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Published in:
IEEE Antennas and Wireless Propagation Letters

DOI:
10.1109/LAWP.2019.2914357

Published: 01/07/2019

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Saarinen, T., Hannula, J.-M., Lehtovuori, A., & Viikari, V. (2019). Combinatory Feeding Method for Mobile Applications. *IEEE Antennas and Wireless Propagation Letters*, *18*(7), 1312-1316. Article 8717619.
https://doi.org/10.1109/LAWP.2019.2914357

Combinatory Feeding Method for Mobile Applications

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***Abstract*—This letter presents a method for implementing frequency reconfigurability without lumped elements. The method is based on feeding an antenna element simultaneously at different locations with differently delayed and amplified signals and dynamically manipulating the number of active feeds. To demonstrate the concept, an example design of a handset antenna that is compatible with most modern mobile phones is presented. The proposed antenna geometry is simple and practical, consisting only of a folded rectangular sheet and four feeding points. The simulated efficiency of the antenna is higher than 50% from nearly 0.7 to 7 GHz with the highest efficiency being above 90% in 2 × 2 multiple-input–multiple-output (MIMO) operation.**

***Index Terms*—Mobile antennas, multifrequency antennas, multiple-input–multiple-output (MIMO) antennas, reconfigurable antennas.**

I. Introduction

THE future mobile communications requires more frequency bands that are narrower and more fragmented than before. Therefore, instead of focusing on individual frequency bands, future mobile antennas need to be designed to cover wide frequency ranges. In addition, antennas in future devices are expected to provide higher order multiple-input–multiple-output (MIMO) and at the same time occupy less and less volume in the device.

Traditionally, multiband operation has been implemented with multiresonant fixed antennas such as in [1]–[4]. Nevertheless, the requirements listed earlier heavily challenge the benefits of fixed antennas, which can provide smaller size and broader bands only at the expense of efficiency. As a result, the future antennas need to be made frequency-reconfigurable so that the instantaneous band can be smaller thus allowing higher efficiency. By far, common methods to establish frequency reconfigurability are switching between matching circuits [5], [6], use of tunable matching components such as varactor diodes [7]–[9], or to use switches to modify the antenna structure [10]–[13]. The downside of these methods is that tunable matching circuits and PIN switches may introduce significant losses and distortion, add complexity and needed printed circuit board (PCB) area, and in some cases require bias and control lines that add design restrictions.

A new approach to frequency reconfigurability that is based on multiport feeding is the concept of antenna clusters and weighted feeding introduced and discussed by Hannula *et al.* in [14]–[16]. The method relies on special multichannel transceiver that is used to weight the feeds of a multielement antenna cluster. This letter significantly extends the method by introducing a completely new combinatory feeding scheme, which significantly improves the achievable efficiency without introducing any additional hardware compared to the designs in [15] and [16].

Combinatory feeding is a novel method where the number of feeding ports on a multiport antenna is adjusted dynamically. The benefit of the method is that a simple antenna element can be used to cover multiple frequency bands with good efficiency without additional matching circuitry. Traditionally, in wideband applications, strong resonances should be avoided to maximize bandwidth [17], thus sacrificing matching level. Compared to a traditional wideband antenna design, with combinatory feeding the frequency band is covered with multiple narrow band resonances of high efficiency.

To further demonstrate the possible uses of the new method, an antenna design covering a wide range of frequency bands from 0.7 to 7 GHz is presented. The antenna geometry is simple, consisting of a folded rectangular sheet and four feeding ports. Simulation results using the proposed method and feed weighting are presented and compared. The antenna achieves better than 50% efficiency in 2 × 2 MIMO operation over the specified range and reaches better than 90% maximum efficiency.

II. Principle of Operation

A multiport antenna is typically presented as an $n \times n$ scattering matrix such that

$$\mathbf{b} = \mathbf{S}\mathbf{a} \tag{1}$$

where n is the number of ports, $\mathbf{S}$ is the scattering matrix, and $\mathbf{a}$ and $\mathbf{b}$ represent the incident and reflected wave vectors at the antenna feed ports, respectively. When an antenna is fed simultaneously from multiple ports, the individual port reflection coefficients are not enough to describe how much power is accepted to the antenna due to coupling between ports. Instead, the total active reflection coefficient (TARC), which is the ratio of total incident and reflected power at the antenna ports, should

Manuscript received February 25, 2019; revised April 10, 2019 and April 26, 2019; accepted April 26, 2019. Date of publication May 17, 2019; date of current version July 3, 2019. This work was supported by Huawei Technologies. *(Corresponding author: Tapio Oskari Saarinen.)*

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Digital Object Identifier 10.1109/LAWP.2019.2914357

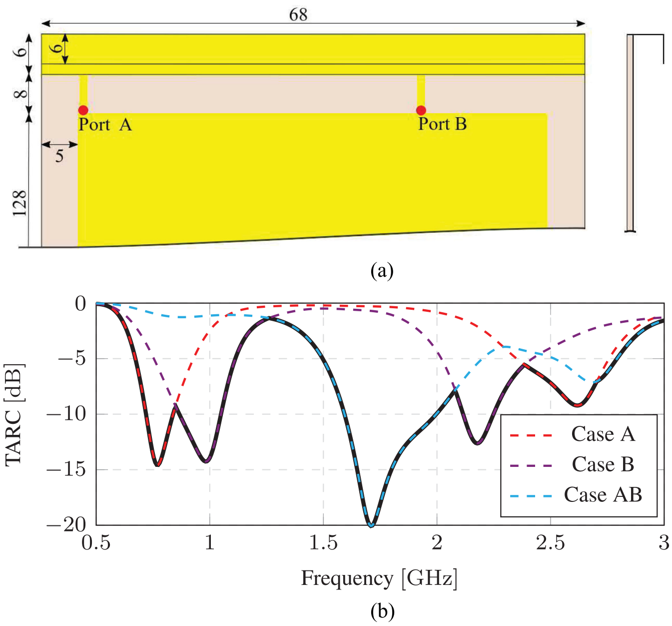

Fig. 1. (a) Simple two port antenna. All dimensions in millimeters. (b) Reflection coefficients of the two port antenna and the TARC.

be used to evaluate the antenna's matching efficiency [18]. In such a case, the matching efficiency for a multiport antenna η_{m} can be calculated from TARC as

$$\eta_{\mathrm{m}} = 1 - \mathrm{TARC}^2. \tag{2}$$

A. Feed Weighting

Weighted feeding [14], [15] is a technique used to improving the matching efficiency of a multiport antenna. The method utilizes the coupling between antenna elements in a coupled antenna cluster to produce a single antenna with high efficiency. To reach optimum performance, each antenna element is fed with a specific amplitude and phase. The feeding coefficients can be either solved from *S*-parameters to minimize reflection losses or from far fields to maximize radiation efficiency [16]. The *S*-parameter approach is computationally much lighter, and it essentially gives identical results to the far-field approach, when material losses are small. We have used the *S*-parameter approach in this letter.

According to the principles introduced in [14], for a scattering matrix $\mathbf{S}$ of a low-loss antenna, the maximal matching efficiency is found to be

$$\eta_{\max} = \max\{\mathrm{eig}(\mathbf{I} - \mathbf{S}^{\mathrm{H}}\mathbf{S})\} \tag{3}$$

which implies that the excitation vector $\mathbf{a}$ from (1) that provides the best matching efficiency $\eta_{\max}$ is the eigenvector of $(\mathbf{I} - \mathbf{S}^{\mathrm{H}}\mathbf{S})$ corresponding to the highest eigenvalue ($\eta_{\max}$).

B. Combinatory Feeding

Combinatory feeding is a novel method introduced in this letter. In contrast to the designs presented in [14] and [15], the method improves the best achievable matching of an antenna cluster by dynamically manipulating the number of antenna feeds. To explain the concept, we will first consider a simple example. Fig. 1(a) illustrates a simple antenna consisting of a 90° folded rectangular metal sheet at the end of a rectangular ground plane with two asymmetrically located ports. The antenna is excited in three different ways. In the first case A, the antenna is fed from port A, and port B is left open. In the second case B, the antenna is fed from port B, and port A is open. Finally, in the third case AB, the antenna is fed simultaneously from both ports with weighting coefficients obtained from (3).

Fig. 1(b) depicts the input reflection coefficients and the TARC of the three cases, respectively. First, in case A, the antenna has a resonant frequency at 0.77 GHz and a second resonance at 2.17 GHz. Next, in case B, the resonances occur at 0.98 and 2.62 GHz. Finally, in case AB, the resonant frequency is at 1.70 GHz. The solid black envelope curve represents the best achievable performance of the antenna, which is obtained by selecting the optimal feeding combination at each frequency.

This simple example demonstrates that different feeding combinations have different resonant frequencies due to the asymmetric port placement. Changing the location of the excitation ports produces different current paths on the antenna that have nonidentical resonant lengths. By increasing the number of feeding combinations, i.e., adding more ports, one can create different resonances, which altogether can cover a large frequency band.

If a port of an n-port scattering matrix is permanently terminated with an impedance other than the reference impedance, such as an open circuit, the resulting network can be represented with a reduced scattering matrix, which accounts for the constant termination in certain ports. As a result, a single antenna structure can be presented with $n^2 - 1$ sets of different reduced *S*-parameters depending on the frequency of interest. In case the handset contains multiple antennas, finding the optimal combinations becomes an optimization task as coupling between antennas depends on the feeding combinations. If multiple frequency bands need to be covered simultaneously, as for example in carrier aggregation, different combinations have to be used, which will naturally result in less than optimal performance.

In this letter, the ports used at a specific frequency to excite the antenna are referred to as the active ports. In the case that number of active ports is larger than one, the matching efficiency is further improved with optimal feeding weights obtained from (3).

III. Example Antenna Design

To further demonstrate the capabilities of combinatory feeding, we present a 2×2 MIMO handset antenna as an example. The handset also utilizes weighted feeding, and thus it is intended to be used in conjunction with a special multichannel transceiver. As of this moment, no such transceiver exists; however, feasibility of such circuit was discussed in [19]. The switching of ports is implemented by biasing the power amplifiers on the transceiver. The input impedance at the output of an unbiased amplifier looks like a small capacitance (on the order of 50 fF), which is effectively an open circuit. In the following sections, the open circuits are modeled as 50 fF capacitances.

The handset antenna is designed for MIMO applications and aimed for future mobile communications. Due to fragmented nature of future mobile bands, the frequency response can be tuned

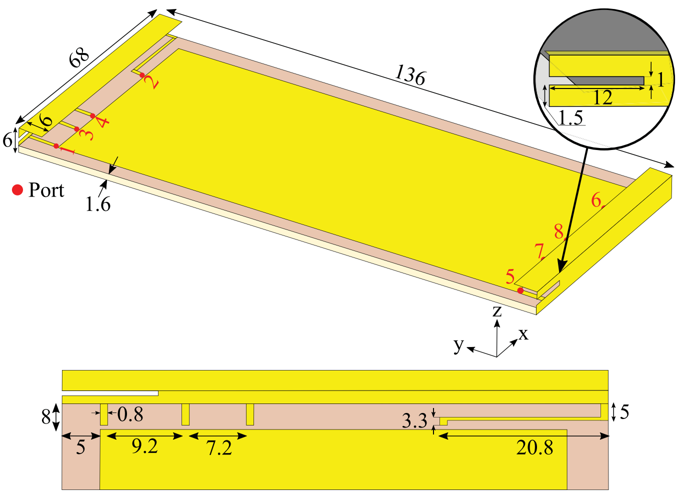

Fig. 2. Proposed antenna design. All dimension are in millimeters.

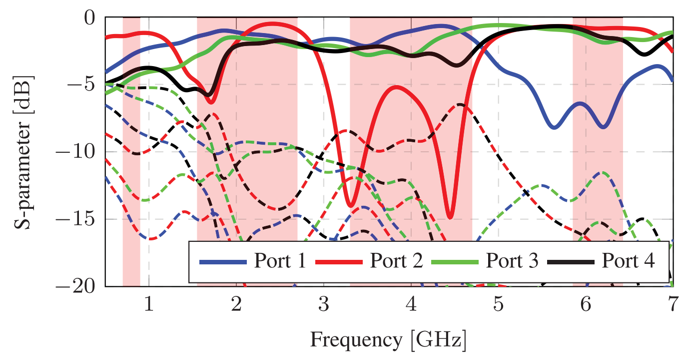

Fig. 3. Simulated S-parameters of the antenna structure. The solid lines represent the reflection coefficients seen at each port, and the dashed lines illustrate the coupling between ports.

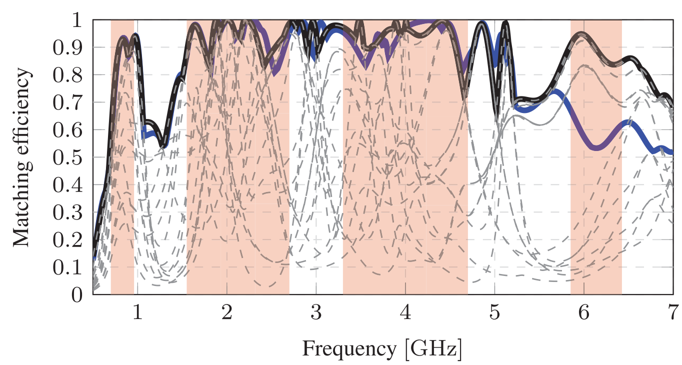

Fig. 4. Matching efficiency of a single antenna with cutout (black) and without (blue). The dashed lines represent the individual feeding combinations.

over a wide frequency range. In the design phase, most emphasis was put onto the following four frequency bands, which are to be used in 5G systems: low band 0.7–0.96 GHz, low middle band 1.55–2.7 GHz, high middle band 3.3–4.7 GHz, and high band 5.85–6.425 GHz.

Fig. 2 illustrates the geometry and the dimensions of the example MIMO antenna. The handset consists of two identical antenna elements with four feed ports each. The proposed antenna geometry was selected as it resembles the end piece of a modern mobile phone chassis. The handset is designed to a Preperm L440 substrate with relative permittivity $\varepsilon_r = 4.4$ and low loss tangent $\tan\delta = 5 \times 10^{-4}$. To improve the frequency response in the high band, each antenna element has a horizontal cutout to introduce an alternative current paths.

The number of feeding ports greatly affects the performance of a combinatorially fed antenna. One has to ensure enough different feeding combinations to create adequate number of resonances for covering all the desired frequency bands. On the other hand, large number of ports will increase the complexity and the number of necessary calculations to analyze the antenna. The feeding ports should be located asymmetrically, as symmetrically located ports will create similar, redundant feeding combinations. In this letter, the optimal number of ports for the proposed antenna proved to be four as it is the smallest number of ports, which can provide enough different resonances to cover all the targeted frequency bands.

Resonances of different excitation combinations are tuned by adjusting the locations of the feeding strips in the x-direction (see Fig. 2). Tuning is done by first finding out the active ports or the ports with most significant fraction of power at the frequency of interest and slightly adjusting the location of the strip. The low-band response mainly depends on the overall dimensions of the antenna element and is not affected if cuts of holes are introduced to the antenna structure.

The example antenna geometry can be scaled to produce antennas for different frequency bands. If the low 0.7–0.96 GHz band is omitted, the maximum dimension of an antenna element can be reduced 2.5 times compared to the proposed antenna. Thus, the proposed method is also suitable with higher order MIMO systems that have multiple antennas placed on the sides of a handset similarly to [20].

IV. Results and Discussion

The handset was modeled and simulated with CST Microwave Studio. Due to the symmetry of the handset, results for both antennas are identical. Fig. 3 depicts the simulated S-parameters of a single antenna. The solid lines represent the reflection coefficients of the ports, and the dashed lines represent the coupling between the ports of respective colors. In general, an important factor when designing multiport antennas that utilize weighted feeding is to ensure sufficient coupling between the antenna ports [14]. The S-parameters confirm that the matching of individual ports is rather poor and the coupling between ports is notable.

The optimal feeding combinations are obtained by first applying the weighted feeding to each port combination, and then selecting the combination that produces the best matching at each frequency. In Fig. 4, the dashed lines illustrate the individual matching efficiencies by all possible feeding combinations.

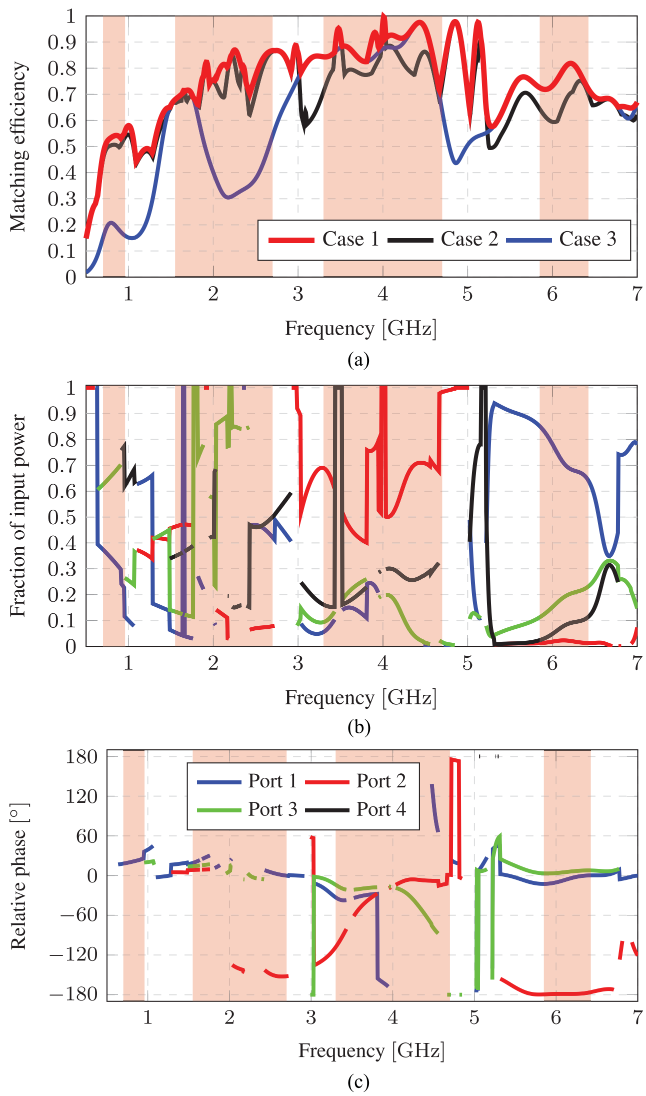

Fig. 5. (a) Matching efficiency in 2 × 2 MIMO. Case 1: Combinatorial feeding. Case 2: the feeds are only switched. Case 3: the feed are only weighted. (b) Antenna weighting coefficients and active ports in case 1. (c) Relative phases between ports. The zero values are omitted for clarity.

The solid black envelope curve denotes the total matching efficiency. By definition, matching efficiency includes both the radiated power and the losses in the material. Nevertheless, due to low-loss materials, the matching efficiency can be approximated as the total efficiency. The instantaneous -3 dB bandwidths of the individual resonances vary between 100 and 800 MHz at frequencies below 4 GHz and the mean bandwidth above 4 GHz is 1.4 GHz.

At frequencies above 4 GHz, the antenna's performance decreases due to the lack of a short resonant current path in the antenna element. Introducing the cutout in Fig. 2 improves the response, but further improving the performance would require even shorter current paths. For comparison, the solid black and blue lines in Fig. 4 illustrate the matching efficiency of the antenna element with and without the cutout, respectively.

First, in case 1, the antenna is fed with combinatorial feeding, i.e., the number of active ports is varied dynamically and the ports are fed with coefficients obtained from (3). Second, in case 2, only the number of active ports is varied, and all ports are fed with equal amplitude and phase. Finally, in case 3, all ports are active, and they are fed with weighting coefficients obtained from (3). In the first case, the antenna reaches near or better than 50% matching efficiency over all specified frequency bands and has better than 90% maximum efficiency. In the case 2, the antenna performance is nearly as good, suggesting that an antenna could be realized utilizing only feed switching. The benefit of such an approach is that the antenna could be also realized without a special transceiver. In contrast to cases 1 and 2, the weighting in case 3 only works well in the middle and high bands where impedance matching and coupling are closest to each other (see Fig. 3). Thus, the best results are obtained when the feed weighting is used to complement the feed switching.

Fig. 5(b) depicts the input power distribution coefficients for a single antenna in case 1. Similarly, Fig. 5(c) displays the required relative phase difference of the feeding signals. For clarity, zero values are not included in the figure. In Fig. 5(b) and (c), same colors are used to mark the same ports. For example, at 0.8 GHz, ports 1 and 3 are used to feed the antenna such that 65% of the total power is fed to port 3 and 35% is fed to port 1. In addition, signal at port 1 has 20° relative phase difference to port 3.

At 0.7 GHz, the loss of matching efficiency in Fig. 5(a) when compared to Fig. 4 is due to coupling between the two antennas on the handset. As explained in [15], the coupling occurs due to short electrical distance between the antennas. Improving the efficiency would require the use of additional decoupling methods, such as neutralization lines [21] or defected ground structures [22], although the practicality of such methods in the proposed application is questionable. In the low middle band, the electrical distance between the antennas increases, and the best performance is obtained in the two middle bands. In the high band, the efficiency is reduced due to the lack of short current path as discussed above. If the two antennas are tuned to different frequencies, the antenna cross coupling decreases, thus improving the matching efficiency toward the ideal case presented in Fig. 4.

V. Conclusion

A novel method for implementing frequency-reconfigurable mobile handset antennas was presented. The method manipulates the number of feeding ports on a multiport antenna to create narrow band resonances that enable high-efficiency operation. In addition, to validate the method, an example antenna design utilizing the proposed method and weighted feeding was introduced. The proposed antenna has simple geometry, and it can be tuned from 0.7 to 7 GHz with close to or better than 50% efficiency in four 5G bands and reaching over 90% maximum efficiency in 2 × 2 MIMO operation. The results suggest that the proposed method could be used to produce wideband antennas with high efficiency for MIMO applications.

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