Assessment and optimization techniques for aperture tunable handset antennas

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Introduction

For smartphones and other portable wireless devices, it is typical that the electromagnetic (EM) environment in which they are operated varies, mostly due to the actions of the user. The user presence radically influences the radiation properties of the device's antenna by EM coupling with the user body. Because all users are electrically different, and the way how they hold and use their device is not the same, there is an element of randomness that must be considered while designing these devices. The wireless link is generally deteriorated by such coupling, and the designer must carefully minimize any problems that may occur due to the varying body effect.

For the design of aperture-tunable antennas, we introduce a novel, compact characterization of handset antennas in varying use cases in terms of obtainable bandwidth and radiation efficiency. This characterization greatly helps the designer to document and perceive the problem at hand, and to select promising design candidates very early in the design process. We use the RF design automation software platform Optenni Lab to create these characterizations, and to synthesize actual circuits for selected sample problems. The platform combines EM-simulated radiation pattern and S-parameter data with circuit simulation to accurately characterize antenna systems, featuring automatic matching circuit synthesis.

For aperture-tunable antennas we also examine the theoretical performance limits of any antenna configuration by finding first the optimal value of the aperture-tuning element giving maximal radiation efficiency. Later in the design process we jointly optimize both the matching circuit and the tuning circuit and then we can verify the optimality of this joint design by comparing its efficiency to the optimal radiation efficiency.

Simulation model of use case configurations

The main phenomena that influence the antenna performance due to body proximity are (1) antenna detuning by dielectric loading, and (2) loss caused by power absorbed in the body tissues. Considering (1), for inherently resonant antennas, the electrical length of the antenna determines its operating frequency. Because dielectric loading makes the antenna's electrical length longer, the operating frequency shifts down. Regarding (2), the power lost in the tissues can be considered as part of the system radiation efficiency.

The simulation model in this article consists of an electrically small smartphone antenna depicted in Figure 1, which is inherently non-resonant at the design frequencies. The antenna is simulated using ANSYS HFSS EM simulator in three configurations: (i) antenna with the smartphone chassis in free space; (ii) antenna with the chassis and a two-hand phantom model holding the phone in approximately browsing position, shown in Figure 2; (iii) antenna with the chassis and a hand-head phantom model holding the phone in approximately talking position, shown in Figure 3. We refer to these configurations as "free space configuration", "hand configuration" and "head configuration".

Novel performance characterization diagram for aperture tuned antennas

There are two basic tuning methods for handset antennas, so-called aperture tuning and impedance tuning, illustrated in Figure 4. In aperture tuning, the tuner component will change the current distributions in the structure thus influencing not only its impedance but also its radiation efficiency. The possibility to optimize radiation efficiency is one of the main reasons why aperture tuning has gained popularity, and we propose a new method to visualize the antenna performance as a function of the aperture component.

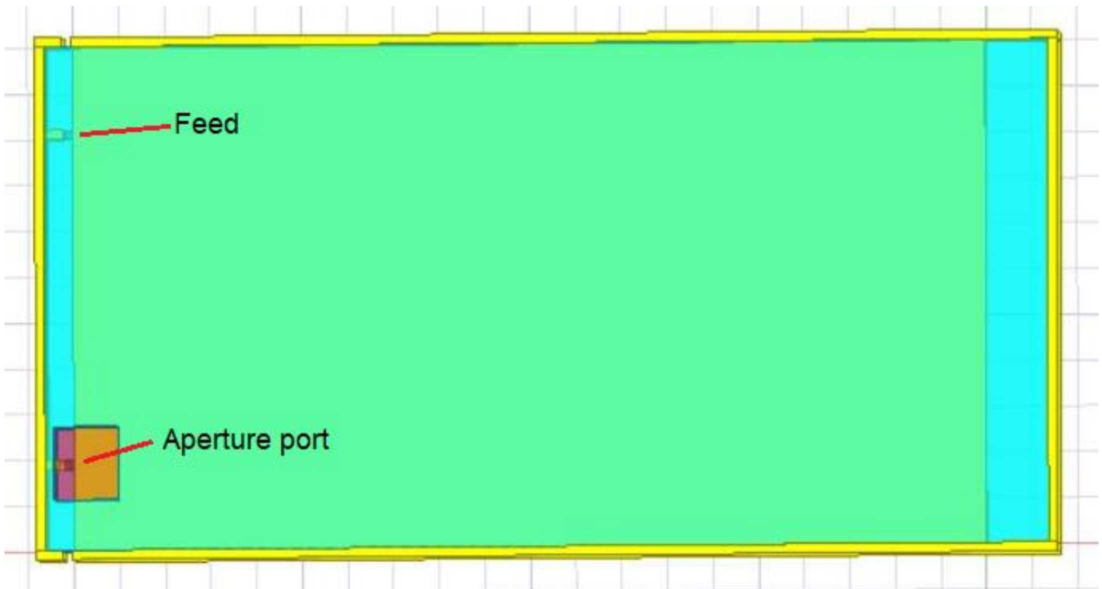

Figure 1. Free space configuration: antenna and device chassis

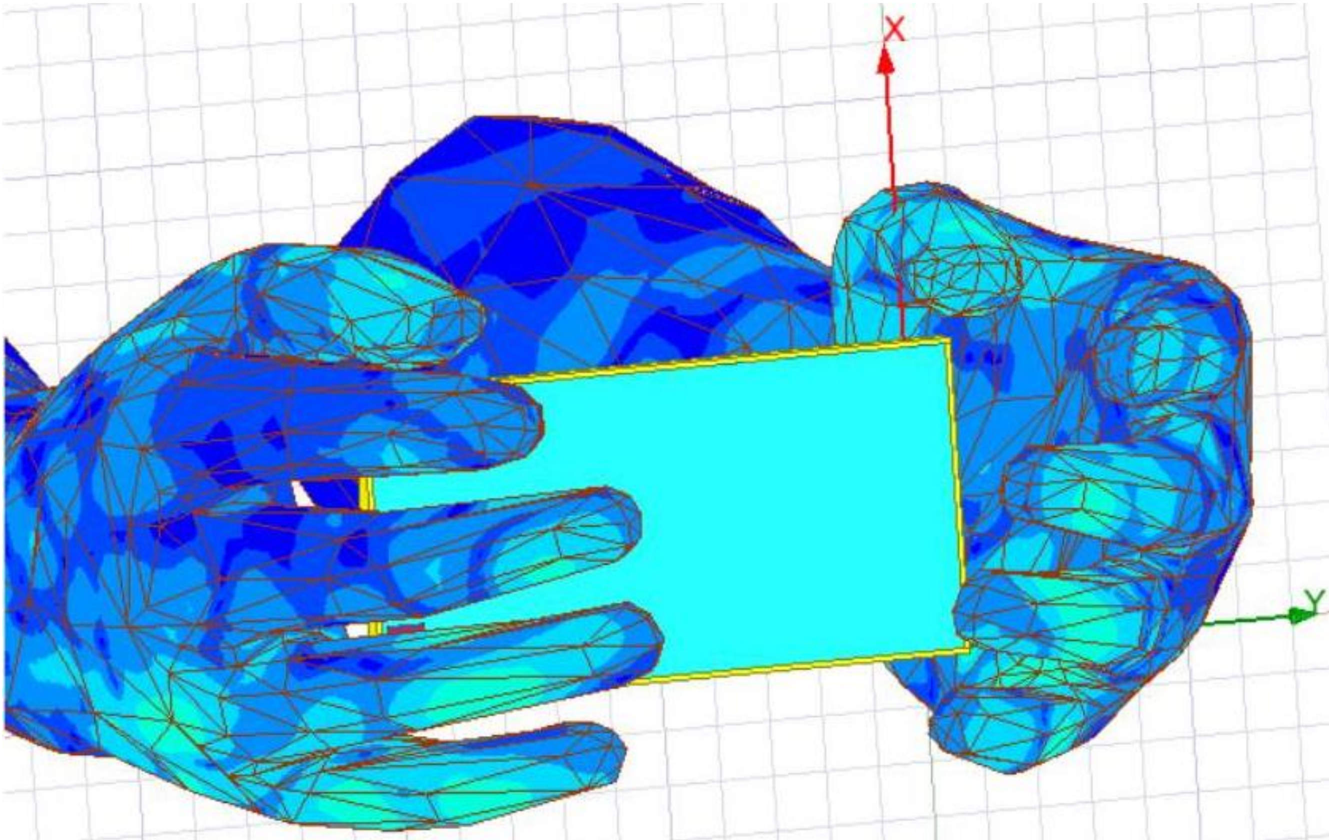

Figure 2. Hand configuration: antenna, chassis and phantom hands

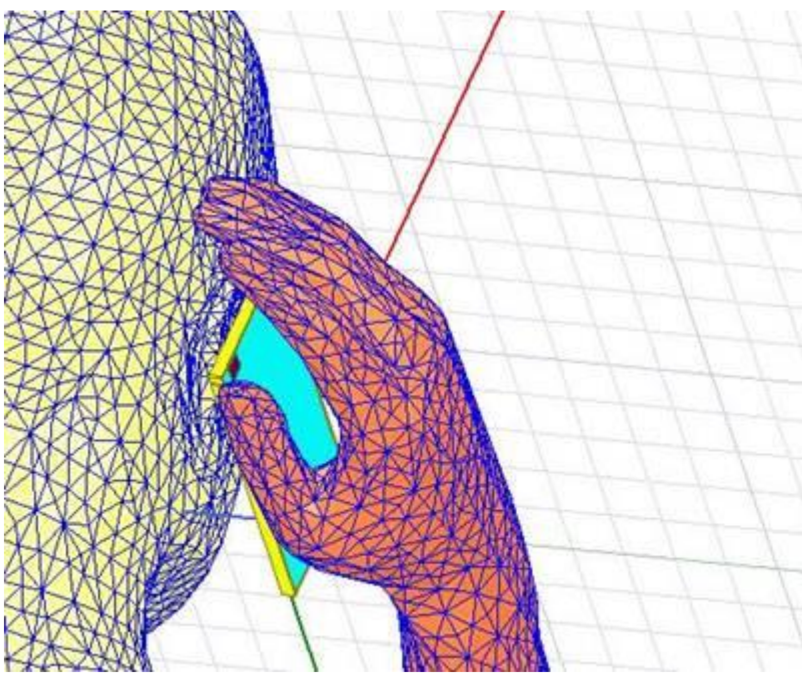

Figure 3. Head configuration: antenna, chassis and phantom hand+head

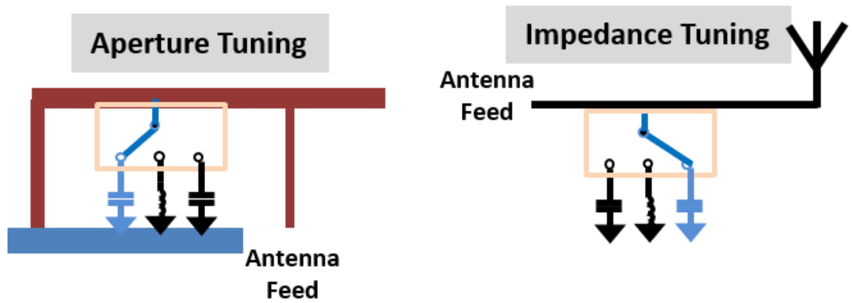

Figure 4. Basic principle of aperture and impedance tuners.

In the RF design automation software platform, when normalized radiation patterns from EM simulator are imported together with the S-parameter matrix of the electromagnetic system, the software can compute the total radiation pattern when terminating circuitry is placed on the ports by superposing the properly weighted port radiation patterns. The resulting total radiation pattern allows direct calculation of the tuner-dependent radiation efficiency, making it easy to study a few representative tuner component values.

The feed port impedance as a function of tuner component is generally not very informative for a small non-resonant antenna, because the antenna is designed to only work with a lumped matching circuit. Instead, we should ask how wide bandwidth is available for a given reference return loss level? The RF design automation software platform features a Bandwidth potential calculation tool [1] that helps to answer this question for any aperture component value.

For Figures 5(a) – 5(c) we have built "maps" for the radiation efficiency and available bandwidth as a function of a few selected aperture component values, for each of the environment configurations. The target return loss level for bandwidth potential calculation is 10 dB.

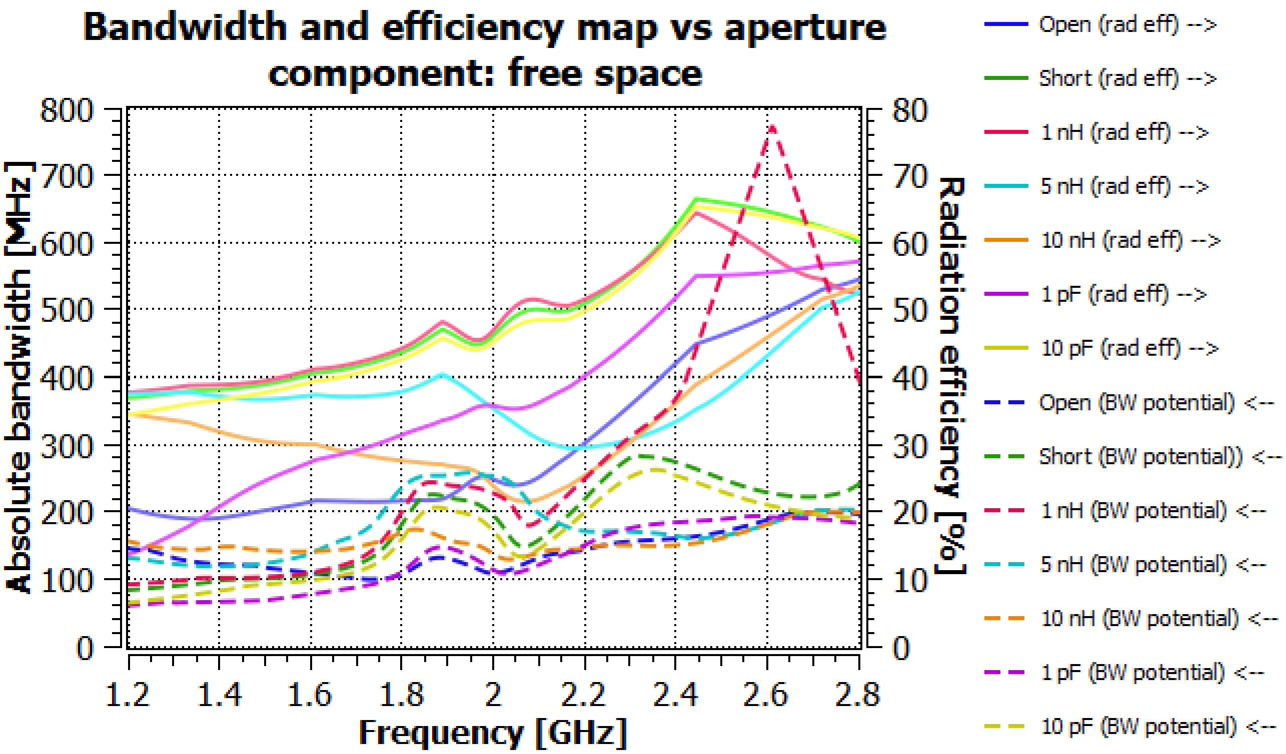

Figure 5(a). Bandwidth potential and radiation efficiency as a function of aperture component, free space configuration.

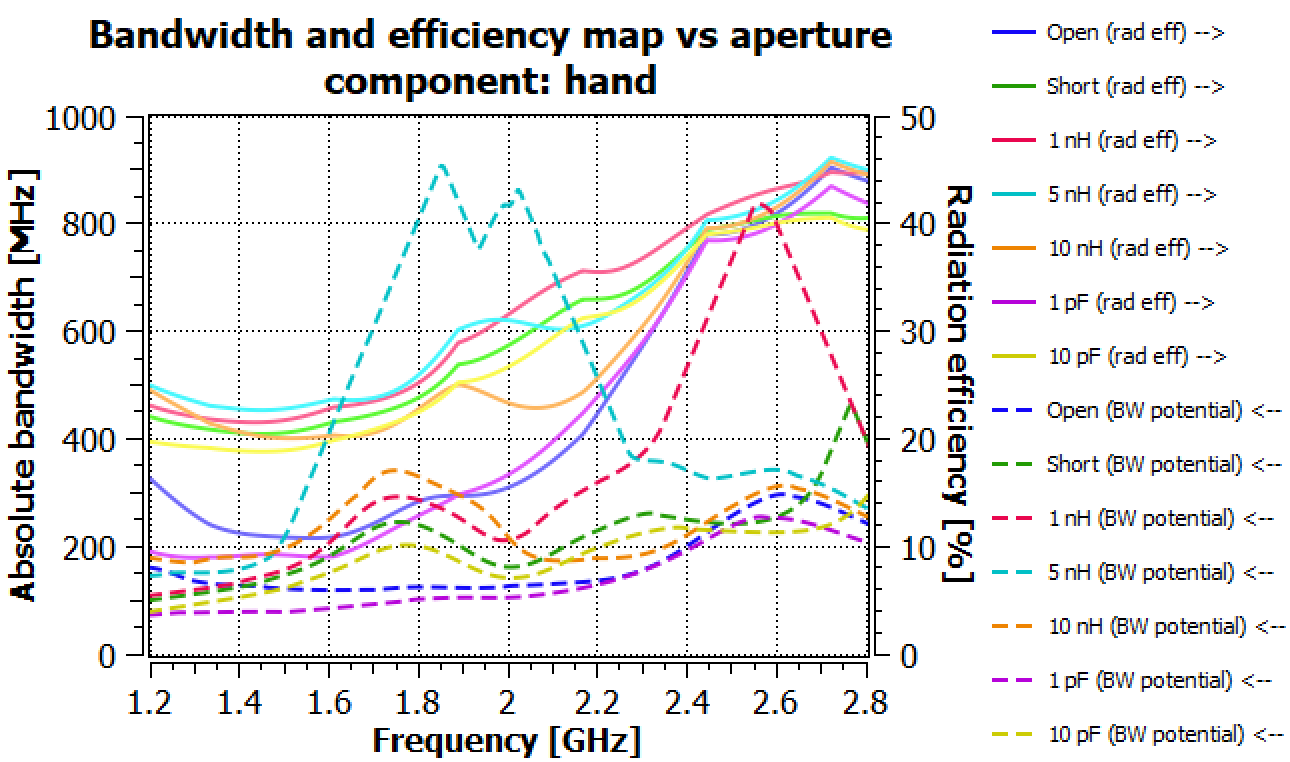

Figure 5(b). Bandwidth potential and radiation efficiency as a function of aperture component, hand configuration. Note different scales than in Figure 5(a).

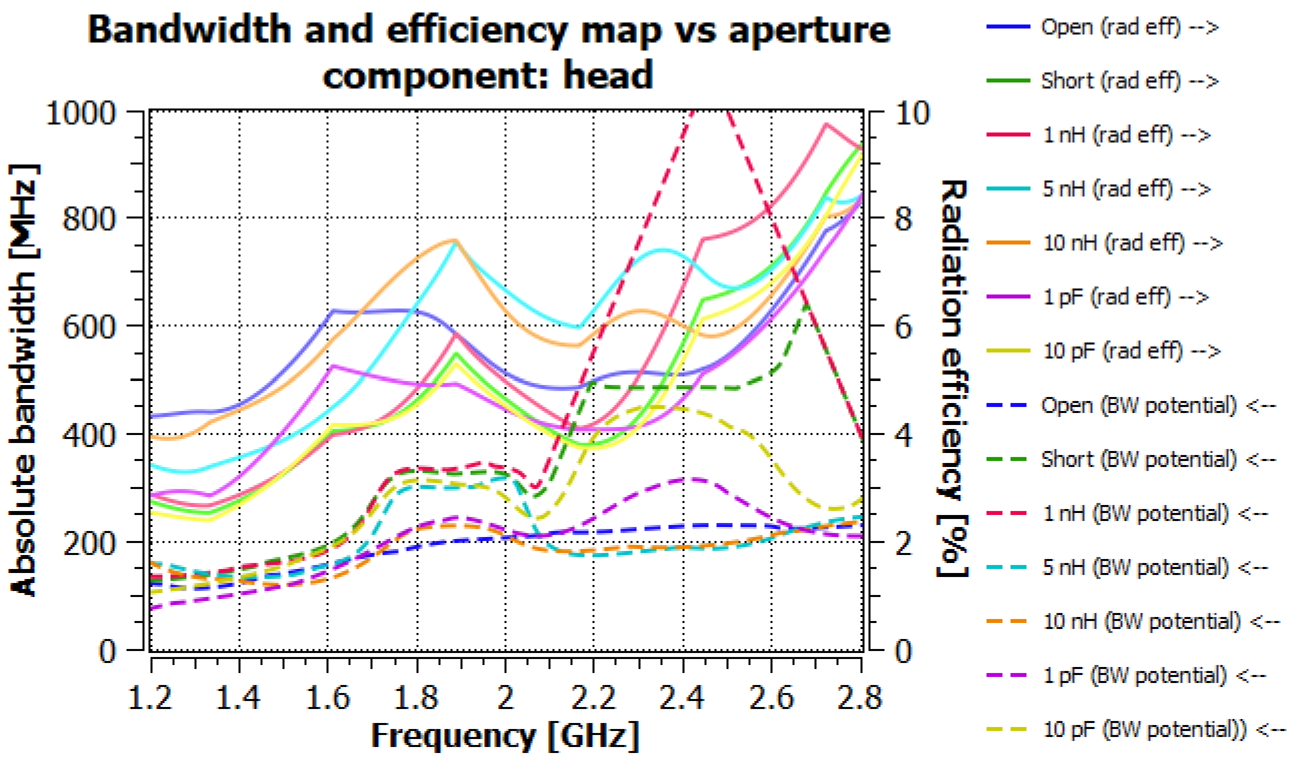

Figure 5(c). Bandwidth potential and radiation efficiency as a function of aperture component, head configuration. Note the strongly zoomed radiation efficiency scale on the right y-axis.

As an example, interpreting Figure 5(a), at around 1.9 GHz, widest impedance bandwidth (254 MHz) to 10 dB return loss level is reached with 5 nH aperture inductor, but 5 nH inductor would provide only 40% radiation efficiency. Instead, 1 nH inductor provides 48% radiation efficiency with almost as wide (240 MHz) bandwidth. The conclusion is that for the free space configuration, aperture component value of about 1 nH provides optimal performance for a design centered at 1.9 GHz.

Similarly, from Figure 5(b) we can see that in the hand configuration the antenna would be nearly optimal and provide enough bandwidth even without any aperture component for Band 7 (2500 – 2690 MHz, blue curves). However, at 1.6 GHz, without any aperture component the antenna would only provide about 11% radiation efficiency but inserting a 5 nH aperture component would increase the efficiency to 23%. For Band 7 the aperture component has only minimal influence on the performance, so 5 nH is a good choice for both 1.6 GHz and Band 7.

In this fashion it is possible to visualize very complex relationships of an antenna system performance metrics in rather simple diagrams, providing important insight for the designer.

Physical performance limits for different configurations

While considering the ultimate performance limits for each of the configurations, we must find optimal value for the aperture component that maximizes the radiation efficiency. The optimal value depends upon the band

and configuration. Knowing the ultimate limits is very helpful when we set up optimization targets and rate design candidate performance.

For the purpose of this study, let us consider two cases: satellite navigation band Beidou B1-2 (about 1587-1592 MHz) and 3GPP Band 1 (1920 – 2170 MHz). For single aperture tuner, the optimum radiation efficiency is easily found by tuning the aperture component value – the RF design automation software platform recalculates the radiation efficiency real time. The results are as follows:

Beidou B1-2

- Free space: $\eta_{rad,max}$=41% (-3.9 dB) with $L_{aperture}$ = 1.4 nH
- Hand: $\eta_{rad,max}$=24% (-6.2 dB) with $L_{aperture}$ = 3.4 nH
- Head: $\eta_{rad,max}$=6% (-12.2 dB) with aperture = open circuit

Band 1

- Free space: $\eta_{rad,max}$=45% (-3.4 dB) with $L_{aperture}$ = 1 nH
- Hand: $\eta_{rad,max}$=32% (-5.0 dB) with $L_{aperture}$ = 3 nH
- Head: $\eta_{rad,max}$=6% (-12.2 dB) with $L_{aperture}$ = 5 nH

Performance of theoretical and practical matching circuits

The radiation efficiency gives a physical upper limit for the antenna total efficiency at a given frequency. Reaching this physical performance limitis not possible in practice, because it would require perfect, lossless impedance matching over the whole band. Moreover, the best possible impedance matching circuit is not necessarily the same for the different configurations. Considering a theoretical closed-loop aperture tuning, where the aperture component adapts to the changes in the environment, we can assume an optimal aperture component value for any configuration. But even such we must accept a compromise of the impedance match over the band and over the configurations.

Case 1: Beidou B1-2

The RF design automation software platform allows synthesis and optimization of a **fixed** passive impedance matching circuit at the input and a **variable** aperture tuner component. A natural starting point in the study is to set the aperture component values that maximize radiation efficiency for each configuration. We can check from Figures 5(a)-(c) that any choice of aperture component provides more than enough bandwidth for the narrow Beidou B1-2 band.

However, here the bottleneck turns out to be the fact that even though it is possible to identify a topology that works for all configurations, the required component values in that topology vary so much that a good compromise is not found. Figure 6 shows the circuits that are optimized to provide ideal performance for each configuration. The biggest issue is the strong impedance detuning with the head configuration.

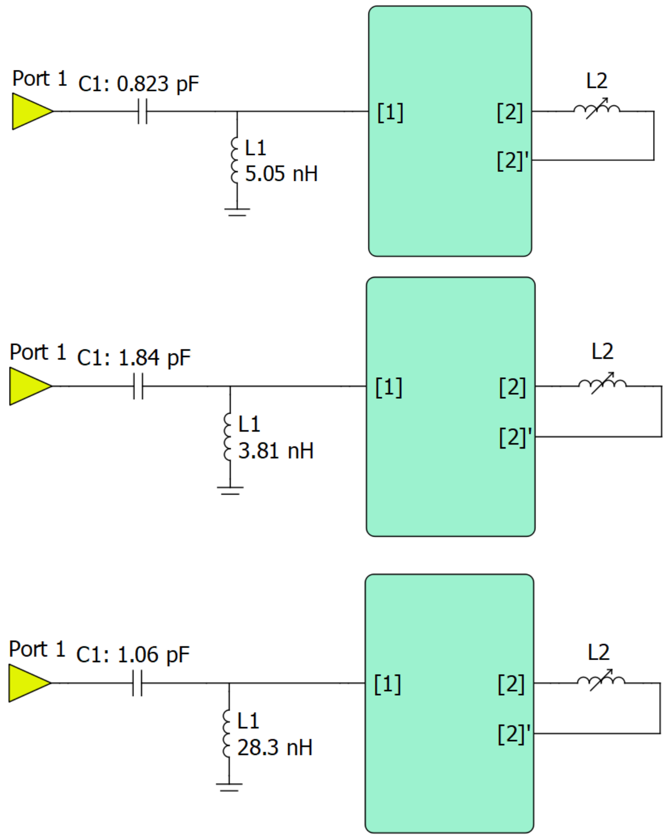

Figure 6. L-topology providing ideal impedance match for free space, hand and head configurations. The inductor L2 assumes values 1.4 nH, 3.4 nH and ∞ (open circuit), respectively.

However, in this case we can find a tunable circuit in the input using a variable shunt capacitor, shown in Figure 7, that provides essentially perfect impedance match for all configurations. This solution employs a hybrid impedance-aperture tuner technique, and it provides a total efficiency within less than 0.1 dB from the physical limit. The efficiency degradation in this study is measured essentially as the worst case degradation over the configurations and frequency bands.

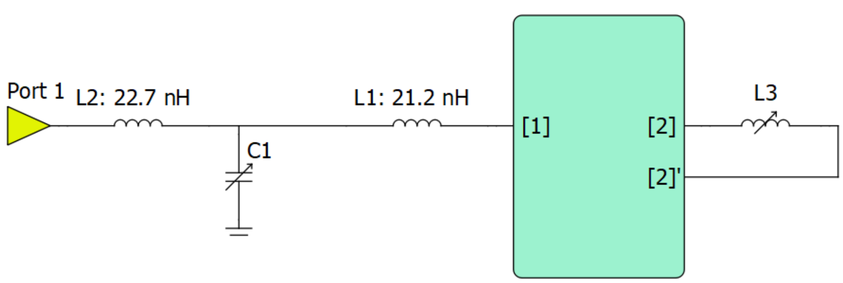

Figure 7. Tunable impedance and aperture matching circuits. The variable capacitor values 1.22 pF, 1.07 pF and 0.73 pF provide perfect match for free space, hand and head configurations, respectively. The values of the variable inductor are the same as in Figure 6.

Practical considerations

There are several idealizations made above. The most significant are: (1) it is barely feasible to assume that the handset could reliably measure the radiation efficiency; (2) tunable inductor with continuous range is not a practical RF-component for a handset; (3) all fixed and variable circuit components are assumed ideal.

Based on the fundamental performance maps in Figure 5(a)-(c) we can anticipate that perhaps a fixed inductance of a few nH would provide enough radiation efficiency for all cases, as the more burning impedance match is solved by the simple tuner circuit of Figure 7. Making the simplifying assumption of a fixed aperture component reveals a reasonably good *all-passive* solution as a result of the synthesis, shown in Figure 8. The performance degradation with respect to the physical limit is -0.9 dB with this circuit.

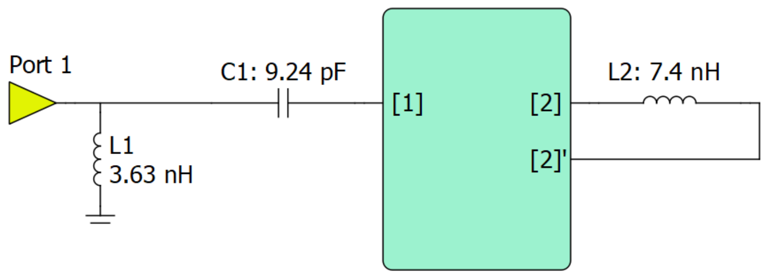

Figure 8. All-passive circuit for Beidou B1-2 case.

The remaining issue is the assumed ideality of the lumped components. In the RF design automation software platform, it is easy to consider practically available lumped components and include their losses/parasitics in the analysis. As an example, we used Coilcraft 0402DC and Murata GJM15 component libraries, and found a realizable all-passive solution with -1.1 dB performance with respect to the physical limit.

Case 2: 3GPP Band 1

The Band 1 case has additional challenge because its bandwidth is considerably wider. Looking carefully the performance map in Figure 5(a) suggests that for free space configuration, aperture component value of 5 nH would provide the best impedance bandwidth (240 MHz) but the corresponding radiation efficiency is quite low (30-35%). On the other hand, 1 nH aperture inductor would provide much better radiation efficiency (45-51%) but the impedance bandwidth is narrower (205 MHz). The optimal value is expected to be between 1 nH and 5 nH. Similarly, for hand configuration, there is enough available bandwidth for all aperture components between 1 nH and 5 nH, and the optimal radiation efficiency over the band also falls between these values. For the head configuration, the impedance bandwidth is not the bottleneck, and highest efficiency is achieved with aperture inductor value close to 5 nH.

Considering a fixed impedance matching circuit at the input and a variable aperture component, the bottleneck is again impedance detuning: best matching circuit for free space configuration is so different from the circuits that work for hand and head configurations that even with theoretical components one must accept a performance degradation of about 0.7 dB from the physical limit. In this case a hybrid impedance-aperture tuning approach turns out to provide only minimal advantage (less than 0.1 dB) over aperture tuning with fixed circuit in the input. The best circuit is shown in Figure 9.

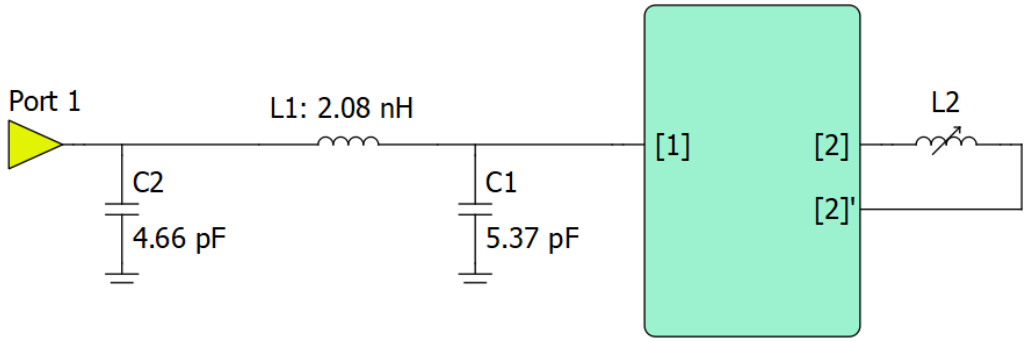

Figure 9. PI-topology providing the best compromise for the impedance match. The inductor L2 assumes values 3.4 nH, 4.1 nH and 3.1 nH for free space, hand and head configurations, respectively.

In comparison, an all-passive synthesis using vendor components gives a realizable solution with -1.2 dB with respect to the physical limit, in other words only 0.5 dB worse than the best theoretical tunable circuit of Figure 9. The S_{11}-parameter along with total and radiation efficiencies as well as the circuit itself are shown in Figure 10.

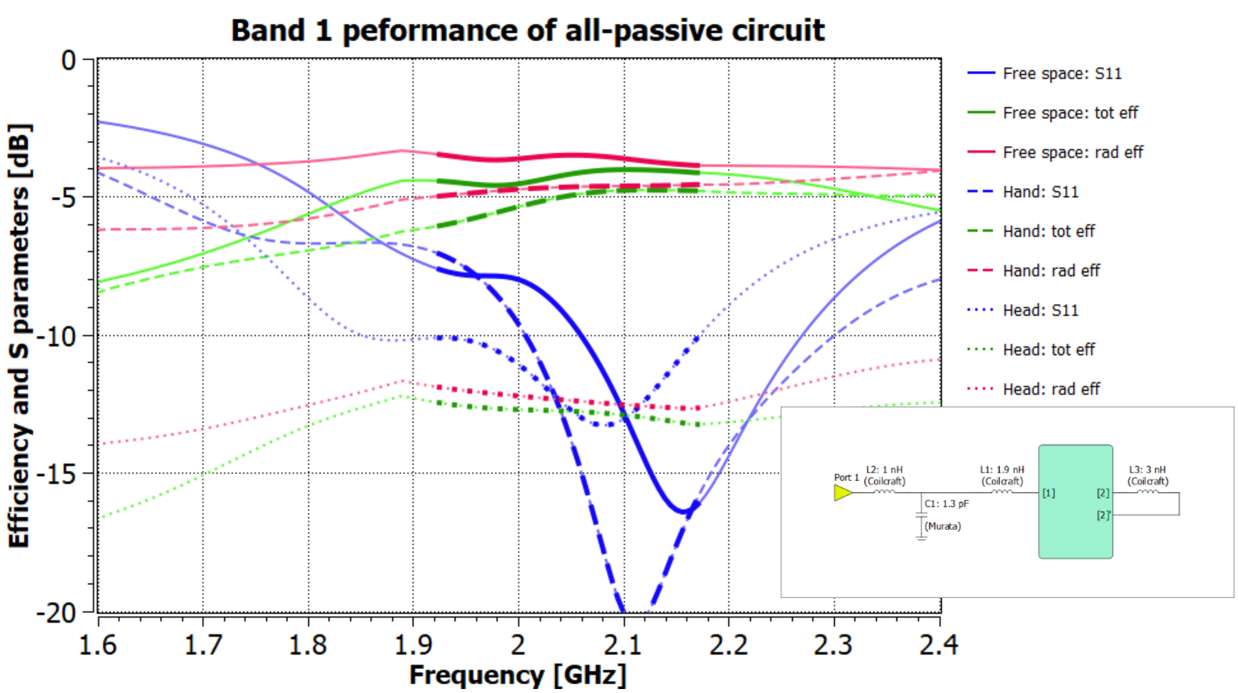

Figure 10. Performance for each configuration of all-passive, realizable circuit. Case 2: 3GPP Band 1. Note dB-scale for the efficiencies.

It is interesting to note that both the narrowband and broadband cases end up with similar conclusion: an all-passive, simple, realizable circuit can provide a performance of about -1.2 dB with respect to the ultimate physical limit.

Multi-band operation

Finally, let us consider the application where the handset supports both Beidou B1-2 and 3GPP Band 1. There are several possible cases and solution architectures. The bands may need to be supported simultaneously, or one at a time. We may employ closed-loop tuning, open-loop (frequency) tuning, combination of them, aperture- and/or impedance tuning or all-passive matching. To limit the discussion, let us consider only the case where the bands are supported one at a time, and study the different tuning alternatives. The physical performance limits we have found above obviously apply also to the more demanding multi-band application.

The RF design automation software platform supports optimization of a combined open- and closed-loop impedance-aperture tuner architecture where the tuner components at the input matching circuit and aperture port adapt both to the environment and the frequency band being served. Synthesizing and optimizing for such a theoretical circuit provides a result with -1.0 dB performance or better for all configurations and frequency bands with respect to the physical limits. We will use this performance as a reference for other matching architectures. The theoretical circuit is shown in Figure 11, where the variable components are modeled using ideal switches for easier illustration.

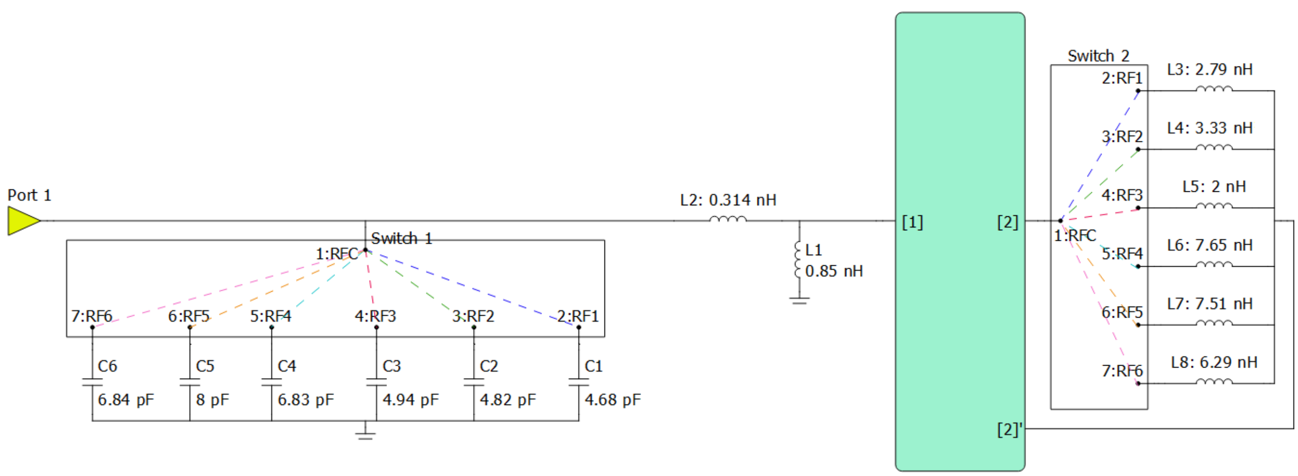

Figure 11. Theoretical open- and closed-loop impedance-aperture tuner circuit. The ideal switch branch assignments are RF1-RF3 for the free space/hand/head configurations at Band1, and RF4-RF6 for Beidou B1-2.

Optimizing the same topology but with a fixed shunt capacitor at the input results in an open- and closed-loop aperture tuner circuit with only 0.1 dB performance degradation to the reference.

Making next a huge simplification by considering only open-loop aperture tuning, where the handset is not assumed being able to adapt to the environment anymore but only to the frequency band, we find a circuit that perhaps surprisingly has nearly as good performance as the combined open- and closed-loop aperture tuner. This means that for this particular example there is no benefit in considering closed-loop technique. Moving forward towards more realistic solutions, considering passive vendor library components instead of ideal components in the open-loop aperture tuner architecture (still with ideal switch) further degrades the performance by 0.3 dB.

The remaining choice is between the open-loop aperture tuning using a real switch model, or an all-passive circuit. We tried several commercially available switch models and found out that the switch losses for this problem contribute typically about 0.6 dB to the performance degradation, so as a realizable open-loop tuner circuit we end up with -2.0 dB performance with respect to the physical limit or -1.0 dB with respect to the theoretical open-closed-loop tuner circuit.

Interesting enough, when an *all-passive* realizable circuit is synthesized with a fixed inductor at the aperture port, it provides 0.1 dB *better* performance than the open-loop tuner, thus providing -1.9 dB performance with respect to the ultimate physical limit. Because this is a passive circuit, it also supports the mode where both frequency bands are operational simultaneously. The circuit and its performance are shown in Figure 12.

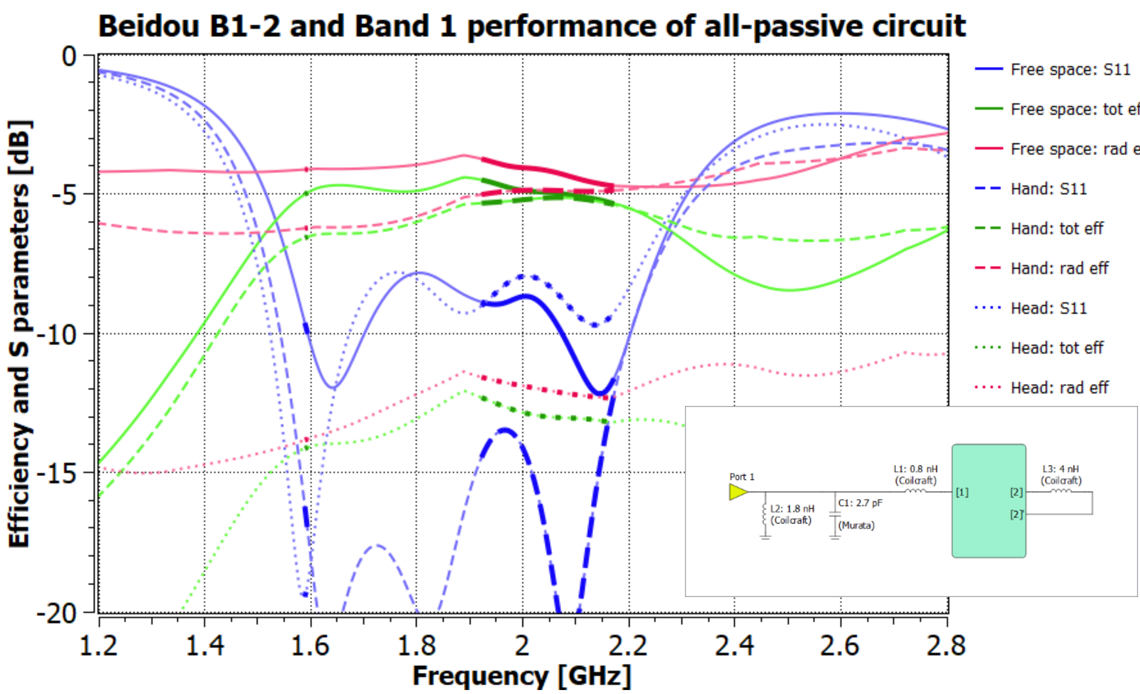

Figure 12. Performance for each configuration of all-passive, realizable circuit for bands Beidou B1-2 and 3GPP Band 1. Note dB-scale for the efficiencies.

Conclusions

In this study we have considered a handset antenna performance optimization of aperture tunable antennas from various aspects and developed a new performance diagram concept that helps the designer to assess design candidates, specifically taking into account the varying electromagnetic environment of the device. We have identified the radiation efficiency optimum as the proper reference for the performance of any theoretical or practical matching circuit, greatly simplifying the setup of optimization tools and comparison between design candidates.

The design example that we considered is somewhat simplistic but aims at representing a realistic situation. The simulation method used combines EM-simulated far-field radiation pattern data with circuit simulation for accurate calculation of total efficiency of the system, taking all loss contributions properly into account. The various passive or tunable solutions are easy to synthesize and compare using the RF design automation software platform used in the study. In this case it turned out that an all-passive circuit with carefully optimized fixed aperture component provides a performance that is within about 1 dB of the performance of an idealized theoretical open- and closed-loop tunable circuit, being the preferred choice for this example due to simplicity and cost. It is to be emphasized that an all-passive solution is not always optimal, but the best architecture depends upon the antenna structure and the frequency bands. The bottom line is that a careful comparative study of each alternative should be carried out in the early design phase in order to make the best choice.

[1] J. Rahola, ”Bandwidth potential and electromagnetic isolation: Tools for analysing the impedance behaviour of antenna systems”, Proceedings of the EuCAP 2009 conference, Berlin, March 23-27, 2009.