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MIMO Performance of Today's Metal-Covered Handset

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Abstract—This paper discusses on the evolution of smartphones in recent years and its effects on antenna performance. Up-to-date design framework is introduced, and comparison of recent metal-rim antennas is presented. Especially, the paper analyzes further the MIMO performance of a recently published realistic metal-covered handset design with LTE, GPS, and Wi-Fi antennas. The designed antennas cover frequency bands 704–960 MHz, 1.56–1.61 GHz, 1.71–2.69 GHz, 2.4–2.484 GHz, and 5.15–5.875 GHz. New results on multiplexing efficiency and ergodic capacity are presented. In very challenging design environment, the design shows good performance despite the modest matching levels and efficiencies.

Index Terms—antenna, ergodic capacity, handset, metal cover, multiple-input multiple-output (MIMO), multiplexing efficiency.

I. INTRODUCTION

Over the years, mobile phones have evolved a lot. The most significant changed aspect is that smartphones have to operate on larger set of frequency bands. Besides cellular LTE frequencies, also Wi-Fi and GPS are required nowadays. In addition, devices have to support Multiple-Input Multiple-Output (MIMO) and Carrier Aggregation (CA) for improved data rates. These requirements set by the network standards, result in a fact that phones must include more antennas than earlier.

The change from the first 1990s phones to the smartphones used today is huge. Even within the last few years, the phones have undergone very rapid and noticeable changes. Modern phones are made robust and visually appealing by using metal covers, but the most noticeable aspect is the significantly increased size of the touchscreen. Generally from antenna-point-of-view, larger chassis implies more space for the antennas. However, a common trend among large displays is maximized screen-to-body ratio. This leads to very small clearances around the display, and hence, to worse antenna performance. The examples in Fig. 1 illustrate the rapid change of smartphones. In 2014, a typical clearance was 10–15 mm [1]–[4]. Since then, clearances have decreased to 7 mm [5]–[8] and currently, the industry targets at a clearance of 2 mm. These very small clearances are already seen in commercial products, e.g. Samsung Galaxy S8 or Apple iPhone X. The phone manufacturers also go visual design first, which is a major constraint for suitable antenna locations. Aesthetics and visual appearance of the device cannot be neglected in the antenna design process.

Figure 1. Typical size of device and display in recent years.

Figure 2. Fourth trade-off parameter in antenna design added by industry.

It is known that small size, wide bandwidth, and good efficiency cannot be achieved at the same time. A rule-of-thumb is that a small antenna can either have high efficiency or large bandwidth. When bandwidth requirement increases, the efficiency will inevitably decrease. Design environment of mobile antennas has changed so much that the commonly used design rules and benchmarks are not valid anymore. For example, in modern systems it is extremely challenging to achieve -6 dB matching levels, and meet also the aesthetic requirements set by the industry and consumers. As Fig. 2 shows, in current antenna systems the trade-off has to be made between four design parameters. Industry adds a fourth dimension to this triangle with the aesthetics of the product.

As an example of a realistic case we use our design of a complete antenna system for a metal-covered handset with a slotless back cover [6]. In this paper, we present new results of

Table I
COMPARISON OF PROPOSED DESIGN AND PREVIOUSLY PUBLISHED ANTENNAS IN METAL-COVERED HANDSETS.

Ref.	Operational bands	Measured efficiency	MIMO capability	Measured ECC	Antenna implementation
[6]	LTE LB & HB, GPS, Wi-Fi	20–60 %	LB, HB, Wi-Fi	LB < 0.4, HB < 0.1	Fixed
[11]	LTE LB* & HB	28–72 %	LB, HB	< 0.19	Fixed
[12]	LTE LB & HB	20–55 %	-	-	Tunable
[13]	LTE LB & HB	20–50 %	-	-	Tunable
[14]	LTE LB & HB	40–70 %	-	-	Fixed
[8]*	LTE LB* & HB	50–86 %	-	-	Fixed
[15]*	LTE LB & HB	45–90 % [§]	HB	< 0.5 [§]	Fixed
[16]*	LTE LB	25–40 %	LB*	< 0.1	Fixed
[17]*	LTE LB & HB	45–90 %	LB, HB	LB < 0.18, HB < 0.1	Tunable

*LB from [11] 746, [8] 824, [16] 850 MHz upwards, *includes only metal rim, [§]simulated value.

that design to give better insight of its usability in practice. We present the simulated and measured multiplexing efficiencies and ergodic capacities [9], [10] to demonstrate the benefits of this MIMO design.

II. ANTENNA CONFIGURATION

Modern mobile phones include more metal than earlier. Metal-covered handsets are not only mechanically strong but also visually appealing. Phone industry emphasizes appearance, which creates challenges for designing and placing antennas to the device. Metal covers basically prevent the use of traditional mobile phone antennas (e.g. planar inverted F antennas), as nothing radiates when the antennas are enclosed by large amounts of metal. This trend has forced antenna designers to develop new type of antennas.

Currently, antennas are more or less integrated into the covers of the phone, taking advantage of the metallic structures. A common method has been cutting slots to the back cover, and using capacitive coupling elements (CCE) [12], [13], [18], [19] as antennas. Also, the slots themselves can be used as antennas [20], [21]. However, cutting slots to the cover raises manufacturing costs and is visually unappealing. In Table I, we have compared our design with recently published antennas for metal-covered and metal-rimmed phones. Many other designs do not include MIMO, or they operate on fewer bands. Including MIMO typically drops the efficiency at the low band 10–20 % or even much more [22].

Our design [6] includes antennas for all the commonly required LTE low and high band (LB and HB, 704–960 MHz and 1710–2690 MHz, respectively), Wi-Fi (2.4–2.484 GHz and 5.15–5.875 GHz), and GPS (1.56–1.61 GHz) frequency bands with fixed matching circuitry. Moreover, the design has MIMO support at LTE and Wi-Fi bands, and it is CA capable. In addition, the phone is modeled with a highly accurate smartphone model, which includes several subsystems and key parts of the phone, e.g. battery, camera, and USB-port.

Fig. 3 shows the placement of antennas in this design. The system consists of the main and the diversity cellular antennas,

Figure 3. Placement of each designed antenna.

and two Wi-Fi antennas one of which also supports GPS. Cellular, and especially the LB, antennas require the most space, and therefore they are located at the distinct ends of the device. Only the main HB antenna is placed on the side among the GPS and Wi-Fi antennas. The antennas in the ends of the device are CCEs with parasitic couplers. Slot antennas are used on the sides.

In Fig. 4 our design for the diversity antenna is shown as an example. We have fitted in a limited space three elements for LB, HB, and aperture matching. In addition, the front camera below the aperture matching element restricts our options for antenna geometry. More detailed information on antenna geometries, configurations, and matching circuits, as well as basic performance results, are presented in [6].

As an example of how aesthetics affect antenna performance Fig. 5a shows the modest matching levels of the diversity antenna, which clearly lack of the traditional –6 dB requirement. Another example considers mutual coupling. In 5b, we see the coupling between the main HB and Wi-Fi 1 antennas. Now, since the two antennas are physically close to each other as Fig. 3 shows, mutual coupling might cause problems even though the antennas are designed for different applications. Small clearances and general lack of space due to

Figure 4. Structure of the diversity antenna.

(a)

(b)

Figure 5. Examples of how aesthetic requirements affect on simulated (a) matching levels and (b) mutual coupling.

the aesthetics requirements clearly affect antenna performance and hinder the design process.

III. MIMO PERFORMANCE

To further analyze the MIMO performance of our design, we present the multiplexing efficiency and ergodic capacity of the MIMO antennas. Both metrics we have calculated from the simulated and measured data, while assuming a reflection-rich Rayleigh-faded environment as channel model and signal-to-noise ratio (SNR) of 20 dB. With these assumptions especially the ergodic capacity is limited only by the handset. Simulations are conducted with CST Microwave Studio and Optenni Lab, and measurements with SATIMO Stargate 64. The measurement setup is seen in Fig. 6b.

(a)

(b)

Figure 6. Photos of the (a) manufactured prototype and (b) measurement setup.

A. Multiplexing Efficiency

Multiplexing efficiency describes the loss of SNR with respect to ideal MIMO antennas. It takes into account total efficiencies and envelope correlation coefficients of the multi-antenna system.

Fig. 7a presents multiplexing efficiencies for all cellular MIMO antennas. The efficiencies are calculated from both, the simulated and the measured data, according to the equations presented in [2], [9]. From both multiplexing efficiencies we can see that they are basically the averages of total efficiencies of each antenna pair, due to the low envelope correlation coefficients.

Especially interesting is the multiplexing efficiency of the LB antennas. The efficiency calculated from the measured data is clearly larger than the one obtained from simulations. This is easily explained due to the fact that in measurements we achieved higher total efficiencies and clearly lower ECC at the

Figure 7. (a) Multiplexing efficiencies and (b) ergodic capacities for the cellular antennas. Solid lines are calculated from measured data and dashed from simulated. In (b) the black and gray horizontal lines show the channel capacities with a reference SNR of 20 dB for ideal 2x2 MIMO and ideal SISO systems, respectively.

low band. At HB, where ECC is basically negligible, we see similar difference between simulations and measurements that is with total efficiencies.

Comparing our design with [2], [5], the multiplexing efficiencies are very similar in the LB and HB. In our design that is mainly between -8 to -4 dB. Wi-Fi antennas are not shown here, but their measurement-based multiplexing efficiencies are slightly better than with cellular antennas, between -5 to -3 dB.

B. Ergodic Capacity

Ergodic capacity of the system is estimated with Monte Carlo simulations. Calculations are based on equations presented in [9] and required correlations are obtained with equations in [23]. The reference SNR is 20 dB.

In ideal single-input single-output (SISO) case, the ergodic capacity should be 5.9 bits/s/Hz, and accordingly in ideal 2x2 MIMO case, 11.3 bits/s/Hz. Based on the measured data, we have estimated the ergodic capacity of the antennas, assuming 2x2 MIMO systems. Fig. 7b shows the results for the cellular antennas. As can be expected, none of the designed MIMO systems reach the ideal value of a 2x2 system, but both are clearly beneficial compared to ideal SISO case. Our estimations based on simulations and measurements match each other very well. In both LB and HB, our measurement-based

estimations result in ergodic capacity of at least 9 bits/s/Hz. Wi-Fi bands are not shown here, but their measurement-based capacities also agree well with simulations with levels similar to cellular antennas.

Our results are similar or better in LB, and generally on a same level in HB with the capacities presented in [24]. Despite that our design has more antennas, it compares very well to others. These capacity estimations also suggest that our design benefits from its complexity, and it could be usable in a real device. MIMO design clearly improves channel capacity despite the modest matching levels and total efficiencies.

Since the design environment of mobile antennas has changed significantly over the years, also new metrics are important to report. Ergodic capacities and multiplexing efficiencies are presented rarely in scientific literature. Our design suggests that even in challenging environment a good performance can be achieved despite the modest levels of the traditional design parameters.

IV. CONCLUSION

The evolution of smartphones is still rapid. The aesthetic of devices plays a larger role in industrial designs deteriorating the performance of antennas. A gap between scientific and industrial designs is at risk to widen. This paper has raised these aspects using as a basis a realistic handset design where 4G, Wi-Fi, and GPS antennas are integrated into the metallic side frame of the device. The design fulfills the requirements from industrial point-of-view. Design performs with modest matching levels and 20–60 % total efficiency. Further analysis on MIMO performance suggests our design is usable in practice, as estimated ergodic capacities are close to the ideal limits and multiplexing efficiencies between -8 to -3 dB. Despite the modest levels of traditional design parameters the overall performance is good.

REFERENCES

- [1] J. Ilvonen, R. Valkonen, J. Holopainen, and V. Viikari, "Design strategy for 4G handset antennas and a multiband hybrid antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 4, pp. 1918–1927, Apr. 2014.
- [2] —, "Multiband frequency reconfigurable 4G handset antenna with MIMO capability," *Prog. Electromagn. Res.*, vol. 148, pp. 233–243, 2014.
- [3] A. Cihangir, F. Ferrero, G. Jacquemod, P. Brachat, and C. Luxey, "Neutralized coupling elements for MIMO operation in 4G mobile terminals," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 141–144, 2014.
- [4] Y. L. Ban, Z. X. Chen, Z. Chen, K. Kang, and J. L. W. Li, "Decoupled closely spaced heptaband antenna array for WWAN/LTE smartphone applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 31–34, 2014.
- [5] K. Rasilainen, A. Lehtovuori, A. Boussada, and V. Viikari, "Carrier aggregation compatible MIMO antenna for LTE handset," *Prog. Electromagn. Res. C*, vol. 78, pp. 1–10, 2017.
- [6] J. Kurvinen, A. Lehtovuori, J. Mai, C. Wang, and V. Viikari, "Metal-covered handset with LTE MIMO, Wi-Fi MIMO, and GPS antennas," *Prog. Electromagn. Res. C*, vol. 80, pp. 89–101, 2018.
- [7] D. Huang, Z. Du, and Y. Wang, "An octa-band monopole antenna with a small nonground portion height for LTE/WLAN mobile phones," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 878–882, Feb. 2017.
- [8] Y. Yang, Z. Zhao, W. Yang, Z. Nie, and Q. H. Liu, "Compact multimode monopole antenna for metal-rimmed mobile phones," *IEEE Trans. Antennas Propag.*, vol. 65, no. 5, pp. 2297–2304, Mar. 2017.

- [9] R. Tian, B. K. Lau, and Z. Ying, "Multiplexing efficiency of MIMO antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 183–186, 2011.
- [10] J. Holopainen, J.-M. Hannula, and V. Viikari, "A study of 5G antennas in a mobile terminal," in *Proc. 11th Eur. Conf. Antennas Propag. (EuCAP)*, 2017, pp. 3079–3081.
- [11] T. Son and Y. Jo, "Wideband mobile MIMO antenna for the metal cover phone," in *2015 IEEE Region 10 Conf. (TENCON)*, 2015, pp. 1–3.
- [12] Y. C. M. Tan, N. G. G. Hong, and Y. S. R. Tay, "Tuning of LTE main antenna using flexible tunable LC resonant circuitry," in *Proc. 11th Eur. Conf. Antennas Propag. (EuCAP)*, 2017, pp. 3082–3085.
- [13] —, "A tunable LTE main antenna solution for metallic cover mobile phone," in *Proc. 11th Eur. Conf. Antennas Propag. (EuCAP)*, 2017, pp. 2969 – 2972.
- [14] C. K. Chang, W. J. Liao, and C. C. Tsai, "Metal body-integrated open-end slot-antenna designs for handset LTE uses," *IEEE Trans. Antennas Propag.*, vol. 64, no. 12, pp. 5436–5440, Sep. 2016.
- [15] M. Stanley, Y. Huang, H. Wang, S. S. Alja'afreh, Q. Xu, and L. Xing, "LTE MIMO antenna using unbroken metallic rim and non resonant CCE element," in *Proc. 10th Eur. Conf. Antennas Propag. (EuCAP)*, 2016, pp. 1–4.
- [16] L. Qu, H. Lee, H. Shin, M. G. Kim, and H. Kim, "MIMO antennas using controlled orthogonal characteristic modes by metal rims," *IET Microw. Antennas Propag.*, vol. 11, no. 7, pp. 1009–1015, Jun. 2017.
- [17] M. Stanley, Y. Huang, H. Wang, H. Zhou, Z. Tian, and Q. Xu, "A novel reconfigurable metal rim integrated open slot antenna for octa-band smartphone applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, May 2017.
- [18] J. Villanen, J. Ollikainen, O. Kivekäs, and P. Vainikainen, "Coupling element based mobile terminal antenna structures," *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2142–2153, Jul. 2006.
- [19] R. Valkonen, M. Kallio, and C. Icheln, "Capacitive coupling element antennas for multi-standard mobile handsets," *IEEE Trans. Antennas Propag.*, vol. 61, no. 5, pp. 2783–2791, Feb. 2013.
- [20] J. Zhong, R. M. Edwards, L. Ma, and X.-W. Sun, "Multiband slot antennas for metal back cover mobile handsets," *Prog. Electromagn. Res. Lett.*, vol. 39, pp. 115–126, 2013.
- [21] C. Y. Wu, Y. L. Kuo, and K. C. Lin, "Low-profile tunable WWAN antenna for whole-metal-covered mobile phone applications," in *2014 Int. Symp. Antennas Propag. (ISAP)*, 2014, pp. 275–276.
- [22] K. Rasilainen, A. Lehtovuori, and V. Viikari, "LTE handset antenna with closely-located radiators, low-band MIMO, and high efficiency," in *Proc. 11th Eur. Conf. Antennas Propag. (EuCAP)*, 2017, pp. 3074–3078.
- [23] S. Blanch, J. Romeu, and I. Corbella, "Exact representation of antenna system diversity performance from input parameter description," *Electronics Lett.*, vol. 39, no. 9, pp. 705–707, 2003.
- [24] A. Abdullah Al-Hadi and R. Tian, "Impact of multiantenna real estate on diversity and MIMO performance in mobile terminals," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1712–1715, 2013.