Handset Antennas: The Next Five Years

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***Abstract*— This paper describes the progress made in the design of antennas for mobile handsets in recent years, during which a handset has become a multi-functional communications and information terminal. The paper describes current benchmarks for dimensions and performance and discusses future increases in functionality. These will require major innovation in order to provide antennas for the growing number of frequency bands and radio systems with which a handset must provide service.**

I. Introduction

Two decades ago, a mobile handset was a simple radio telephone operating on one designated frequency band. The antenna was normally an external whip, sometimes made more compact by winding it into a helix. In the mid-1990's, digital services were introduced and in many countries it became necessary for handsets to operate on two frequency bands (usually 900/1800MHz or 850/1900MHz). The travel requirements of customers for high-end handsets and the economics of manufacture led to the appearance of quad-band handsets in 2004.

The antenna designer's task was complicated by the ever-diminishing size of typical handsets, the widespread fashion for clamshell (flip) phones and the growing expectation of users that antennas should be inside handsets rather than projecting externally.

The development of 3-G services during the mid 2000's required the addition of a further band, extending the upper frequency of the high band to 2170MHz.

II. Handset antenna constraints

The design of handset antennas for the major international mobile frequency bands has been driven by a number of factors:

- Frequency bands to be covered
- Dimensions available in the handset
- Cost
- Performance
- Coexistence with other handset hardware

The rank order of these often-conflicting factors is a matter of great contention between the designers of the industrial design (ID) of new handsets and antenna engineers.

A. A handset as an integrated RF device

The RF performance of a handset is measured by its *total radiated power* (TRP) when transmitting and its *total isotropic sensitivity* (TIS) when receiving. These are largely determined by the RF efficiency of the handset, which is the ratio of the total radiated power to the power offered (forward power) to the antenna. This is often termed the antenna efficiency, but as has been shown [1], is a function not just of the antenna, but of the RF design of the entire handset platform. During the design process the layout of handset components – displays, keypads, cameras, batteries, loud-speakers, circuit boards, antennas and more – is usually carried out by engineers whose skills lie in 3-D mechanical design and PCB layout.

This approach to design fails to recognise the extent to which RF performance depends on the design and inter-connection of almost every major handset component. It results in a continuing gap between the RF performance that is achieved and the potentially much higher performance that could be obtained by optimised handset design. With the increasing use of data, and the high network costs of sub-standard handset performance in a data-dominated environment, in future more emphasis should be placed on handset optimisation.

A well-designed small antenna on a handset-size groundplane can provide an efficiency of around 70% over five bands, as shown in Fig. 1. A well-designed handset achieves an efficiency of at least 50%, while some handsets on the market in 2010 fall below 10% at some band edges. The results in Figs 1 and 2 were obtained in the same SATIMO S-64 measurement facility and highlight this performance gap. These are free-space efficiencies, and will fall by 10-15dB when the handset is held next to the user's head.

B. Antenna designs

Most current pentaband antennas take the form of planar inverted-F antennas (PIFAs) or monopoles. In both cases they will usually have a 2-branch radiating structure, one serving the low bands (824-960MHz) and the other the high bands (1710-2170MHz). PIFAs are frequently positioned over one end of the main PCB, while monopoles usually project from the end of the PCB.

During the past five years the dimensions of handset antennas has continued to diminish despite the requirement for increased bandwidth. An effective pentaband antenna currently occupies a volume of around 2cc, although sometimes an even smaller volume is available on the handset.

This paper is not intended as a technical description of existing handset designs, many of which can be found in [1] and the further references it cites.

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A glance through many academic papers and research proposals shows a continuing gap between what is currently being achieved in industry and the expectations of researchers. This is accounted for by the rate of progress in industry, the lack of knowledge of existing commercial performance levels by researchers, and their lack of experience in dealing with the interaction of the antenna and the handset.

Facilities to measure handset performance are not available to many university-based researchers unless they cooperate with an industrial partner – a reason why so few published papers include measurements of TRP and TIS.

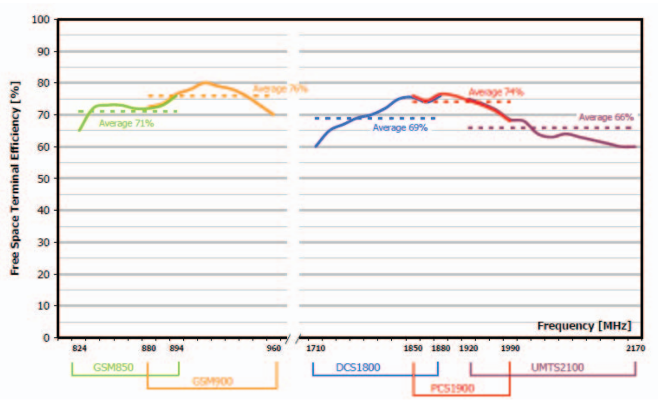

Fig. 1: The efficiency as a function of frequency of a well-designed off-groundplane pentaband antenna mounted on a bare PCB. The antenna dimensions are 40mm x 10mm x 3.2mm; the assembly, including the antenna measures 110mm x 40mm x 4.5mm.

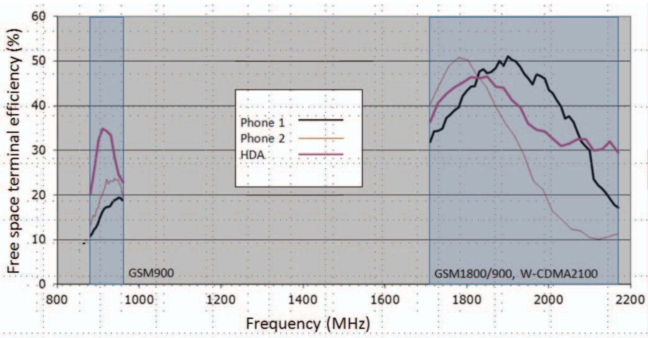

Fig. 2: The efficiency of two pentaband handsets purchased in a network operator's shop in 2010. The curve identified as HDA was obtained using a redesigned antenna, but the fundamental problems lie elsewhere in the handset.

III. Future Handsets

It is clear that we are at a time of substantial change in users' expectations of what a 'handset' can do. The manufacturers who are currently leading the industry have shown that there is a growing market for handheld devices which can perform a wide variety of functions including voice phone, music, video, games, navigation and pictures, both still and moving.

This functionality requires far more support from remote networks than a traditional mobile phone.

A. *Mobile radio standards*

The shortage of spectrum in existing mobile bands for the burgeoning volume of data traffic is increasing the demand for more bands to be refarmed for mobile use. The need to provide higher data rates to users is matched by evolving radio interface standards, first from GSM and the equivalent US CDMA system to 3-G (usually W-CDMA), now to LTE and in future to LTE-A. In some countries, other standards such as WiMAX will compete with LTE, and it remains to be seen how these standards will coexist or find their own application niches.

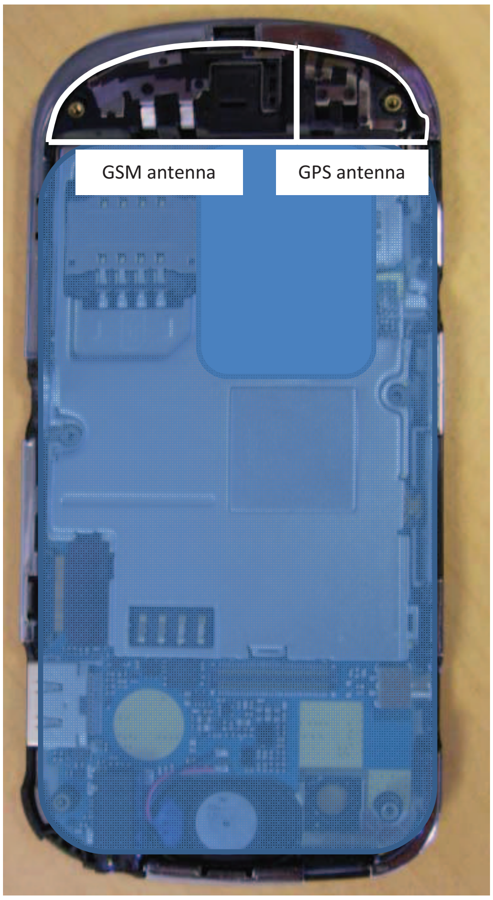

Fig. 3: Typical current-generation handset showing the relative size of the antennas. The small space that has been allocated has then been divide to provide a multiband GSM/3G antenna and a separate GPS antenna.

The termination of analog TV broadcasting and the conversion of the TV service to digital formats will release spectrum and mobile radio networks see the lower propagation losses of the frequencies involved as offering improved indoor network coverage.

The use of the radio spectrum is currently far from optimum. Frequencies are traditionally allocated to particular services and users, though their individual occupancy of the spectrum may be limited in time. Large protection ratios are provided so users will not suffer interference, even in abnormally enhanced propagation conditions. To exploit the potential for using these temporal and spatial opportunities, so-called *white spaces*, new systems are being developed; these are likely to use a mixture of geographical information and channel sounding before selecting an operating frequency on an opportunistic basis. While these may not be fully cognitive radio systems in the sense understood by researchers, they are developing in that direction and are likely to be implemented in the 5-year period discussed in this paper. A feature of many such systems is that they require a very sensitive receiver in order to find unoccupied channels where transmissions are less likely to cause disturbance to an existing occupant.

The main international standards organisation in the mobile radio world, 3GPP, now lists 17 standard frequency bands for LTE between 698 and 2170MHz [2] and the number continues to grow every year. There is an increasing tendency for administrations to allow 'technology independent' use of newly-released frequency bands, in which it is the licensee, not the spectrum authority, which determines which radio interface is used. This is creating an increasingly complex worldwide matrix of bands and standards, driving equipment manufacturers towards the use of multi-standard modems and multi-band radios.

B. *Multi-antenna techniques*

The increasingly complex network services offered by LTE/WiMAX and LTE-A anticipate the ability to use a wide range of MIMO techniques on small mobile platforms. The use of adaptive modulation and coding schemes, together with the way in which MIMO performance degrades gracefully as signal conditions deteriorate all mean that the result of RF underperformance by user terminal results in lower user data rates and lower network throughput. If the need for multiple antennas on small platforms results in loss of efficiency, then the expected benefits of MIMO will be not be achieved.

New lower-frequency bands offer better in-building penetration but, at lower frequencies on a small platform, antennas become less efficient and increasingly coupled because they excite the same dominant current modes in the same physical conductors. Several 3GPP papers assume the use of dual polarisation in mobile platforms [3], but in a handset effective dual-polar antennas are only likely to be practicable in the higher frequency bands. Enhancing antenna isolation using compensating cross-coupling techniques is helpful, but if over-applied, like any other feedback system, the result is more loss and less tolerance of disturbance – for example by the user's hand.

At present, a small number of advanced handsets use a single-band diversity receiving antenna, but some of these are specified with performance which can provide only very small diversity gain. Diversity antennas are more common on laptop platforms, and it is clear that MIMO is a more practicable proposition on platforms of this size.

Many internet connections carry data which is asymmetric, typically with the downlink carrying far more data than the uplink – for example streamed audio or video. It is therefore easy to imagine that we only need to provide effective MIMO to support high-speed data on the downlink and a slow uplink will carry much less penalty; however the LTE/WiMAX link to a fast-moving vehicle depends on very frequent updates to the channel state information, transmitted on the uplink. Without this, the downlink will slow down. For FDD systems this implies that any multiple antennas must operate both in the transmit and receive bands, increasing the requirement for antenna bandwidth. Poor terminal RF performance greatly accelerates battery depletion – the user data rate falls, the time for transmission is increased and at the same time higher RF power is needed.

C. *Multi-function platforms*

In addition to support for new mobile network interfaces, a wide variety of other radio-based services are either needed now, or will be in the near future. These include:

- WLAN for web and low-cost VoIP (2.4, 5GHz)
- Bluetooth for headsets and peer connectivity
- GPS for navigation, geo-tagging and LBS
- VHF/FM radio and its digital successor(s)
- Digital TV (in the UHF and VHF broadcast bands)
- HF DRM (3-30MHz)
- MF AM/DRM (550-1650kHz)

The necessary silicon to support these functions is in most cases already available, or will shortly be so. The dimensions and power of digital circuits continue to track Moore's law to an extent that surprises us all; there is no doubt that a handset-sized device will be soon be able to support all these functions, together with even better displays, innovative user interfaces and more complex speed- and latency-sensitive applications than those available on today's market-leading devices.

Adding antennas to support this extended functionality, together with multiple, multi-band mobile network antennas, presents a huge engineering challenge. The timescale within which these problems must be addressed *and solved* is short when compared with the usual time cycle of academic research. The present explosion of mobile data traffic is driving the adoption of LTE/WiMAX and new frequency bands are already opening.

D. *M2M platforms*

At present it is normal for the RF performance of machine-to-machine (M2M) platforms to be significantly lower than that of consumer handsets. This is partly a reflection of the high development costs of more optimised platforms and the comparatively low production volumes of many M2M devices. Many existing devices transmit only small amounts of data, and they have large batteries, so this lack of efficiency is not obvious. Future devices may transmit much more data – for example pictures, fingerprints and DNA data. Sub-standard performance will then be far less tolerable.

IV. FUTURE ANTENNA TECHNOLOGIES

Although they are closely related, the areas needing development to address the issues raised above lie is several different areas:

1) *Handset integration:* This really should be a soft target. Between 1.5dB and 3dB of link budget is lost between potential RF performance and achieved performance, even on well-designed handsets. Unless it is exceptionally poor, RF performance is currently not obvious to users, who will normally blame poor network coverage or new technology for their problems. The industry will only achieve this order of improvement if it is driven by the network operators who often subsidise handset costs but will in future bear the increasing cost of their poor performance. It requires better design process, a more integrated approach to RF design and a higher priority for RF performance in device design objectives.

2) *Tuneable and reconfigurable antennas:* This is an area in which good research has already been done [4], but many published papers fail to take into account the losses that are encountered in real switches and tuning devices. These losses particularly affect configurations in which series components are placed near current maxima or parallel components near voltage maxima – both being locations where they are likely to be most effective from the point of view of tuning range. Some published designs use multiple switches which require effective low-loss decoupling of the associated DC control lines. When implemented in small SMD components, loss is always an issue. Small antennas are intrinsically sensitive to internal resistive losses.

3) *Switching and tuning devices:* In order to be considered for application in handsets, switching and tuning devices must have low loss, low control voltages, low power consumption, low intermodulation products, small dimensions and low cost. They must have high peak power ratings, high reliability and high repeatability in production. Varactor diodes are a mature technology, but new components are needed with low operating voltages, low minimum capacitance and a wide tuning range. MEMs devices are promising, but there is still much work to be done if they are to find application in high-performance handset antennas,

4) *Multiple antenna techniques on small platforms:* A typical handset platform is around 105mm long (0.3 wavelengths at 800MHz). While various studies have investigated the decorrelation available with antennas spaced by this distance, antennas placed at each end of the groundplane in a handset excite the same current mode in the groundplane; the effective separation between the phase centres of the antennas is smaller than the distance between the physical antennas. There is some useful asymmetry in the radiation patterns of the two antennas, so some pattern diversity is achieved, but any assumptions of performance that fail to take into account the user's hand – typically covering one antenna and not the other – may reach incorrect and optimistic conclusions about the effectiveness of MIMO.

The trade-offs involved in the use of lower frequencies need better quantification, taking into account reduced propagation losses, but also the diminishing performance of mobile antennas and the reduced space for a MIMO antenna suite.

5) *Compensation techniques:* Studies of possible ways in which antennas can be terminated, matched or cross-coupled in order to decrease the correlation between their outputs in a multipath signal environment need to be extended to include realistic component losses, antenna losses and hand effects.

6) *Dual-polar antennas:* Handset antennas have traditionally been limited to plane-polar operation, the plane of propagation being strongly aligned with the axis of the handset PCB. Handset dimensions make it possible to create a pair of orthogonally polarised antennas in the high bands, but the limited width of a handset makes it difficult to design an orthogonal antenna pair with wide bandwidth in the low bands; however a tuned solution might be possible.

7) *New antenna structures:* New, smaller, efficient broadband antennas will always find ready application. While it may be possible to create new antenna structures with wider bandwidths, we are close to fundamental size/bandwidth/efficiency limits related to the whole dimensions of the handset. It is however not clear exactly how small the device that excites the radiating modes in the handset (the physical component we call the antenna) can be. This is a subject that needs further work.

8) *Electrically very small antennas:* Some future applications use frequencies at which the handset is only 0.002λ long or less (this example is for 100mm at 6MHz). At these frequencies the environment is very noisy; if we add a low noise amplifier between the antenna and the receiver the penalty for poor antenna efficiency can be less than we may expect. The small size of the receiving element means that non-linear effects should be controllable. More work is needed here to investigate the best way to make use of the very small available dimensions, the presence of the handset groundplane and available low-noise semiconductor devices.

9) *Cooperative platforms:* This is a system-level technique that could enhance user experience while allowing more realistic performance objectives. A second terminal – for example in a vehicle – which provides one or more of the MIMO signal streams could work cooperatively with a small user device to

provide it with a much higher data rate than the device operating by itself. A laptop and a handset could co-operate in the same way. Similar techniques are already planned for base stations.

10) *Multi-function user platforms:* The co-existence of the multiple radio functions, concurrently transmitting on a small platform creates major problems of potential mutual interference. This creates further constraints on antenna placement and dimensions and may require new solutions in both antenna hardware, platform design and system software.

V. An Agenda for Research

Many current devices have indifferent performance; new transmission systems require more and better antennas in small devices if they are to deliver the spectrum efficiency, economic benefits and user experience which are the reasons for their introduction.

The current industry-wide lack of RF engineers has resulted in the antenna engineering community having unique knowledge and skills that are necessary to improve the performance of mobile devices. They cannot do this alone, but must engage everyone involved in the process of handset design, specification and testing.

Taking a world perspective of research in this area there is a large gap between the theoretical modelling of networks and protocols, and the nuts-and-bolts work of developing and characterising antennas and RF platforms. Too much academic resource is spent following what has already been done in industry – but is generally not published for commercial competitive reasons. At the same time, many research projects claim applicability to small mobile devices, even when a little thought suggests that such an application is entirely unrealistic.

In many countries, the timescales for the introduction of LTE/WiMAX networks are short, yet as demonstrated in this paper there is still very important and challenging work to be done if we are to realise the potential of these systems. Some of the problems are fundamental, bearing on issues such as the spectrum that is most suitable for their deployment.

VI. Conclusions

A substantial deficit exists between the theoretically possible RF performance of a handset and the performance typically achieved. This deficit is currently only occasionally seen by users, but with the introduction of LTE/WiMAX it will impact both user experience and network costs.

The issues involved are cross-disciplinary. They embrace antenna and platform RF design, radio propagation phenomena, system protocols and spectrum planning. They extend down the whole value chain, from component manufacturers, handset designers and network operators to users. Their solution – or at least their mitigation – requires cooperation between workers in the disciplines involved and also between academia, industry and network operators.

Acknowledgment

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