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Tunable Antennas for Mobile Devices: Achieving High Performance in Compelling Form Factors

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Abstract — The evolution of modern mobile terminals has been driven by two key factors, the user interface and broadband connectivity. However, while the peak performance near the base station may be state-of-the-art, real world performance (in-building, in suburbs and rural areas, in-car and on-person) has substantially fallen over the years. This has not only impacted achievable data rates and reduced battery life but, in many cases, actually prevented useful connections for voice or data. The key factor driving this degradation has been changing antenna location and reduced antenna volume driven by the race for thinner and display-dominated platforms. Reduced antenna volume leads to a tradeoff between bandwidth and efficiency. To maintain acceptable efficiency, tunable and reconfigurable antennas are being deployed to enable effective use of reduced instantaneous bandwidths. This capability brings new challenges as well as new opportunities to the handset designer.

Index Terms — Handsets, mobile devices, smart-phones, antennas, tunability, RF, MIMO, diversity, RF front ends.

I. Introduction

The evolution of modern mobile terminals has been driven by two key factors, the user interface and broadband connectivity. The consumer has seen rapid progress in the range and complexity of tasks that they can accomplish with these platforms leading to a market explosion. However, in the rush to provide these capabilities in compelling form factors, the RF performance of these devices has been seriously compromised. Thus, while the peak performance near the base station may be following the digital state-of-the-art, real world performance (in-building, in suburbs and rural areas, in-car and on-person) has substantially fallen over the years. This not only impacts typical achievable data rates and reduces battery life but, in many cases, actually prevents useful connections for voice or data. The key factor driving this degradation has been changing antenna location and reduced antenna volume driven by the desire for thinner and display-dominated platforms. Antennas have moved within the core outline to reduce and then remove the unsightly 'bump'. This relocation together with the screen-maximization forces the antennas into a small volume near the edge of the handset. Reduced antenna volume leads to a tradeoff between bandwidth and efficiency [1]. The edge location increases the impact of external loading from the user and other objects [2]. To maintain acceptable efficiency under these constraints, tunable and reconfigurable antennas are being deployed to enable effective use of reduced instantaneous bandwidths resulting from the smaller antenna volume and to compensate for external loading effects. Tuning capability brings new design and performance challenges along with new opportunities to the handset designer.

II. Radiated Performance Trends

A. Historical handset antenna form-factors

Handsets prior to 1990 typically had extendable whip antennas to enable optimum performance at bands well below 1 GHz like the original AMPS standard in the US and the NMT standard in Scandinavia. These whips devolved into a fixed stub and finally shrank to become entirely internal coinciding with the rollout of the high band digital PCS/DCS systems in the mid 1990's. Terminals with such smooth contours were (and continue to be) preferred by consumers.

In [3], commercial phones with a helix antenna, an internal patch antenna and an extractable half-wave dipole antenna were compared in terms of TRP and TIS for the GSM-900 and DCS-1800 bands. TRP variations in free space between the low-band and the high-band are found to be from 30 dBm to 26 dBm for the helical antenna, from 31 dBm to 28 dBm for the patch antenna and from 27 dBm to 26 dBm for the half-wave dipole. The human body in close proximity of the antenna in hand-held phones results in significant radiation performance degradation. In free-space, the helix antenna and the internal patch antenna perform similarly in the DCS band. However, in the presence of a user, the helix antenna is degraded by 10 dB in average, and the patch y only 3 dB in average [4].

B. Recent handset evolution

Prior to 2010, the lowest frequency of operation in the USA was 824 MHz. LTE has been deployed in the USA since 2010, with the lowest frequency now at 698 MHz, while antenna volume remains similar or reduced due to increased priority on display and battery requirements. This has applied further constraints on the antenna performance yielding efficiencies of 30% and lower, to provide the necessary bandwidth [5].

TABLE I

MEASURED VARIATION IN HEAD/HAND LOADED TERMINAL OTA PERFORMANCE

	GSM 900		GSM 1800		UMTS Band VIII		UMTS Band I	
	TRP (dBm)	TIS (dBm)	TRP (dBm)	TIS (dBm)	TRP (dBm)	TIS (dBm)	TRP (dBm)	TIS (dBm)
Average	17.9	-93.1	18.5	-97.6	8.5	-96.4	11.1	-99.8
Spread	3.5	7.2	4.6	9.0	3.7	7.5	7.0	6.5
Model Change	-0.5	+3.4	-1.0	+0.6	-0.9	-0.1	-1.7	-0.6

Tuning and switched reconfiguration has been applied to handset designs to enhance the usable bandwidth towards the lowest frequency of operation in the space-constrained platforms (typically US LTE), but has not been utilized to raise the performance bar. A summary of measurements from [6] on recent handsets shown in Table I illustrates that radiated performance of popular models has decreased over successive generations, likely driven by the market demand for compelling form-factors. Note that the average TRP in DCS band has decreased from 25 dBm for the early internal patch antennas to 18 dBm for today's phones. This is not surprising since the consumer is not provided any information regarding the RF performance to guide their purchase decision. Regulators in Europe and elsewhere are seriously considering adding such labeling to enable informed consumer choice and help spur performance improvements.

III. TUNABLE ANTENNA DESIGN

Tunable and reconfigurable antennas have been under study for many years. As mentioned previously, reducing the required antenna size is a strong market trend. Since the instantaneous bandwidth is less for a smaller antenna, tuning is required to cover all required bands. Tuning elements can be placed to affect the radiator directly, impact the coupling to the radiator, adjust the feed impedance match or a combination of these.

While the volume of the radiating system should be as small as possible for form-factor considerations, a minimum effective volume must be maintained for a given mode. To first order this is given by the Wheeler-Chu limit [7] for minimum antenna Q obtainable for a given size antenna.

$$Q = \frac{1}{(ka)^3} + \frac{1}{(ka)} \cong \frac{1}{(ka)^3} \text{ for small antennas} \quad (1)$$

Unfortunately, this formula cannot typically be applied rigorously since the antenna mode volume, particularly for electrically small antennas, is difficult to determine from geometry. Therefore, the inverse-bandwidth formula is typically used [8].

$$Q(\omega) \approx \frac{2\sqrt{\beta}}{FBW(\omega)}, \sqrt{\beta} = \frac{s-1}{2\sqrt{s}} \quad (2$$

where FBW(ω) is the fractional bandwidth and s is the VSWR mismatch limit for the passband edges.

Note that the ground plane is a key part of the radiating system, particularly at the lower frequencies (below 1GHz). For example, LTE Band 12 operating at a given 10 MHz channel pair in full duplex requires 40 MHz of instantaneous bandwidth. Note that in [9] the antenna occupies 3.9 cc to exhibit acceptable performance and in [10] the antenna occupies 2.5 cc for efficiency above -2 dB in free-space.

To provide the widest tunability at high efficiency, it is preferred that the antenna is not highly matched to the transmission line. Ideally the feed is driving a non-resonant coupling element [11] that is matched utilizing a tunable circuit. This structure makes the best use out of the ground plane. However ground currents limit MIMO implementation because of strong antenna coupling.

Note that a TX-only, RX-only or TDD radiating system would only need the instantaneous bandwidth for the channel itself, enabling a LTE Band 12 antenna with the same efficiency to occupy 4x smaller volume. This method has a major advantage for bands with a very wide duplex-spacing, e.g. 400 MHz for band IV [12]. Thus it is expected that such approaches will become more common in future systems.

Active control approaches bring more value by dynamically compensating for environmental variations including the user. A wide range of methods for sensing the impact of the variation and for deriving the appropriate control settings are being explored throughout the industry, e.g. closed-loop impedance tuners to match the antenna to the front-end and ensure maximum power transmission dynamically [13].

Obtaining accurate efficiency estimates from simulation of high-Q tunable antennas can be challenging with conventional simulators used for low-Q antennas [14]. Also, these simulators are typically time-domain solvers that are efficient at computing the response of well-damped systems. However, when simulating a highly resonant system, the time-domain tools require a long simulation time and often have convergence issues. There are varying approaches to adding tunability to a handset antenna to approach the limits described above. An overview is given in [15]. They break down into three general categories: impedance tuners, feed/coupler tuners and load/aperture tuners. Impedance tuners are placed in-line with the transmission line feeding the antenna, feed/coupler tuners are placed within the transition from the transmission line to the radiating structure, and load/aperture tuners directly load the radiating structure.

Tuners that are not placed on the antenna structure serve to match the antenna at different bands, utilize the full potential of the board and do not leave much freedom to MIMO implementation. They also lend themselves more easily to dynamic tuning for environmental compensation. Tuners placed on the antenna effectively change its electrical length to affect its resonance frequency, additionally fields become more confined around the radiating structure enhancing MIMO operation, while making less use of the ground plane yields a smaller effective antenna volume and thus constrains the radiation efficiency and instantaneous bandwidth. Optimum performance arise from leveraging both approaches.

IV. Tuner Requirements and Technologies

Adding a new, adjustable component in the antenna system adds factors that must be properly specified. Key among these are tuning ratio, voltage handling, linearity, control and Q. The volume and efficiency are set by the lowest frequency bandwidth requirements. This also then determines the loading required to reach that frequency. The tuning ratio follows from the highest frequency. If the frequency range is from 700-1000 MHz, a tuning ratio of at least 2 is needed if the element is aperture tuned and end-loaded with 3-4 being sufficient for engineering margin. However, the end tuning position puts the highest requirements on tuner voltage handling and Q. Having a higher tuner ratio of 7-15 enables higher radiation performance and puts less voltage stress on the tuner, leading to higher reliability and system linearity.

The capacitive tuner must be stable and reliable at the voltages developed at full power in all modes of operation. RF voltages > $40V_{rms}$ are often seen and > $100V_{rms}$ will be seen for some designs and modes. The Q of a capacitive tuner is typically limited by the equivalent series resistance (ESR). The ESR must be kept well below the radiation resistance for all states of the tuned radiator to maintain high efficiency.

TABLE II - Tuning Technology Comparison

	SOI/SOS	j-pHEMT	BST	RF-MEMS
Quality Factor (Q)	Low	Moderate	Moderate	**High**
Intercept Point	Moderate	High	Moderate	**High**
Harmonics	Poor	Moderate	Poor	**Excellent**
C Ratio	Moderate	Moderate	Low	**High**
Max Voltage	Low	Moderate	Moderate	**High**
Lifetime	Excellent	Excellent	Excellent	Excellent
Cost	**Low**	Moderate	Moderate	Moderate

The linearity of the front end including the tuned antenna is particularly critical for co-existence and carrier aggregation scenarios. One key carrier aggregation case is for Band 12 transmit and Bands 12+4 receive where the 3rd harmonic of the Band 12 transmitter may fall into the Band 4 receive bandwidth. If a common antenna feed is used for both bands, the 3rd harmonic from all sources must be substantially less less than -106 dBm for +24 dBm transmit power to avoid desensitizing the receiver [12].

There are four technologies currently being leveraged to build tuners for handset antennas: SOI switches, J-PHEMT switches, BST para-electrics and RF-MEMS. Table II compares and contrasts these widely different technologies. Only MEMS appears able to meet the linearity requirements above for carrier aggregation as shown in figure 1.

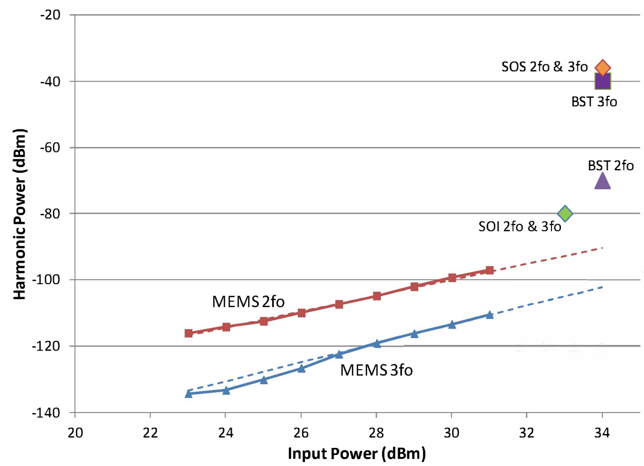

Figure 1. Harmonics of various tuner technologies.

Antennas designed for tunability will not contain a strong matched resonance in the tuning band as mentioned above. Figure 2 illustrates the highly reactive return loss performance for an antenna which has been designed for wide tunability in low bands below 1 GHz, where the return loss is typically worse than -1.5dB. At the same time it has been designed to be well-matched thus not requiring tuning in the upper bands.

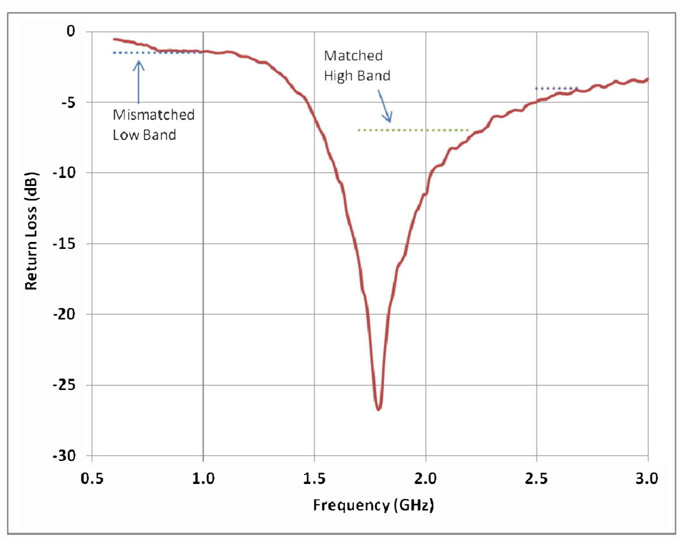

Figure 2. Response of antenna designed for efficient widely tunable response for cellular low bands

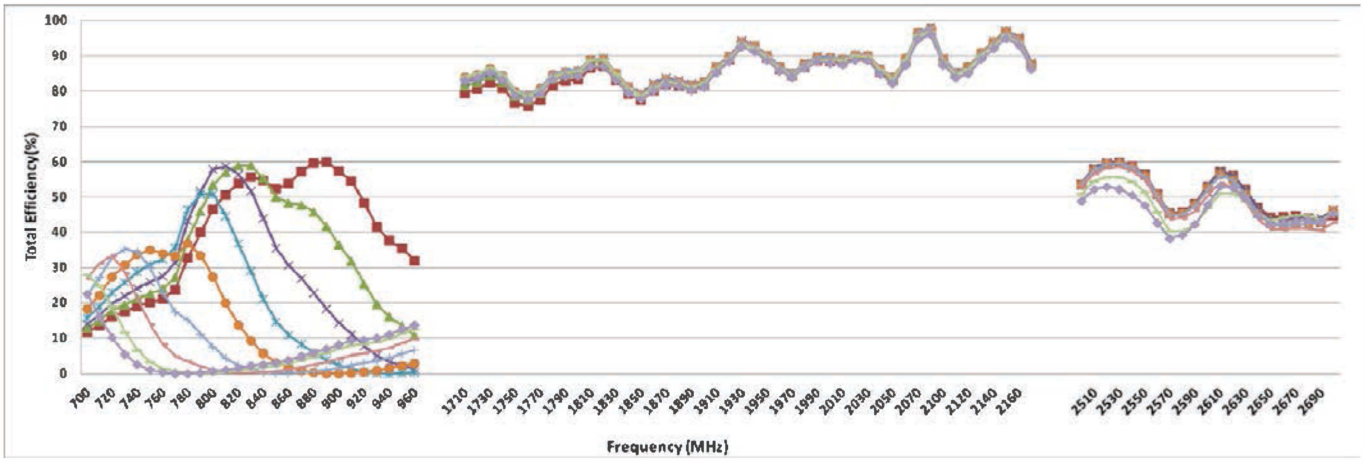

Figure 3. Tuned efficiency of antenna for multiple feed tuner states

This antenna design leverages a fairly simple monopole and uses a total volume including all keep-out area of 1.5cc within a handset form factor. The antenna has been tuned utilizing a RF-MEMS feed tuner with the resulting tuned total efficiency over the tuning range shown in Figure 3.

Note that while the tuned antenna efficiency measurement system was limited to frequencies of 700 MHz, the trend implies useful efficiencies > 20% for frequencies well into the proposed 600 MHz band. It should also be noted that this approach is targeted for low/high carrier aggregation leveraging the high tuner linearity shown in figure 1 and the fact that low and high bands can be used simultaneously since the tuning has minimal impact on the high band response which maintains exceptional efficiency.

V. Conclusion

Tuning can be utilized to provide high performance with the reduced volume available in modern mobile platforms but optimum approaches are still a topic of intense development. High performance tuning technology is required to effectively implement these advanced designs and to avoid introducing unacceptable interference. Antennas properly designed to leverage tuning can be used to address wide frequency ranges and achieve high efficiency.

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