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ANTENNA AND RF SUBSYSTEM INTEGRATION IN CELLULAR COMMUNICATIONS

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We discuss in this article a number of techniques that can be used to improve the RF performance on a mobile device. All those techniques rely on tight antenna and modem subsystem codesign. In a short introduction, the article outlines the need of these techniques, based on the advent of new wireless standards and demanding power and size requirements. The first technique is based on integrating the antenna as part of the RF filtering chain to relax the requirements of current duplex filters up to 30dB off-band. We also outline a discussion on the different approaches for adaptive antenna matching, depending on the system's requirements. A particular antenna concept that implements two different wireless systems (LTE and Wi-Fi) is outlined in a subsequent section. Such a structure can reduce the volume required for antennas on a mobile device. The article concludes with an example of how the antenna design can directly impact the throughput of the whole system, showing the impact of the correlation coefficient on the signal to noise ratio.

Introduction

In the past, mobile communications and by extension cellular modem design has typically focused on delivering performance on a 50 Ohm connection reference, keeping only the RF modem into one "codesigned" box. As a further path for increasing RF performance, this article discusses possible solutions to also push the antenna system into the codesign box of the whole RF subsystem and device itself, including industrial design (ID) and air interface. This way, a whole end-to-end optimization from air to bit can be achieved, delivering better overall performance in an appealing form factor.

The frequency spectrum for mobile communication has increased dramatically due to the deployment of Long Term Evolution (LTE).^[1] It is expected that mobile devices are able to operate at these frequencies without taking too much printed circuit board (PCB) volume or consuming a lot of power, impacting the size and the battery life of mobile communications products. In addition, different parts of the world have different frequency bands, making it quite challenging to support all the bands in a single stock keeping unit (SKU). It may require either more components (or larger ones) in the mobile device to be able to support multiple geographic configurations, thereby impacting the cost and reducing the benefit margin.

Integration has proven to be a technology success driver since electronics' early days. This trend materializes in the personal modems' segment as an aggregation of radio access technologies, hence their respective spectral allocation requirements.

This article explores possible device-antenna-RF codesign as an alternative way to cope with the problems described above, following a top-down approach. First, an implementation in which the filtering capabilities of the antenna system can positively impact the RF modem itself is investigated. A brief study of antenna control techniques to enable this filtering behavior under control will be exposed. The antenna concept and how it fits into the device design itself will follow to end up on the air interface with the antenna and its impact in throughput.

Different stages of codesign will focus on different improvements in performance, which will be quantified by simulation models and measurements.

The Antenna as Part of the RF Chain Filtering

The mobile platform has several radio frequency (RF) signal paths due to the many supported frequency bands. Each of these RF signal paths contains a duplex filter, a power amplifier, a low noise amplifier, and so on, resulting in various parallel paths. All this leads to a complicated RF front end (FE).

Figure 1a illustrates a simplified version of such a multipath FE.

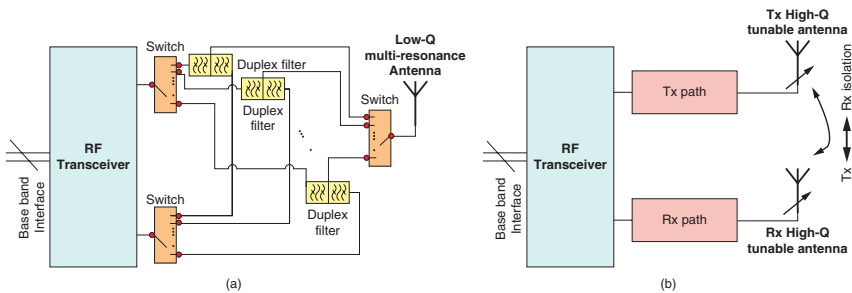


Figure 1: Simplified conventional FE (a), simplified proposed FE (b)
(Source: Intel Corporation, 2014)

On the antenna side, this means many antenna subsystems or two very broadband antennas (for supporting MIMO and carrier aggregation). While broadband antennas are large and occupy more space in order to be efficient, multiband antennas with reasonable performance become a very cumbersome task to design in a small mobile form factor device due to the fundamental limitation of antennas.^[2]

This can be addressed through codesign of the RF FE and the antenna system, resulting in a miniaturized FE and antenna, yet with coverage of the increased number of bands. Such an approach has separate transmitter and receiver paths throughout the FE, including the antennas.

Figure 1b presents a simplified block diagram of the architecture that integrates the antenna and the RF system.

While the traditional FE uses duplex filters and switches to separate Tx and Rx, the proposed FE relies on the filtering characteristics of the antennas together with tunable filters to separate the Rx from the Tx. In such a design, for each mode or application in the mobile terminal, the bandwidth is reduced to just the needed channel bandwidth, which for LTE is between 1.4 MHz and 20 MHz. Therefore, the Tx and Rx antennas can be designed to be quite narrowband. Tuning can be exploited to cover the required frequency range. This approach brings major advantages; some of them are listed below:

- It helps in reducing the PCB area for the RF engine. The Tx and Rx antennas exhibit high isolation because of the narrowband characteristic and frequency offset, providing filtering that can be used to replace some of the otherwise required filters from the FE. Also the space occupied by the antennas is reduced because the same elements can be used to cover all the requisite bands. This reduction in size will enable new and innovative industrial designs of mobile devices.
- It provides power and cost savings, because some of the otherwise necessary filters and switches can be removed from the FE, resulting in lower insertion loss, which lowers the power consumption in the total RF engine solution.
- It provides dynamic optimized overall FE efficiency by controlling the tunable antennas to mitigate the effects of the external environment, such as the handheld terminal user.

“The antennas have no PCB cutback and have a volume of only 0.3 cc each. With such small volumes, these tunable narrowband antennas are capable of covering a frequency range of 700 MHz through 1 GHz.”

A practical example of the narrowband antennas and their advantages are presented in the following.

A PCB with mounted Tx and Rx antennas is depicted in Figure 2. The antennas have no PCB cutback and have a volume of only 0.3 cc each. With such small volumes, these tunable narrowband antennas are capable of covering a frequency range of 700 MHz through 1 GHz.

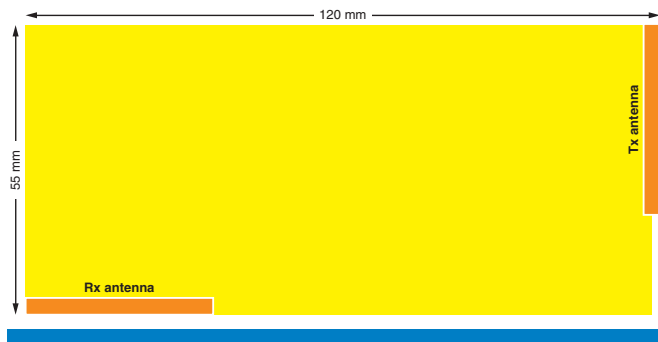


Figure 2: Narrowband Tx and Rx antennas on a PCB
(Source: Intel Corporation, 2014)

The antenna tunability is illustrated in Figure 3. Coverage of the low band can be obtained by applying a capacitance range of 0.7 through 4 pF using 29 tuning states.

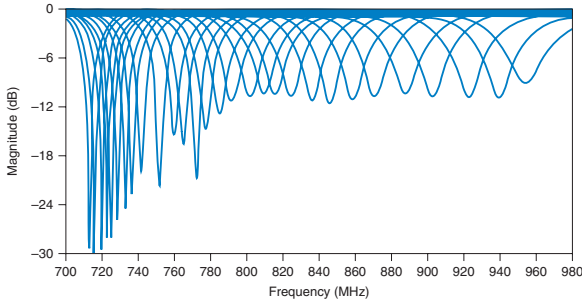


Figure 3: Narrowband antenna tuned to cover the low band
(Source: Intel Corporation, 2014)

Figure 4 shows that the Tx tunable antenna covers the frequency range 700–915 MHz with a bandwidth of 24 MHz at the highest operation frequency and 10 MHz at the lowest operation frequency. The Rx antenna can cover 729–975 MHz with a bandwidth of 21 MHz at the highest operation frequency and 9 MHz at the lowest operation frequency.

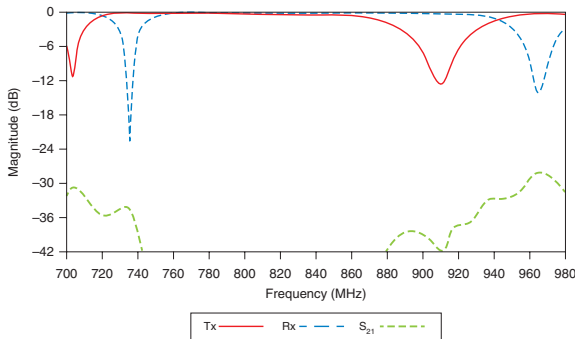


Figure 4: Narrowband Tx and Rx antennas reflection coefficients S_{11} (red), S_{22} (blue), and coupling coefficient S_{21} (green)
(Source: Intel Corporation, 2014)

Since the proposed FE relies on the filtering characteristic of the antennas, it is relevant to show the near field (antenna isolation/coupling) and far field filtering characteristic. The near field filtering or isolation between the antennas is better than -28 dB across the entire frequency range. Such a high isolation at

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“Above 1080 MHz and below 600 MHz, the antenna ensures 30 dB filtering. This is a very interesting result because filter requirements in the FE can be relaxed if the attenuation of unwanted RF blockers in the antenna is accounted for.”

these low frequencies is achieved due to the narrowband nature of the antennas and frequency offset. Moreover, the antennas are not exciting the same PCB mode, which also contributes to the incredibly high isolation.

The far field filtering characteristic, inherently in the Tx antenna, is measured and shown in Figure 5. The antenna is tuned to 740 MHz and has an efficiency of -3.3 dB at that frequency. Outside the frequency band of interest the antenna acts as a filter. Above 1080 MHz and below 600 MHz, the antenna ensures 30 dB filtering. This is a very interesting result because filter requirements in the FE can be relaxed if the attenuation of unwanted RF blockers in the antenna is accounted for.

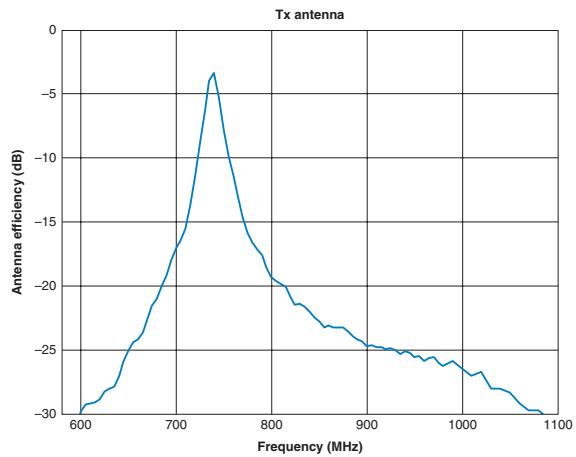


Figure 5: Narrowband Tx antenna efficiency measurement in an anechoic chamber
(Source: Intel Corporation, 2014)

The efficiencies are listed in Table 1, where it is noted that Tx antenna efficiency varies between -1.0 dB and -3.3 dB and Rx antenna efficiency varies between -1.2 dB and -3.6 dB.

	f_t [MHz]	eff. [dB]
Tx antenna	910	-1.0
	705	-3.3
Rx antenna	965	-1.2
	735	-3.6

Table 1: Total efficiencies at lowest and highest tuning frequencies of the Tx and Rx antennas.
(Source: Intel Corporation, 2014)

Antenna Control and Adaptive Matching

Classical antenna literature is however conclusive on the electromagnetic limits regarding radiating structures. It is clear that a proper concept for controlling the antenna bandwidth and resonant frequency of the element is required to achieve the “filtering effect” on the antenna. Out of the diverse approaches to control the antenna bandwidth, the reconfigurable antenna tuning solution is discussed in this section in more detail. The different concepts for implementation are presented also in conjunction with adaptive matching under user interaction scenarios.

“...a proper concept for controlling the antenna bandwidth and resonant frequency of the element is required to achieve the “filtering effect” on the antenna.”

Hardware Integration: The World Indoors

Devices devoted to implement reconfigurability in antennas are diverse and so are the radiation mechanism reconfiguration techniques. A set of these is analyzed as in the Figure 6.

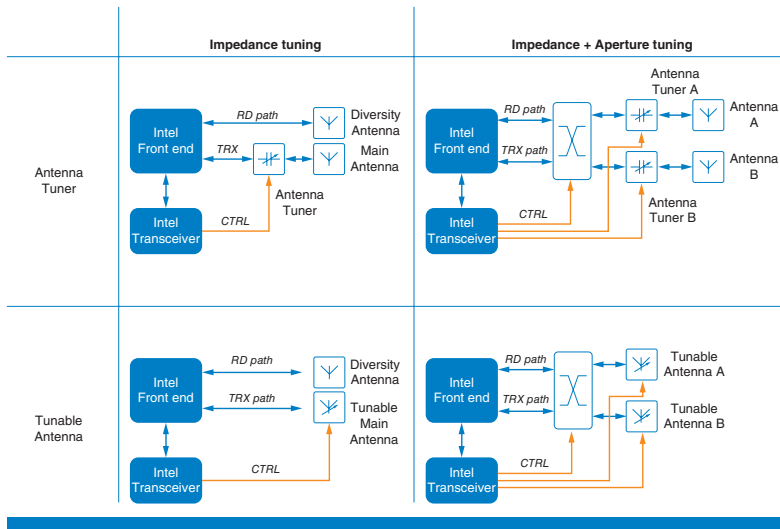


Figure 6: Reconfigurable antenna lineups
(Source: Intel Corporation, 2014)

Rows stand for the integration trend. Antenna tuners act as reconfigurable impedance transformers, being two-port devices committed to interface an arbitrary impedance drifting antenna port with the front end’s nominal 50 ohm port, according to a certain criterion. Gaining in integration is here linked to a loss in parameterization capabilities for the tuning device. Impedance transformation between two ports can be tabulated and then processed so a certain tuning criterion is met. Limitation arises for the one-port

device since that tabulation requires knowledge of further information, such as a user case interaction scheme, thus introducing an environment segmentation that stands for a nailed-down vision of the electromagnetic environment from where the antenna radiates. This inherent ill-conditioned nature of one-port devices tuning has as a tangible consequence a reformulation in the tuning criterion, leading to suboptimal tuning with respect to their two-port counterparts.

Radio Wave Radiation: The World Outdoors

The tuning criteria design follows an RF performance-increase commitment, linked to the circuital perspective of the radiating devices. Radiation-mechanism reconfiguration lays out of the action range of antenna tuners and its higher integration versions as well as the criteria they are operated with. Aperture tuning broadens this scenario by introducing further reconfiguration variables, which potentially diversify the radiating element's location, polarization, and feeding.

Most immediate approaches identify shadow conditions for certain antennas in the array thus redirecting RF power. This binary approach to signal routing may be refined with an upper layer—implemented either by means of antenna tuners or tunable antennas—whose reconfiguration criteria cooperates with the routing capabilities introduced by the switch.

Aperture tuning has a formal impact that materializes in a larger sphere of criteria. Antennas are seen beyond its circuit perspective, and coordination between binary routing and impedance matching criteria is desired so suboptimal reconfiguration can be avoided.

All in all, reconfigurable antenna designs have become a must in the mobile communication industry; however, performance advantages can only be expected out of this technology when tuning criteria are consistent for the level of hardware integration one is willing to set up in a mobile platform.

Antenna Sharing in Cellular Communications

Once a proper (hopefully tunable) antenna concept has been selected, the designer faces the next problem when trying to build a mobile communications device: the number of antennas needed in modern smartphones is increasing, in order to support different bands, MIMO, carrier aggregation, WLAN, NFC and GPS, which is a major challenge due to the volume required for each antenna to achieve good performance. The performance of antennas in mobile phones is directly related to the volume allocated and the physical placement in the phone. Increasing the allocated volume for the antenna will in theory result in better antenna performance in terms of S_{11} and radiated efficiency. Also, the best performance of the antennas is obtained when they are placed at the circumference of the

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phone. The width of the display and battery is often nearly as wide as the smartphone itself, whereby the available volume for antennas at the circumference near these components is very limited and in many cases not usable for antennas. Other components like the USB connector, audio jack, and different user control buttons are normally also placed at the circumference of the phone, thereby reducing the available volume for the antenna even more. This means that the space for good antenna performance on a modern smartphone is very limited. It would be a big advantage if some of the wireless systems and/or cellular bands could share the same antenna element and operate concurrently without a significant degradation of the performance. This would reduce the total number of antenna elements needed in the phone.

This section shows a new and unique way of simultaneously coupling multiple wireless systems, such as one cellular band and two Wi-Fi* bands on to the same antenna element, without significantly degrading the performance of either systems.

Sharing of antenna elements between for example GPS and Wi-Fi has been done before by making a standard single-feed dual-resonance antenna and then feeding the GPS and Wi-Fi signal through a duplexer/diplexer to the antenna. This solution could in theory also be used for a cellular and Wi-Fi configuration if the added insertion loss of 1 dB to 2 dB of the duplex filter could be accepted.

A switched solution is also an option, where each system/band is switched on and off to the antenna element, so that only one band/system is coupled to the antenna element at a time. This solution does not support concurrent operation and also introduces loss, complexity, and an increase of price due to the additional switches.

Sharing of Cellular Low Band and WLAN

This example shows an antenna concept that couples the cellular low-band systems between 700 MHz and 960 MHz as well as the 2.4 GHz system onto the same antenna element, without increasing the volume of the antenna element itself needed to cover the low-band frequencies alone (700 MHz to 960 MHz).

The concept is based on indirect feeding, where the antenna is fed through a coupler and the element itself is either directly connected to ground, if it is resonating at the desired frequency, or forced to resonate at a desired frequency with an inductor, capacitor, or even a combination of these.

The original concept uses one coupler per single resonance element, whereby two elements and two couplers are needed for dual resonance operation. The antenna elements are often simple monopole type elements

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as shown in Figure 7a. These types of elements can be relatively easily made into dual resonance elements by adding a slot in the element as shown in Figure 7b.

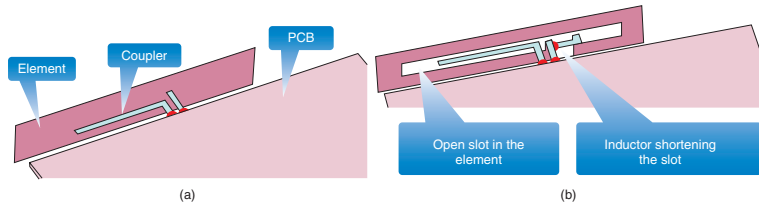


Figure 7: Indirect feeding technique; (a) original single resonance concept, (b) new dual resonance concept for antenna sharing (Source: Intel Corporation, 2014)

The second element resonance can be “picked up” by adding a second coupler. The example concept shown in Figure 7b is designed to cover the cellular low-band frequency range from 704 MHz to 960 MHz and the WLAN 2.4 GHz frequency range from 2400 MHz to 2484 MHz. The impedances to the feedings are shown in Figure 8a and 8b. The simulation results show a good impedance matching over the bandwidth of interest.

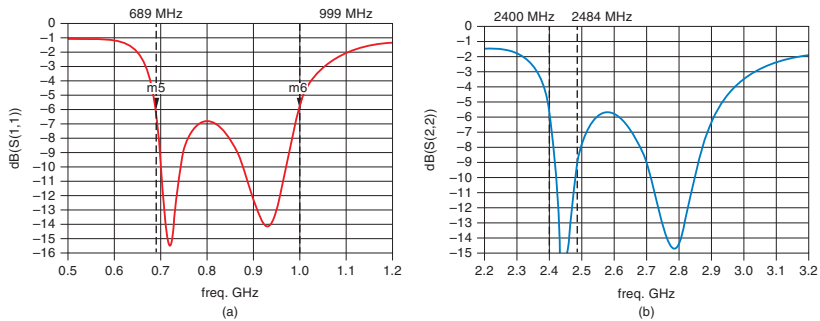


Figure 8: Impedances and isolation of the MCE concept; (a) S_{11} cellular low band, (b) S_{11} WLAN 2.4 GHz (Source: Intel Corporation, 2014)

The use of these concepts can reduce the number of needed antenna elements in wireless devices, whereby more compact stack-ups can be made and/or more metal can be accepted on the phone, giving more degrees of freedom to the industrial designers.

MIMO and the New Challenge to Design for Throughput

The scope of antenna-device and RF codesign can be pushed to even higher levels in order to maximize overall performance of a mobile device. In previous sections, this performance improvement came by increasing filtering on the antenna (thus reducing the PCB area and/or current consumption) or by reducing the volume required for the antenna itself. In this section, throughput is discussed as another performance parameter that can be increased by a good antenna codesign.

The introduction of the spatial degree of freedom in modern communication systems introduces new opportunities and new challenges in the design of modern antenna systems. It offers in fact an expansion in the number of parameters to monitor and optimize for, the two most important ones being antenna correlation and power ratio (BPR). The importance of such quantities derives directly from the fact that these are the very parameters that limit the linear increase in capacity, and by extension throughput, to be expected from MIMO systems,^[3] just as it has been shown previously for various combining techniques.^[4]

In order to illustrate this aspect, here we focus on a simple 2x2 MIMO system and adopt the common approach that describes the antennas in terms of total efficiency per antenna, BPR, and correlation coefficient between the branches. As can be expected, these parameters are highly dependent on the propagation channel and its properties. Indeed, it is worth observing that the very definition of total efficiency cannot be given without assuming a specific channel—the isotropic one. Unless otherwise noted, we also use the assumption of isotropic incoming power. It must be stressed, however, that this assumption is by no means realistic, as pointed out in literature.^{[5][6][7]} Here it is used just because of its mathematical simplicity.

The influence of the correlation coefficient and BPR at different SNR levels can be seen in Figure 9. The graphs in this figure are generated by computing the open loop channel capacity as the receiver correlation coefficient in the Kronecker model^[8] sweeps between 0 and 1 (x-axis) and the BPR sweeps between 0 and -15 dB (y-axis). As for the power carried by the entire channel, it is worth mentioning that the channel matrices were always normalized to have unitary power. The normalization of the capacity was in turn done with respect to the maximum achievable capacity for the given SNR point, which is found when correlation and BPR are respectively equal to zero and 0 dB.

Figure 9 shows that the influence of BRP and correlation varies with the level of the SNR. At low SNRs, the BPR is more significant in determining the overall capacity. As the SNR increases, however, the correlation starts playing a noticeable role. In all cases, nonetheless, the capacity depends on both parameters nonlinearly. Before continuing, it is also worth observing that it is thanks to such analyses and considerations that the current industry “rule of thumb” numbers, between 0.5 and 0.7 for correlation and up to about 3 dB for the BPR, are considered a reasonable balance between what is realistically possible to implement and MIMO performance penalties.

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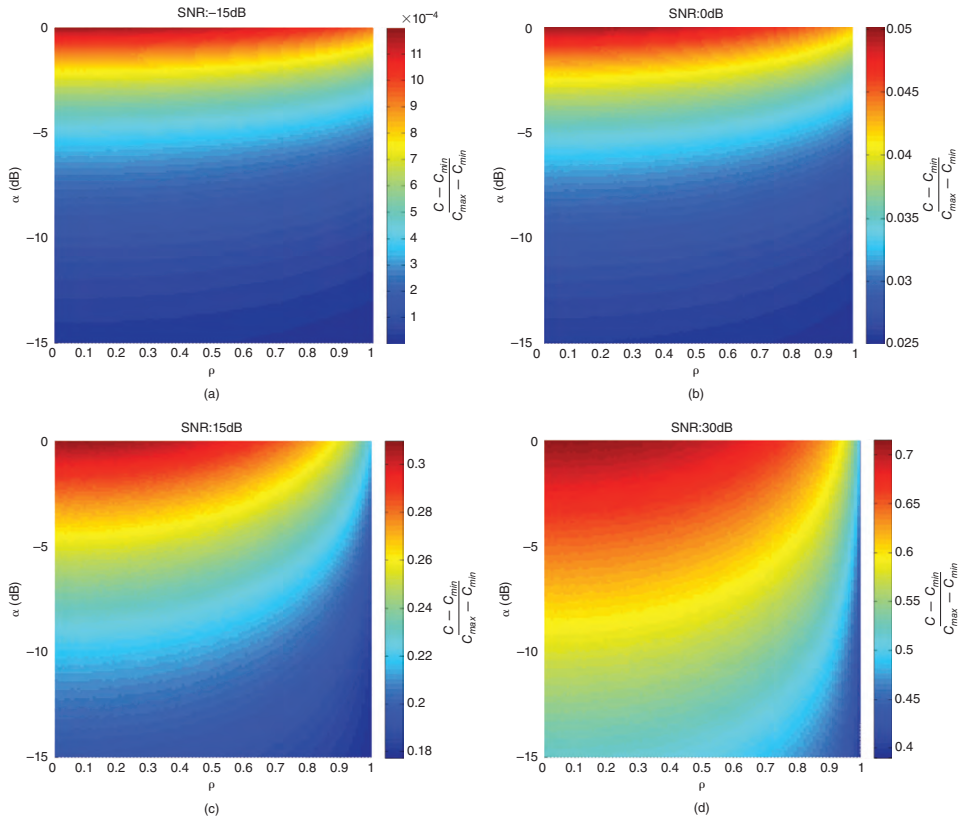


Figure 9: The influence of the correlation coefficient and BPR at different SNR levels
(Source: Intel Corporation, 2014)

In looking at the aforementioned figures, another aspect to keep in mind is that correlation and BPR are, strictly speaking, not related—a any combination between them is possible for the various antenna systems. In reality, however, it is almost impossible to decouple one from the other. Changes in efficiency lead in fact to changes in BPR and correlation. This is an aspect that plays a major role in the design of tunable antennas. For tunable antennas and RF front ends it is in fact possible to control these dependencies in order to optimize the achievable throughput for any given propagation condition.

Traditionally antennas are designed for the highest efficiency possible. Indeed, a number of publications demonstrate that channel capacity depends mostly on the total receiver power. This for instance can be seen in the work of Yanakiev et al.^[9], which shows that designs optimized for low correlation can produce only marginally different performance under realistic channel and operation conditions. Whether or not such a traditional guideline should always be followed can, however, be challenged.

The aspect can be understood by looking into the statistical sample described by Nielsen et al.^[10], which represents real world measurement—3000 measurements in free space, with multiple users gripping the phone in various predefined positions as well as 10 different antenna systems.^[10] Figure 10 shows a set of metrics derived using such a sample.

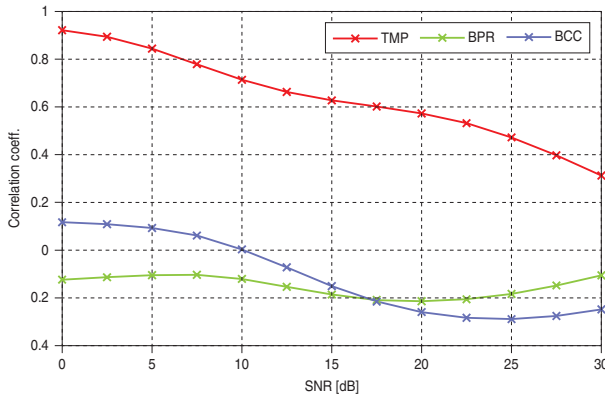


Figure 10: Correlation of capacity spread and TMP/BPR/BCC, vs. SNR
(Source: Aalborg University, 2014)

In Figure 10, TMP stands for total mean power and BCC is the branch correlation coefficient. On the x-axis, various SNR operating points are shown, while the y-axis accounts for the correlation that the three plotted parameters have with the capacity spread. This last metric is defined as the difference between the 90th and 10th percentiles.

In looking at Figure 10, it is worth observing that the total power collected is crucial in determining the channel capacity. However, at certain SNR levels, the direct connection between power and capacity weakens and there is room for optimizing correlation and BPR with the aim of maximizing throughput. As mentioned above, this can be achieved with modern tunable antennas and smart RF front ends.

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“...the total power collected is crucial in determining the channel capacity.”

Conclusions

A number of techniques that can improve the RF performance and mobile device design have been discussed in this article. The approaches are based on taking into consideration the antenna design when building a mobile device: that is, when we “pull” the antenna design into the RF modem and the industrial design of the device itself. The key performance indicators (KPIs) that can be improved are current consumption (which will reflect on the battery life of the device) PCB area (impacting the size of the device) or throughput (which can translate into higher download rates and better user experience).

This allows for the development of better modems with superior performance, lower current consumption, and eventually, platforms that would require smaller area and lower cost, which can be more attractive to end users.

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