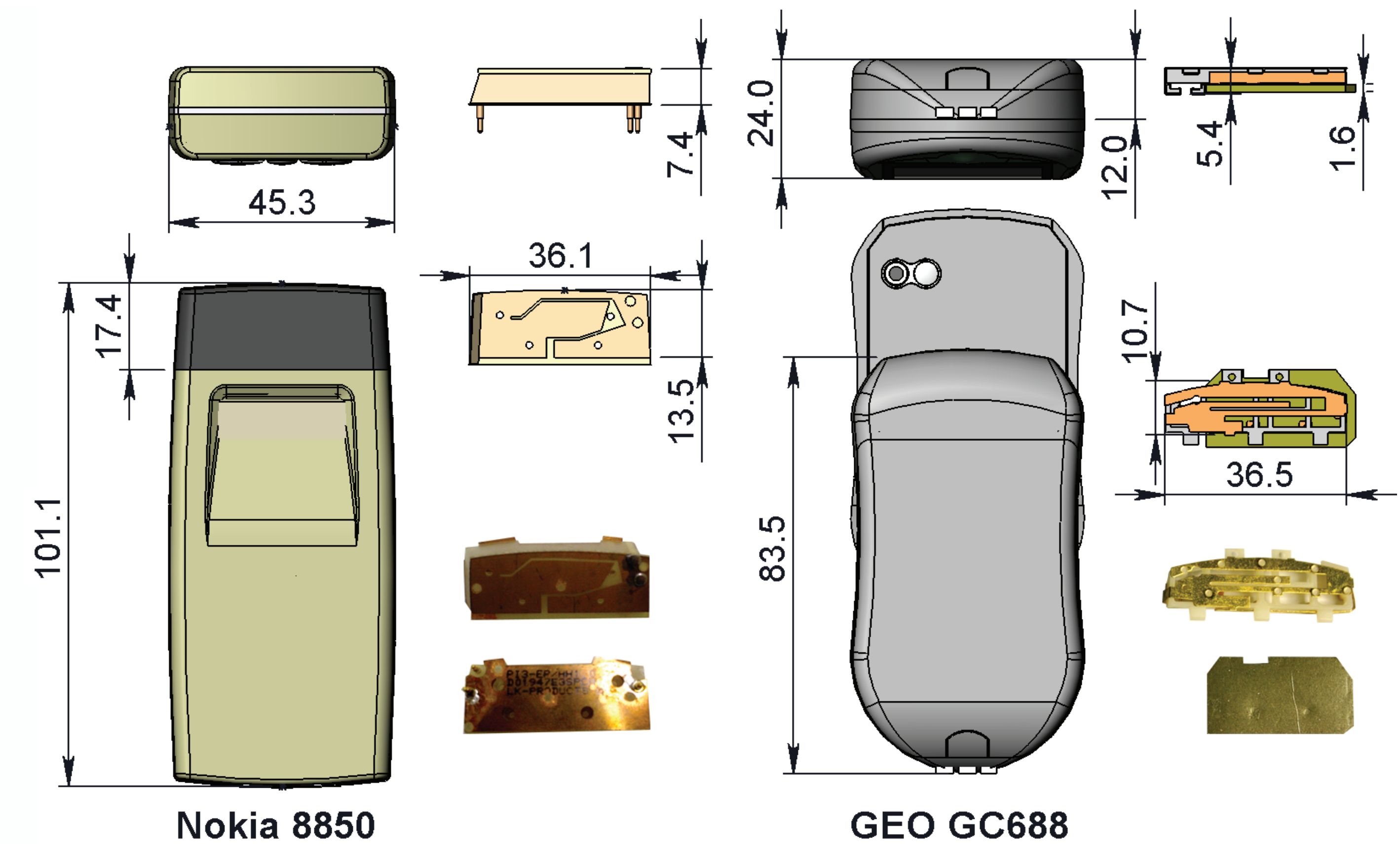


Figure 13. Lossy ground planes: The Nokia 8850 had a chrome-plated mid-deck beneath the antenna. In order to ensure good antenna performance, a ground plane was integrated into the antenna and connected via pogo pins to the PCB ground. The Geo GC688 used a resistive foam material as the ground plane in order to achieve quad-band bandwidth performance. As a consequence, the handset radiation efficiency was 5% (dimensions are in mm).

Table 6. The effects of iPhone4 cases on antenna efficiency and absorption in the user's hand.

Case Type	Efficiency		Hand Peak SAR (mW/g)	
	GSM900	3G	GSM900	3G
No Case	14%	16%	19.3	27.0
Plastic Case (t = 1 mm)	16%	17%	11.6	12.6
Plastic Case (t = 2 mm)	18%	17%	7.1	8.0
Plastic Case (t = 4 mm)	18%	17%	2.3	5.4
Ring: Plastic (t = 1 mm)	16%	16%	12.7	11.3
Ring: Plastic (t = 2 mm)	18%	16%	7.9	8.5
Metal Case (t = 1 mm)	0%	1%	0.0	0.2
Ring Metal Case (t = 2 mm)	0%	3%	0.0	0.0
Chrome Plated Plastic (t = 2 mm)	4%	7%	9.2	11.7
Ring: Metal (0.3 mm) + Air (3 mm)	23%	15%	16.3	25.8
Ring: Metal (0.3 mm) + Air (1 mm)	11%	17%	3.6	21.5
Ring: Plastic (1 mm) + Air (3 mm)	24%	22%	7.4	9.8
Ring: Plastic (1 mm) + Air (1 mm)	22%	21%	7.9	9.6

3.8 Component and Antenna Placement

3.8.1 Battery Placement

The battery is a mix of plastic and metal materials, similar to a resistor. If the battery is not properly isolated from the antenna, the antenna's radiation/efficiency performance will decrease [35].

3.8.2 Speaker Placement

Since speakers generally require an acoustic cavity, they are often integrated together with the antenna. The speaker affects the higher frequencies, and needs to be isolated by serial inductors on the PCB [35].

3.8.3 Metal and Chrome Rings

Several phones use a chrome or metal ring around the outside of the handset. Depending on how this ring is grounded to the PCB and the antenna, there can be significant coupling of the antenna's currents to the outside of the handset. Figure 7 shows the current coupling to both the chrome ring in the iPhone 3G, and to the metal frame in the iPhone 4. While this coupling to the outer ring of the handset increases the antenna's size and performance in free space, the coupling is also more susceptible to detuning and power loss due to the user's hand, as seen in the following Section 4.2. The iPhone 4 "frame" antenna has a feed directly contacting the metal frame. However, it excites the mid-deck of the phone in addition to the outer frame, distributing the currents throughout the lower section of the handset, similar to planar monopole antennas in other handsets. The outer ring is well grounded to the PCB ground, in order to prevent the random parasitic effect of a floating metallic component.

3.8.4 Form Factor

The form factor of a mobile-phone handset has a significant effect on the antenna's performance. The form factor can be separated into two categories: fixed PCB/RF ground length, and non-fixed PCB/RF ground length. The phones with a fixed PCB length are called "candy bar" style phones. In contrast, the phones with a non-fixed PCB length have a variety of manifestations: the flip (or clamshell), the slider, and the twister. For a non-fixed PCB mobile phone, the effective RF ground changes according to whether the phone is open or closed. Depending on the antenna placement, there is a large effect on the antenna's resonance, bandwidth, and efficiency, since the PCB is an integral part of the antenna [33]. If a planar monopole is used as the main antenna with either form factor, then the length of the PCB affects the resonant frequency of the antenna, and any component at the opposite end of the PCB (from the antenna) also affects the antenna's performance.

3.8.5 Antenna Mounting

There are three common methods of placing an antenna inside the handset. The first directly etches the antenna on the PCB. This method is used mostly for narrowband antennas for short-range communications, since the height of the antenna (and, consequently, its performance) are limited. The second method is to place the antenna on the inside of the outer cover of the handset. This method suffers from larger manufacturing tolerances, between of the phone cover and the PCB and the removal of an air gap between the antenna and the plastic, thereby placing the antenna in more-direct contact with the user's hand. The third (although the most complex) is the most common: a separate piece with connections to the PCB, using different manufacturing technologies for the combination of the antenna and the antenna carrier.

3.9 Manufacturing Technologies

Although the antenna engineer has a large selection of antenna designs that can be used to meet the design specifications, ultimately the choice of manufacturing technologies will determine the design rules for the antenna engineer. Table 7 summarizes the limitations of several antenna-fabrication technologies. The following sections discuss the most popular manufacturing technologies in more detail.

3.9.1 MID

The manufacturing technology with the greatest flexibility is MID (metal interconnect device). There are two types of MID. The first is single-shot MID with a single type of plastic, where the pattern is often laser etched into electroplated metal, as found in the Sony-Ericsson Z600. Single-shot MID allows for flexibility for surface designs, allowing double-curved profiles, and complex patterns. However, single-shot MID is not well suited for three-dimensional designs that integrate via holes and feeding structures into the antenna part. The second type is two-shot MID, with two kinds of plastic molded together. Two-shot MID, using standard plastic molding and electroplating equipment, is cheaper than single-shot MID for large production runs. In addition, two-shot MID gives antenna engineers maximum flexibility in design, together with optimizing the space available to the antenna. Although two-shot MID gives engineers excellent flexibility in the antenna's design, it is the most expensive process, requires the antenna pattern to be fixed in advance. It also does not allow for easy alterations, since this would require redesigning the hard tools for the plastic-molding machines.

3.9.2 Metal Stamping

This is one of the cheapest methods of manufacturing cell-phone antennas, with a stamped piece of metal that is either glued or heat-staked to a piece of plastic. This is widely used by cell phones. However, metal-stamping technology places the greatest restrictions on the antenna designer, as it does not allow double-curved surfaces, and requires a minimum line width for structural stability. Due to the greater error spread (alignment, attaching to PCB, etc.), metal stamping encourages designs that do not depend on very small dimensions (for example, a capacitive load with a 0.35 mm gap between it and the antenna).

3.9.3 Flexfilm

Flexfilm is a flexible PCB circuit that has been adapted for use in antennas. It allows the manufacturer to integrate various circuit components and connections onto a single flex-PCB together with the antenna. These components can include a camera, a speaker, and a microphone. Because the antenna generally requires a 50-ohm feeding line, it is difficult to prevent interference and coupling if the RF connections are mixed together with the other component connections and they are fed all together on a board connector. In order to avoid the coupling and high-loss board-to-board connector, the flex-film antenna can use a separate feed connection to the main PCB. The feed connections are either pogo-pins or stamped metal. The flex-film antennas allow for higher one-dimensional curvature than metal stamping, but cannot be used for space optimizing two-dimensional-curvature designs found in MID antennas.

4. Measurement Results

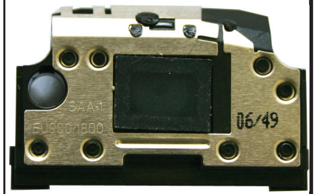
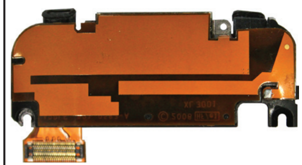
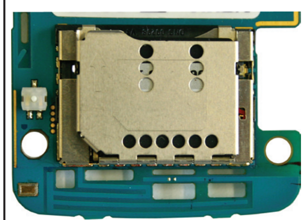
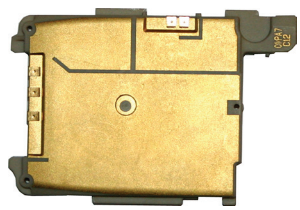
4.1 Antenna Size Effects on Handset Bandwidth and Efficiency

Wheeler first addressed the effect of antenna size on the antenna's bandwidth and efficiency in his 1947 paper [36]. There, he defined an electrically small antenna as one with a maximum dimension less than the wavenumber, $k = 2\pi/\lambda$. This relationship is often expressed in the form $ka < 1$. The maximum dimension, a, is the radius of a sphere enclosing the maximum dimension of the antenna. This is because the electromagnetic waves are spherical waves, and this sphere defines the maximum performance achievable with perfect antennas (no conductive losses, no material losses, no matching-network losses). For antennas inside a mobile phone, the average maximum dimension is between 30 and 50 mm, with a $ka = 0.5$ to 1.0 for the lower GSM850/900 frequency bands, and $ka = 1$ to 3 for the higher GSM1800/1900 and 3G frequency bands.

A PIFA can be modeled as a microstrip antenna with resonator characteristics (narrow bandwidth, well-contained electromagnetic fields), where the maximum radius, a, is set equal to the maximum length of the antenna. However, the planar monopole is more closely related to an unbalanced dipole, with the PCB acting as the other radiator. In this case, the maximum radius, a, is half the maximum length of the entire handset, except for the clamshell and slider form factors where the radius increases when the phone is in talk position. The ka range for a PIFA antenna at the lower frequencies is $ka = 0.5$ to 0.9, and for the planar monopole, $ka = 0.75$ to 2.0.

It was established in [36, 37] that for an electrically small antenna within a given spherical volume, there is an inherent

Table 7. A comparison of manufacturing technologies.

Type	Theory	Advantages	Disadvantages	Examples
Stamped metal	Stamped steel part integrated together with plastic piece	Easy assembly, versatile, spring clip contacts can be integrated into antenna	Long lead times for patterns, minimum line width, cannot utilize layered antennas or 3D curves	
Flex-film	Copper etched flexible film glued onto plastic piece	Copper has high conductivity, can contain air gap (between antenna and back cover) or mounted on inside of cover to maximum volume	Requires several parts-more logistics, glue and mechanical tolerances	
Hot stamp	Uses heat and pressure to place a metal part to a surface (no 2-D curves to bend over)	Stable pattern, no pealing, similar performance to copper flexfilm	Flat pattern only, no 3D curves	
PCB trace	Antenna trace on PCB	In-expensive, no assembly	Design limited to flat surface, worse performance due to proximity of antenna to PCB components	
MID (Metal Interconnect Device)				
1-shot: 3D masking or laser etching	Uses a 3-D mask to print the pattern onto a plastic piece or laser to etch a pattern in electroplated metal,	Shorter lead times for antenna pattern changes, stable pattern-no pealing	Expensive, antenna pattern limited to outer surface, not suitable for mass production	
2-shot	Two different kinds of plastic are molded together-metal adheres to one plastic and not the other	Suitable for mass-production, stable pattern-no pealing, allows complete RF design freedom	Expensive. PCB mount only, long lead times	

minimum value of Q. This Q defines a physical limit of the attainable impedance bandwidth at a particular efficiency/gain. The higher the antenna's Q, the smaller the impedance bandwidth is at a fixed efficiency.

The minimum Q for an electrically small antenna in free space that is linearly polarized (refined since Wheeler's original postulation by McLean in 1996 [37]) is

$$Q_{LP} = \frac{1}{k^3 a^3} + \frac{1}{ka}.$$

Since a circularly polarized antenna can excite different modes of the antenna, it has a tighter requirement for Q:

$$Q_{CP} = \frac{1}{2}\left[\frac{1}{k^3 a^3} + \frac{2}{ka}\right]$$

For the PIFA, it is modeled as a linearly polarized small antenna, with the a set to be the maximum length of the PIFA. Although the handset PCB does contribute to the PIFA's radiation, it is much smaller than in the case of a planar monopole antenna, so for the Q and bandwidth calculations involving ka, its effect is ignored.

The approximate bandwidth for a typical RLC circuit in terms of Q is [29]

$$BW_I = \frac{S-1}{Q\sqrt{S}},$$

where S is the $S{:}1$ VSWR, and BW_I is the normalized impedance bandwidth. Replacing Q with ηQ, where η is the antenna's efficiency, it can be shown that the achievable impedance bandwidth increases for lower antenna efficiencies

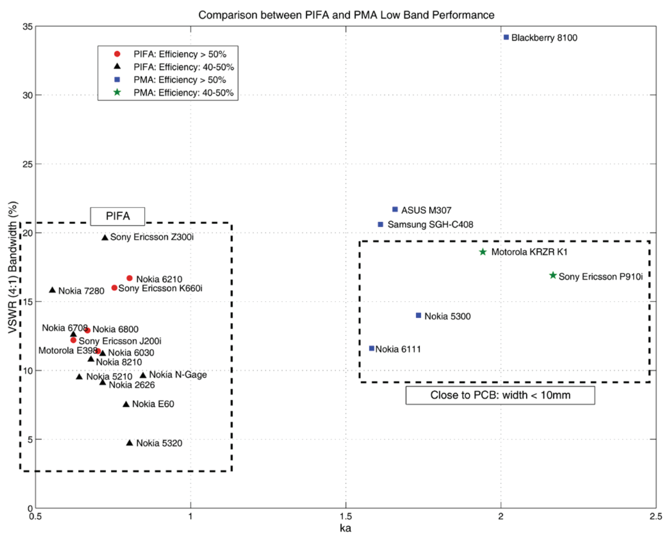


Figure 14. The measurement results for the VSWR bandwidths and efficiencies of PIFA and PMA (planar monopole antenna) handsets as a function of *ka* in the low bands (GSM850/900).

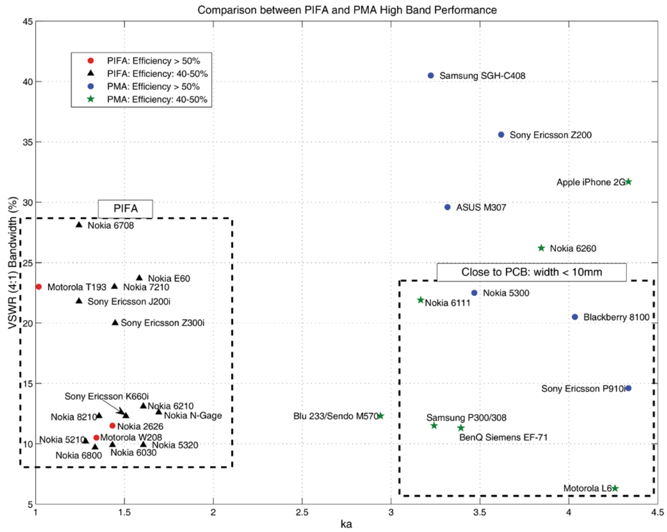


Figure 15. The measurement results for the VSWR bandwidths and efficiencies of PIFA and PMA (planar monopole antenna) handsets as a function of *ka* in the high bands (GSM1800/GSM1900/3G).

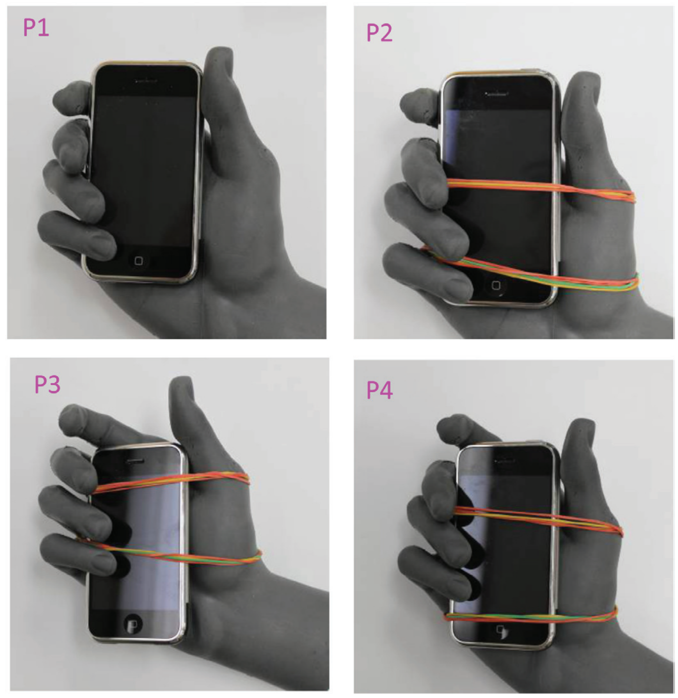


Figure 16. Hand positions: Three models of the Apple iPhone were tested in different hand positions, using the IndexSAR hand phantom (IXB-060R), inside a Satimo Starlab Chamber with an R&S CMU200 for active measurements.

[38]. Using the Wheeler relationship among bandwidth, antenna size, and efficiency, the results from the handset antenna study are presented in a similar fashion.

Since mobile-phone antennas are matched to 50 Ω, the measured bandwidth is similar to the impedance bandwidth, BW_I. The results from the measurements of S_{11} and efficiency of the mobile-phone antennas are plotted in Figures 14 and 15 for two different sets of efficiency values. As seen in both figures, the PIFAs were limited to a maximum bandwidth of roughly 20% in the low bands, and 30% in the high bands. Planar monopole antennas that were close to the ground plane with widths less than 10 mm had similar performance to the PIFAs. When the width of the planar monopole antenna increased above 15 mm, its bandwidth substantially increased. Both figures illustrated the effect of materials and components on the antenna's performance, with similarly sized antennas achieving a wide range of values.

As an example of the effect of lossy ground planes, the Geo GC688 PIFA antenna had a maximum length of 36 mm or $ka = 0.69$, but an effective antenna volume of 2.3 cc. The (4:1) VSWR bandwidth of the GC688 was 40% in the GSM850/900 frequency bands, much higher than the average 10% for a PIFA. The theoretical maximum impedance bandwidth was 35% for a radiation efficiency of 100% with equivalent *ka*, but the GC688 antenna had a lossy ground and an average radiation efficiency of 4.5%.

If the planar monopole antenna were considered independently from the ground plane of the handset, the achievable performance would shift to the left in Figures 14 and 15. However, as simulations show (Figures 6 and 7), planar monopole antennas generate significant currents on the PCB that radiate (as also illustrated in the near-field SAR measurements in Table 5), such that the PCB must be considered as part of the antenna's maximum dimension when calculating *ka*.

4.2 User Interaction

There have been several studies [39-42] modeling and measuring the effects of the user's head and hand next to a mobile phone. These have conclusively demonstrated that the presence of nearby human tissue decreases the antenna's efficiency and often increases the antenna's bandwidth, as well.

Building on prior work, this paper compares the performance of a handset in different hand positions, and presents measurements of the active handset performance: the total radiated power and total isotropic sensitivity. The active measurements determined the antenna's and matching circuit's performance without interference from a cable used in passive measurements. Four different hand positions were tested, as shown in Figure 16, with a summary of the results presented in Table 8. In the table, the P1-P4 results were compared to the P0 (no hand) performance for each handset. While all three were planar-monopole-antenna (PMA) types of antennas, located at the bottom of the handset, the iPhone 4 used the outside frame in the lower section as part of the antenna. As a result, its performance in P4 with more-direct hand contact around the base of the handset was 3 dB worse than the other two handsets.

Table 8. Total radiated power (TRP) and total isotropic sensitivity (TIS) measurements for Apple iPhones in different hand positions.

TRP-GSM	P0	P1	P2	P3	P4
iPhone 2	27.5	–8.7	–9.0	–4.2	–8.3
iPhone 3G	27.3	–8.2	–9.8	–3.5	–8.1
iPhone 4	28.5	–6.9	–8.8	–4.1	–11.6
TRP-3G	**P0**	**P1**	**P2**	**P3**	**P4**
iPhone 3G	19.0	–7.6	–9.7	–3.4	–8.5
iPhone 4	20.6	–7.2	–10.2	–4.0	–11.1
TIS-GSM	**P0**	**P1**	**P2**	**P3**	**P4**
iPhone 2	105.3	–7.9	–8.8	–3.9	–7.8
iPhone 3G	106.2	–8.2	–9.2	–4.2	–9.2
iPhone 4	106.6	–7.4	–8.6	–4.6	–11.2
TIS-3G	**P0**	**P1**	**P2**	**P3**	**P4**
iPhone 3G	106.9	–7.5	–9.2	–3.7	–8.8
iPhone 4	109.0	–6.9	–10.8	–3.8	–11.2

5. Conclusions

This paper summarized the important parameters for designing antennas for mobile-phone handsets. It closely analyzed several GSM handsets from the past 15 years, together with the limitations of current manufacturing technologies on antenna design. Future work includes analyzing additional handsets, developing a mathematical model for the antenna and handset interaction, and further computer modeling of the handsets. The handsets analyzed in this paper are a subset of the handsets analyzed in reports on the ASTRI Web site, which can be downloaded for free. The authors would like to acknowledge the contributions made by the ASTRI Antenna team [43].

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