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Method to Dynamically Optimize MIMO Throughput of Coupled Tunable Antennas

Vivek Bharambe

Matthew Slater

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Abstract:

Many wireless communication standards (4G LTE, 5G NR, Wi-Fi, etc.) can leverage multiple antennas within a device through multiple-input multiple-output (MIMO) communication protocols. Antenna tuners are often used to tune the individual antennas for various transmission and reception characteristics. Traditional means of tuning the antennas, however, do not account for coupling between the antennas. Often, MIMO antennas are packaged within proximity of each other due to tight packaging constraints in modern electronic devices. In these types of coupled MIMO systems, maximum throughput is achieved when the coupling between the antennas is accounted for, even though a single antenna may not be optimized. By utilizing a signal-to-noise (SNR) matrix that includes coupling terms between the antennas to determine tuning parameters, the MIMO antennas can be dynamically optimized as a system rather than individual tunable antennas.

Keywords:

Wireless network, MIMO, antenna tuning, Wi-Fi, Bluetooth, 4G LTE, 5G NR, SNR matrix, antenna coupling, antenna loading.

Background:

As MIMO systems in wireless communication devices become more common, so too does the need to optimize such systems. While conventional techniques may be able to tune multiple antennas individually, there is currently no way to account for coupling between the antennas in a MIMO system. Antenna coupling becomes significant within modern electronic devices and can reduce overall throughput of the MIMO system if not accounted for when tuning the antennas.

Description:

A MIMO system enables an electronic device to leverage multiple antennas to increase downlink throughput. An example MIMO system using two antennas is shown in Figure 1.

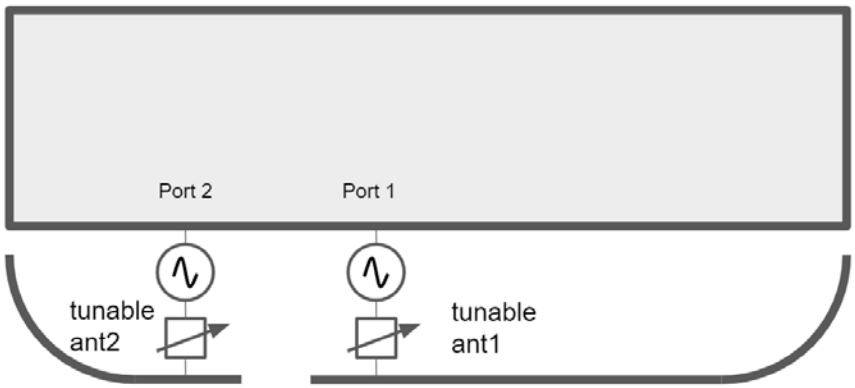

Figure 1. Typical cellular antenna layout on one end of the device showing two strongly coupled antennas

While traditional techniques may be able to tune the respective antennas individually, when a coupling exists (as in the example above where the antennas are within proximity of each other), individual antenna tuning often does not provide the best throughput for the system. By optimizing the antennas as a system, however, the overall throughput can be optimized, even though a single antenna may not be optimized. To do so, this publication describes ways to dynamically infer tuning parameters for the system of antennas based on impedance measurements of only the transmit antenna.

Equations:

The overall throughput of a MIMO system is related proportionally to the log of the determinant of the Signal-to-Noise (SNR) matrix:

$$C \propto \log_2(\ |I + SNR|)$$

where I is the identity matrix and the SNR matrix, assuming a constant noise environment, contains antenna gains and mutual coupling terms.

For a two-antenna system, such as in Figure 1, the SNR matrix is given by:

$$[SNR] = \frac{1}{N}\begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$$

where N is the noise power, P_{11} and P_{22} are the powers radiated by antenna 1 and antenna 2, and P_{12} and P_{21} are the powers delivered between antennas. P_{11} and P_{22} are related to the antenna efficiency and return losses of each antenna. To maximize the determinant of the matrix [I+SNR] and, thus, system throughput, P_{11} P_{22} must be maximized, while simultaneously minimizing P_{12} and P_{21}.

P_{11} and P_{22} can be calculated with the help of input powers P_{in1}, P_{in2}, the antenna efficiencies η_1, η_2 and the reflection coefficients:

$$P_{11} = P_{in1}\eta_1\left|1 - \Gamma_{in1}^2\right|$$
$$P_{22} = P_{in2}\,\eta_2\left|1 - \Gamma_{in2}^2\right|$$

where Γ_{in1} and Γ_{in2} are the reflection coefficients looking into the respective antennas.

The other terms $|P_{12}|$ and $|P_{21}|$ can be calculated by:

$$|P_{12}| = \left|\sqrt{P_{11}P_{22}}\left(S_{11}^*S_{12} + S_{21}^*S_{22}\right)\right|$$
$$|P_{21}| = \left|\sqrt{P_{11}P_{22}}\left(S_{22}^*S_{21} + S_{12}^*S_{11}\right)\right|$$

where the S terms denote terms of the coupling matrix (see derivation below). If the other port is perfectly matched or if the antennas are not coupled, S_{11} and S_{22} are equivalent to Γ_{in1} and Γ_{in2}. In this case, however, the antennas are coupled and not perfectly matched all the time, thus S_{11} and S_{22} must be determined.

These equations show that all elements of the SNR matrix are a function of antenna tuning. The efficiency terms (P_{11} and P_{22}) can be optimized using conventional antenna open- or closed-loop tuning schemes, but to achieve the best throughput, the coupling terms must also be optimized. The input impedance of the transmitting antenna is known in real-time very accurately using traditional closed-loop feedback.

Procedure:

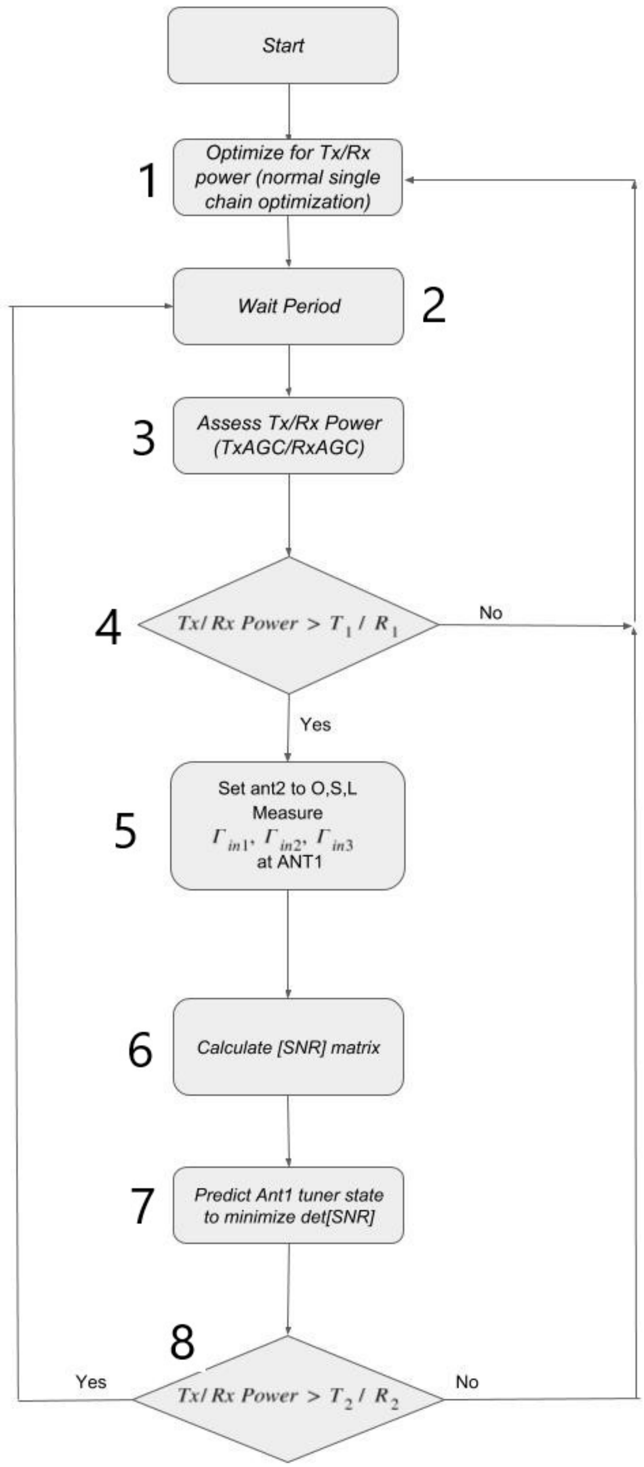

Figure 2. The flowchart for the dynamic MIMO throughput optimization algorithm.

The following procedure refers to the flowchart of Figure 2.

At step 1, under normal operation, the method optimizes the Ant1 and Ant2 tuners for single chain operation to improve total radiated power (TRP) for transmission (Tx) and total isotropic sensitivity (TIS) for receiving (Rx), using traditional closed-loop tuning.

At step 2, the method proceeds to enter the wait state with a programmable wait period.

At step 3, the device then assesses the Tx/Rx power using transmission automatic gain control (TxAGC) and reception automatic gain control (RxAGC).

At step 4, the Tx/Rx power is then compared to two programmable thresholds: $T_1/\ R_1$ and $T_2/\ R_2$ for the Tx/Rx power, respectively.

a. If Tx/Rx > T_2, then the antenna Tx and Rx powers are acceptable and meet the relevant carrier specifications (with some buffer margin). In this case, the throughput optimization steps are skipped, and the method returns to step 1.
b. If Tx/Rx >T_1, then the antenna Tx/Rx powers are higher than the carrier specifications and can likely be traded off to improve MIMO throughput performance, e.g., Ant 1 and Ant 2 tuner can be tuned to reduce Tx/Rx power. In this case, the method proceeds to step 5.

At step 5, Ant2 tuner is set to present an Open, Short and matched load (50 Ω impedance) termination to the Ant 2 and the corresponding reflection coefficients Γ_{in1}, Γ_{in2}, Γ_{in3} are measured at Ant 1.

At step 6, the SNR matrix is built based on the reflection coefficients (see derivation below). The magnitude and the phase of S_{12} and S_{22} are related to the coupling between the two antennas.

At step 7, the Ant1 tuner state is determined based on the Ant1 tuner state causing a maximization of the determinant of the SNR matrix.

At step 8, after changing the Ant1 tuner state (step 7), the method assesses Tx/Rx power and compares it with the thresholds defined in step 4.

c. If Tx/Rx > T_2, the method returns to step 1.

d. If Tx/Rx < T_2, the method returns to step 2 and optimizes the Tx/Rx power.

The above antenna optimization method can be performed on the device dynamically, and the method is effective for any of the standard antenna loading cases, e.g., Free Space condition, Behind Left/ Right Hand conditions, Behind Head condition, and Hand Left/Right conditions. The method can dynamically determine antenna parameters, e.g., tuning states, that incorporate antenna tuning and loading characteristics without pre-characterization. Accordingly, maximum throughput may be achieved in a variety of situations by looking at the antennas as a system (including coupling between antennas) instead of merely optimizing the respective individual antennas.

Equation Derivation:

Figure 3 is a schematic of the example system of Figure 1 showing reference planes for the dynamic measurements for Ant1 and Ant2 and the basis for the derivations shown below.

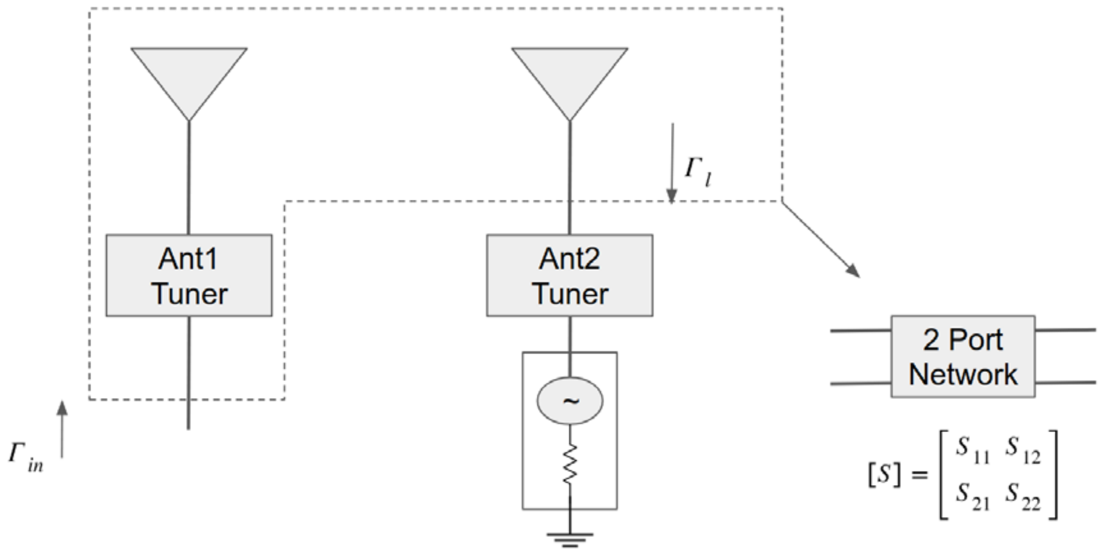

Figure 3. Reference planes for the derivation of coupling terms

$$\Gamma_{in} = S_{11} + \frac{S_{12} S_{21} \Gamma_l}{1 - S_{22} \Gamma_l} \quad [1]$$

For a passive two port network, $S_{12} = S_{21}$

$$\Gamma_{in} = S_{11} + \frac{S_{21}^2 \Gamma_l}{1 - S_{22} \Gamma_l} \quad [2]$$

If Port 2 is matched, i.e. $\Gamma_l = 0$

$$\Gamma_{in_1} = S_{11} \quad [3]$$

If Port 2 is short circuited, i.e. $\Gamma_l = -1$

$$\Gamma_{in_2} = S_{11} - \frac{S_{21}^2}{1+S_{22}}$$

$$\Gamma_{in_2} = \Gamma_{in_1} - \frac{S_{21}^2}{1+S_{22}}$$

$$\Gamma_{in_2} - \Gamma_{in_1} = -\frac{S_{21}^2}{1+S_{22}}$$

$$\left(\Gamma_{in_2} - \Gamma_{in_1}\right)\left(1+S_{22}\right) = -S_{21}^2$$

[4]

If Port 2 is open circuited, i.e. $\Gamma_l = 1$,

$$\Gamma_{in_3} = S_{11} + \frac{S_{21}^2}{1-S_{22}}$$

$$\Gamma_{in_3} = \Gamma_{in_1} + \frac{S_{21}^2}{1-S_{22}}$$

$$\Gamma_{in_3} - \Gamma_{in_1} = \frac{S_{21}^2}{1-S_{22}}$$

$$\left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(1-S_{22}\right) = S_{21}^2$$

[5]

Combining equations [4] and [5]:

$$-\left(\Gamma_{in_2} - \Gamma_{in_1}\right)\left(1+S_{22}\right) = \left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(1-S_{22}\right)$$

$$\left(\Gamma_{in_1} - \Gamma_{in_2}\right)\left(1+S_{22}\right) = \left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(1-S_{22}\right)$$

$$\Gamma_{in_1} - \Gamma_{in_2} + S_{22}\Gamma_{in_1} - S_{22}\Gamma_{in_2} = \Gamma_{in_3} - \Gamma_{in_1} - S_{22}\Gamma_{in_3} + S_{22}\Gamma_{in_1}$$

$$2\Gamma_{in_1} - \Gamma_{in_2} - \Gamma_{in_3} = S_{22}\left(\Gamma_{in_2} + \Gamma_{in_3}\right)$$

$$\frac{\left(2\Gamma_{in_1} - \Gamma_{in_2} - \Gamma_{in_3}\right)}{\left(\Gamma_{in_2} + \Gamma_{in_3}\right)} = S_{22}$$

[6]

Substituting equation [6] into equation [5]:

$$\left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(1 - \frac{2\,\Gamma_{in_1} - \Gamma_{in_2} - \Gamma_{in_3}}{\Gamma_{in_2} - \Gamma_{in_3}}\right) = S_{21}^2$$

$$\left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(\frac{\Gamma_{in_2} - \Gamma_{in_3} - 2\,\Gamma_{in_1} + \Gamma_{in_2} + \Gamma_{in_3}}{\Gamma_{in_2} - \Gamma_{in_3}}\right) = S_{21}^2$$

$$\left(\frac{2\left(\Gamma_{in_3} - \Gamma_{in_1}\right)\left(\Gamma_{in_2} - \Gamma_{in_1}\right)}{\left(\Gamma_{in_2} - \Gamma_{in_3}\right)}\right) = S_{21}^2 \qquad [7]$$

Conclusion:

The techniques described in this publication tune respective MIMO antennas as a system rather than individually. By doing so, an overall throughput can be optimized, even though a single antenna may not be optimized. Tuning parameters, e.g. antenna tuning states, are dynamically inferred for the system of antennas without pre-characterization based on impedance measurements of only the transmit antenna. Accordingly, maximum throughput may be achieved in a variety of situations by looking at the antennas as a system (including coupling between antennas) instead of merely optimizing the respective individual antennas.