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Concept for Frequency Reconfigurable Antenna Based on Distributed Transceivers

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***Abstract*—This letter presents a new concept for frequency reconfigurable antennas. The concept involves a multiport antenna, whose elements are mutually coupled. By properly weighting the excitation signals in each port, the total reflected power can be minimized and radiation efficiency maximized. Different frequency components of the transmitter can be weighted differently to obtain broad instantaneous band. The concept is studied by simulations.**

***Index Terms*—Antennas, antenna feeds, frequency control, scattering matrices**

I. Introduction

ANTENNAS continue to have stricter and stricter performance requirements with the advancement of communications technology. The increasing requirements for the data rate of mobile devices require new techniques to achieve, especially considering the scarce availability of the microwave spectrum. A mobile antenna might already have to operate at different frequencies in different countries or for different operators. Carrier Aggregation (CA) requires the antenna to operate in multiple bands simultaneously, e.g., in high and low band. Obtaining efficient operation over all the required frequencies is challenging, especially with the limited volume available for the antenna. It is well known that the limited size has a degrading effect on the bandwidth and efficiency of an antenna [1]–[3].

An antenna does not necessarily have to function at all operating frequencies simultaneously, making it possible to circumvent the bandwidth requirements via frequency reconfigurability. This could be used in mobile phones that operate in different channels or in military applications requiring frequency-hopping. Instead of covering all the operating frequencies simultaneously, only the required channels are covered at a time, reducing the bandwidth requirements. Existing solutions for frequency reconfigurability include matching networks with tunable capacitors [4], [5] and switchable matching networks [6]. These involve having separate matching circuits for the separate frequency bands, and the matching circuit is selected via switching. Multiple matching networks require additional space on the circuit board and also introduce losses to the system. Alternatively, the antenna element itself can be made reconfigurable by modifying the antenna geometry. PIN diodes are commonly used to redirect the flow of the currents in the antenna, therefore modifying the operation [7], [8]. This approach, however, offers only a limited tuning range. There are also no solutions that tune multiple frequency bands independently.

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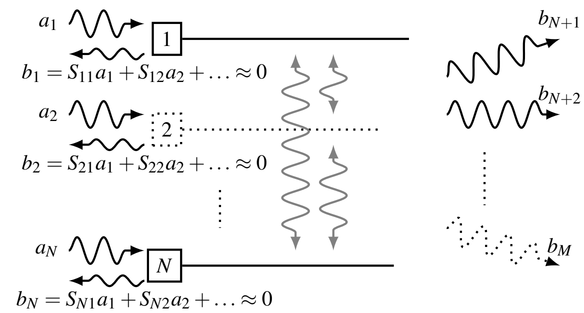

Fig. 1. The antenna concept presented in this letter. The antenna consists of multiple elements that have strong mutual coupling between them. By properly weighting the incident signals a_i in each element, the total reflected power can be minimized and matching efficiency maximized.

We propose a new technique for obtaining efficient operation across a large frequency range. Instead of the antenna system consisting of an antenna connected to a single transceiver, we create the system from several antenna elements and coherent transceivers. The antennas are placed close to each other but instead of trying to avoid the mutual coupling between closely spaced antenna elements, the technique takes advantage of it. The signal to be transmitted is fed to each antenna element, but the signals are weighted differently for each element by modifying the amplitude and phase of each signal. By weighting the feed signals optimally, the reflected signals due to impedance mismatch can be cancelled in all the ports, i.e. the coupled waves interfere destructively with the reflected waves. The weights can be calculated mathematically from the scattering parameters of the antenna. Ideally all the reflected waves are cancelled, resulting in very efficient operation. This concept is illustrated in Fig. 1.

Similar techniques are already used in digital beamforming (DBF) techniques. In these applications, the elements of the array are weighted in specific ways to steer the beam or adjust the polarization [9]. Our proposed technique is similar to these applications, with the difference that we adjust the frequency characteristics of the array. Also, unlike in beamforming, we take advantage of the mutual coupling instead of avoiding it. This makes it possible to fit the antenna elements in a smaller volume. To the best of our knowledge, no earlier study exists on this concept, with the exception of a patent application [10] that has some similarities to this work. However in [10], a multi-feed antenna is used instead of separate antennas and it contains no theory for calculating the feeding weights.

This proposed concept enables frequency reconfigurability and requires much less PCB area than the current adaptive antenna tuners based on switched tuning circuits or tunable components. A drawback of the proposed concept is that it necessitates multiple transceivers instead of one. Nevertheless, integrated circuits are advancing much faster than for instance passive components used for matching and therefore we expect this concept to become feasible. The prevalence of DBF in future wireless systems will also drive this development forward.

In this letter we show a proof-of-concept for the proposed technique and provide the theoretical background for optimizing the operation. We focus mainly on the antenna side of the system, whereas the transceiver side is only conceptual. The letter uses terminology related to transmitting operation of the antenna, but the same principles apply in reverse to reception.

II. Theory

We represent the antenna using a matrix

$$\begin{bmatrix} b_1 \\ \vdots \\ b_N \\ \vdots \\ b_M \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1N} & \cdots & S_{1M} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} & \cdots & S_{NM} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ S_{M1} & \cdots & S_{MN} & \cdots & S_{MM} \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \\ \vdots \\ a_M \end{bmatrix} \quad (1)$$

where subscripts $1 \dots N$ refer to the feed ports and $N + 1 \dots M$ to the far-field modes of the antenna. We want to maximize the power that couples to the far-field modes $b_{N+1} \dots b_M$.

In this letter, we assume the antenna to be lossless for simplified analysis. In the lossless case we can assume that all the power that is not reflected goes to the far field. It is also assumed that there is no power coming from the far field. The problem therefore transforms to minimizing the voltages reflected back to the ports $b_1 \dots b_N$. The matrix of (1) reduces to

$$\mathbf{b} = \begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix} = \mathbf{Sa} \quad (2)$$

which is the scattering matrix of the feed ports of a multiport antenna.

Completely negating the reflected power, i.e. $\mathbf{b} = \mathbf{0}$, would require that $\det \mathbf{S} = 0$, which is not practically achievable. In practice, the reflected power can be made non-zero, but adequately small. To do so, we calculate the matching efficiency η of the antenna, which is the ratio of accepted power P_{acc} and available power P_{av}, as a function of the incident and reflected power waves. Using (2), the efficiency is

$$\eta = \frac{P_{\mathrm{acc}}}{P_{\mathrm{av}}} = \frac{\mathbf{a}^{\mathrm{H}}\mathbf{a} - \mathbf{b}^{\mathrm{H}}\mathbf{b}}{\mathbf{a}^{\mathrm{H}}\mathbf{a}} = \frac{\mathbf{a}^{\mathrm{H}}\mathbf{a} - \mathbf{a}^{\mathrm{H}}\mathbf{S}^{\mathrm{H}}\mathbf{S}\mathbf{a}}{\mathbf{a}^{\mathrm{H}}\mathbf{a}} = \frac{\mathbf{a}^{\mathrm{H}}\mathbf{D}\mathbf{a}}{\mathbf{a}^{\mathrm{H}}\mathbf{a}} \quad (3)$$

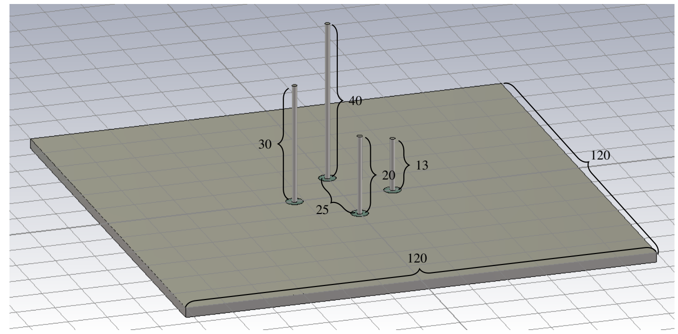

Fig. 2. Simulated antenna model in CST Microwave Studio. The monopoles are fed via coaxial connectors through the ground plane. All dimensions are in millimeters.

where $\mathbf{D} = \mathbf{I} - \mathbf{S}^{\mathrm{H}}\mathbf{S}$ is the dissipation matrix describing the amount of power accepted by the network, i.e. the radiated power, $\mathbf{I}$ is the identity matrix, and $(\cdot)^{\mathrm{H}}$ is the conjugate transpose.

The efficiency is maximized by finding a complex weight vector $\mathbf{a}$ that maximizes (3). Equation (3) is a Rayleigh quotient, for which the largest value is given by the largest eigenvalue of $\mathbf{D}$. This applies to Hermitian matrices, which $\mathbf{D}$ is due to being a product of a scattering matrix and its conjugate transpose. Additionally, the optimal weight vector $\mathbf{a}$ is equal to the eigenvector of $\mathbf{D}$ corresponding to the largest eigenvalue [11].

The scattering parameters themselves can not be used to directly characterize the multiport antenna. An useful parameter for evaluating the multiport system is the total active reflection coefficient (TARC) [12]

$$\mathrm{TARC} = \frac{\sqrt{\mathbf{b}^{\mathrm{H}}\mathbf{b}}}{\sqrt{\mathbf{a}^{\mathrm{H}}\mathbf{a}}} \quad (4)$$

which is the effective reflection coefficient for the entire antenna for a specific excitation. TARC relates to efficiency via the relation

$$\eta = 1 - (\mathrm{TARC})^2 \quad (5)$$

which can be seen directly from (3) and (4).

The antenna design problem becomes a question of designing an antenna with such a scattering matrix that the largest eigenvalue of the $\mathbf{D}$-matrix is maximized at the desired frequencies of operation. The scattering matrix is different at different frequency points and therefore the calculated weights also change with frequency.

III. Simulations

A. Antenna Design

We demonstrate the explained concept using an example antenna structure. The structure consists of four closely spaced monopoles, as illustrated in Fig. 2. The structure resembles an antenna array but unlike in a typical antenna array, each antenna element is different. The assumption for the design is that if none of the antenna elements are matched at the desired frequency, all power is reflected and the mutual coupling cannot be used to compensate for the mismatch. With each element resonating at a different frequencies, there is at least

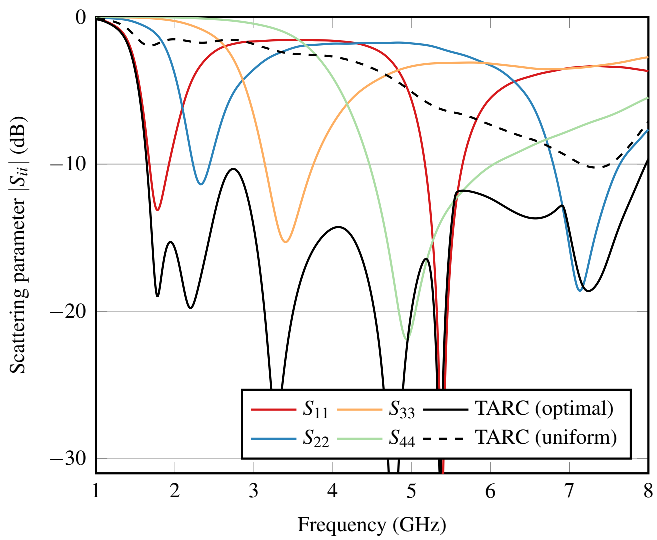

Fig. 3. Obtained TARC with optimized weights. TARC < -10 dB corresponds to a matching efficiency >90 %. The initial scattering parameters $|S_{ii}|$ are shown for comparison.

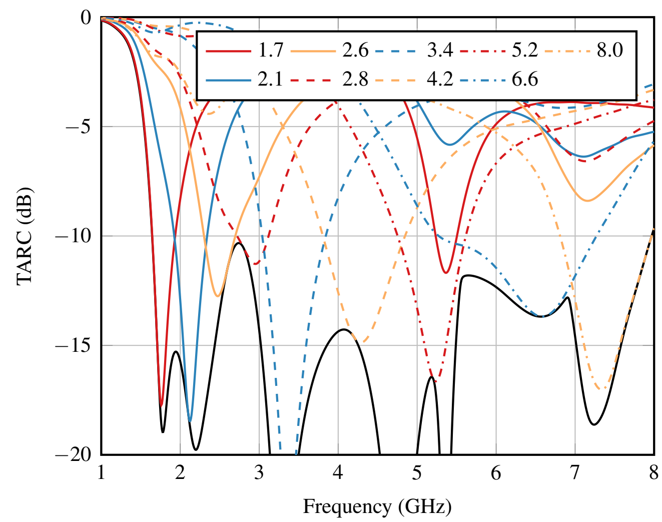

Fig. 4. An example for covering the frequency band from 1.65 to 7.95 GHz, with the criterion TARC < -10 dB. Each curve corresponds to an optimization point (frequency in GHz). The minimum obtainable TARC from Fig. 3, is also shown for reference. The minimum TARC is reached at the optimization points.

some power initially accepted by the antenna. This can then be used to compensate for both the initial mismatch in the other ports and to prevent the power coupling to the ports.

In this simulated example design, we use four elements to obtain frequency reconfigurability over a large continuous frequency band. The design criterion is selected to be $> 90\,\%$ efficiency, corresponding to TARC < -10 dB, over the frequency band 1.5–8 GHz. The diameter of the monopoles is 1.3 mm and the thickness of the ground plane is 2.5 mm. The remaining dimensions of the antenna are shown in Fig. 2. The antennas are fed through $50\,\Omega$ coaxial lines, which are modeled as a typical SMA connector. The lengths of the monopoles are selected in such a way that the resonant frequencies of the elements are spaced across the specified frequency band.

The optimal number of elements is something to consider in future studies. Fewer elements reduce the cost, size, and complexity of the device. A larger number of elements can increase the usable impedance bandwidth.

B. Weight Calculation

Fig. 3 shows the S-parameters corresponding to the reflections (S_{ii}) from the different ports as a function of frequency. Although ports are well-matched at certain frequencies, it is not feasible to use these ports individually because the mutual coupling will reduce the overall efficiency of the individual ports. The weighting coefficients for the simulated multiport antenna are then obtained from (3) using the simulated S-parameters of the antenna. The coefficients are calculated separately for each frequency point. The result is shown in Fig. 3 with TARC calculated from (4). The antenna was designed to obtain a larger than 90 % efficiency over the frequency band of interest. Fig. 3 also shows the importance of proper weighting. With uniform weighting, i.e. all $a_i = 1$, the antenna barely fulfills the design criterion at approximately 7.4 GHz but not at any other frequencies.

Note that the result in Fig. 3 is obtained by optimizing at point frequencies and does not show the instantaneous bandwidth obtainable with a specific signal. This is considered in the next section.

The design problem for this kind of antenna is different from the typical case. Analysing the effects of the different parameters of a 4-by-4 matrix is rather impractical. Nevertheless, several observations can be made from the results. The results suggest that the minimum operating frequency of the antenna is defined by the resonant frequency of the largest antenna element because the TARC corresponds to the scattering parameter in that port. Below 1.65 GHz the TARC can not be made any smaller than S_{11}. This is understandable, considering that all the other ports are completely mismatched at those frequencies. Proper weighting of course compensates for the efficiency reduction caused by the coupling. As such, this gives the required size for the antenna elements for operating at a specific frequency. Based on the initial observations from the simulations, an antenna with a wider bandwidth (with a poorer matching criterion) than one with a sharp resonance seems to function better for this purpose.

The results here focus only on the matching efficiency of the antenna. The radiation efficiency of the antenna is also an important factor. The far-field properties of the antenna will be investigated in future work.

IV. Multiband Operation

The result in Fig. 3 illustrated the minimum obtainable TARC at each frequency point. Each frequency point therefore corresponds to a specific set of weighting coefficients. Optimizing at each frequency point would be inpractical, so it would be preferable to have wider instantaneous bandwidths. The instantaneous bandwidth can be defined using a specific criterion for the matching efficiency, in this case 90 %. Fig.

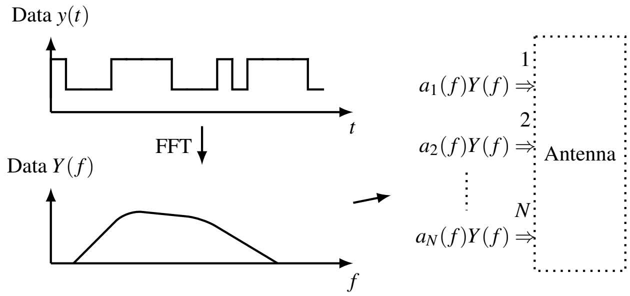

Fig. 5. Obtaining wideband operation. The frequency spectrum of the digital signal is split into several bands and the weights are calculated for each band and antenna element. The weighted signal is then fed to the antenna ports to obtain the wideband operation.

4 shows one example how the frequency band from 1.65 to 7.95 GHz could be covered.

The weighting matches the antenna at the desired frequency, but in some applications it can be necessary to match multiple frequency bands simultaneously. One such example is the inter-band carrier aggregation.

To demonstrate the multiband operation of this antenna concept, let us consider the digital signal to be transmitted, as depicted in Fig. 5. When translated to the frequency domain, the signal appears over a larger frequency band. The spectrum can then be split into several parts corresponding to the coefficients that match the antenna, as was illustrated in Fig. 4. The signal is then fed to the antennas after weighting it individually for each element.

V. Conclusion

In this letter we presented a novel concept for obtaining frequency-reconfigurable antenna operation. The results suggest that efficient frequency reconfigurability is obtainable over a wide bandwidth. The simulated antenna was a proof-of-concept to demonstrate the technique, showing promising results.

We have focused on the aspects related to the antennas. The properties of the front-end are also important in this concept. More research on the system side on the cost and implementation of distributed, coherent IC transceivers is needed. This includes the practical realization of the weighting, such as the design of variable-gain amplifiers and tunable phase shifters.

The antenna itself should also be researched further. How the antenna should be designed. The presented proof-of-concept structure is not practical for many applications. Different antenna structures should be investigated, especially antennas that fit inside a mobile device. Frequency reconfigurability is a needed feature in mobile communications, due to the small sizes of the mobile devices. There is great potential if the technique can be extended to antenna structures that fit inside such a device.

Antenna research questions include, e.g., how the resonance frequencies and the coupling should be designed. Additionally, more detailed analysis on the performance change from adding or removing elements should be performed, such as how many elements are needed to provide sufficient advantage to justify the added complexity.

This letter focused on presenting the concept using simulations to validate our theoretical results. In the future, we will build a prototype and verify the operation in the practical realization. Building a prototype is also important to verify these results in practice. The research on far-field calculations and measurements is also needed, to investigate the effect of the losses in the antenna.

References

[1] L. J. Chu, "Physical limitations of omni-directional antennas," *J. Appl. Phys.*, vol. 19, no. 12, pp. 1163–1175, Dec. 1948.
[2] R. F. Harrington, "Effect of antenna size on gain, bandwidth, and efficiency," *J. Res. Nat. Bur. Stand*, vol. 64, no. 1, pp. 1–12, Jan.–Feb. 1960.
[3] H. Wheeler, "Small antennas," *IEEE Trans. Antennas Propag.*, vol. 23, no. 4, pp. 462–469, Jul. 1975.
[4] J. Ilvonen, R. Valkonen, J. Holopainen, and V. Viikari, "Multiband frequency reconfigurable 4G handset antenna with MIMO capability," *Prog. Electromagn. Res.*, vol. 148, pp. 233–243, 2014.
[5] S. Caporal Del Barrio, A. Tatomirescu, G. Pedersen, and A. Morris, "Novel architecture for LTE world-phones," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1676–1679, 2013.
[6] R. Valkonen, C. Luxey, J. Holopainen, C. Icheln, and P. Vainikainen, "Frequency-reconfigurable mobile terminal antenna with MEMS switches," in *Proc. 4th Eur. Conf. Antennas Propag. (EuCAP)*, Barcelona, Spain, Apr. 2010, pp. 1–5.
[7] Y. Li, Z. Zhang, J. Zheng, Z. Feng, and M. Iskander, "A compact hepta-band loop-inverted f reconfigurable antenna for mobile phone," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 389–392, Jan. 2012.
[8] X.-l. Yang, J.-c. Lin, G. Chen, and F.-l. Kong, "Frequency reconfigurable antenna for wireless communications using GaAs FET switch," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 807–810, 2015.
[9] S. Han, C.-L. I, Z. Xu, and C. Rowell, "Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 186–194, Jan. 2015.
[10] O. Alrabadi, A. Tatomirescu, M. Knudsen, G. Pedersen, M. Pelosi, S. Caporal Del Barrio, P. Olesen, and P. Bundgaard, "Antenna tuning via multi-feed transceiver architecture," U.S. Patent Application 20 140 062 813, Mar. 6, 2014.
[11] C. Volmer, J. Weber, R. Stephan, K. Blau, and M. Hein, "An eigen-analysis of compact antenna arrays and its application to port decoupling," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 360–370, Feb. 2008.
[12] M. Manteghi and Y. Rahmat-Samii, "Multiport characteristics of a wide-band cavity backed annular patch antenna for multipolarization operations," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 466–474, Jan. 2005.