# *Chapter 2*
# Systematic Generation of *All* Elementary Wide-Band Amplifiers

## 2.1 Introduction

Designers, generally conceive new amplifier circuits by exploiting their creativity, insight and experience. As this is a largely unstructured process, it is unlikely that *all* the useful amplifier alternatives are found. In contrast, this chapter describes a radically different approach that generates a*ll* potentially useful alternatives to well-known elementary wide-band amplifiers like the common-gate and the common-source shunt-feedback stage. This is done by defining a methodology that generates systematically *all* the two-port amplifiers that can be modelled as circuits with 2 Voltage Controlled Current Sources (VCCS). Important reasons to exploit a VCCS as circuit generating element are:

- The small-signal operation of a MOSFET -in saturation- is essentially that of a linear VCCS element "I=g·V" with "g" equal to the device transconductance "$g_m$". This simplified model is valid for frequencies where the non quasi-static effects of the device are negligible [1]: up to tens of GHz for a deep sub-micron CMOS process.
- Commonly used elementary amplifiers [2] such as the common gate, common drain and the common source shunt-feedback stages exploit the "$g_m$" of a MOST to define their small-signal transfer properties like gain and port impedances. Their functional behaviour is adequately represented when regarding them as circuits with 1 VCCS or with 2 VCCSs (i.e. 1VCCS or 2VCCS circuits).
- Several different transistor circuits are automatically covered because a 4-terminal VCCS plus extra interconnections can model any combinations of MOSFETs and resistors acting as a transconductor circuit as well as a simple resistor as illustrated in figure 2.1.

Furthermore, at least 2 VCCSs are required in order to provide voltage (or current) gain larger than one. Next, as will become clear later in this chapter, the use of only 2VCCS means that the achievements of previous work can be directly exploited.

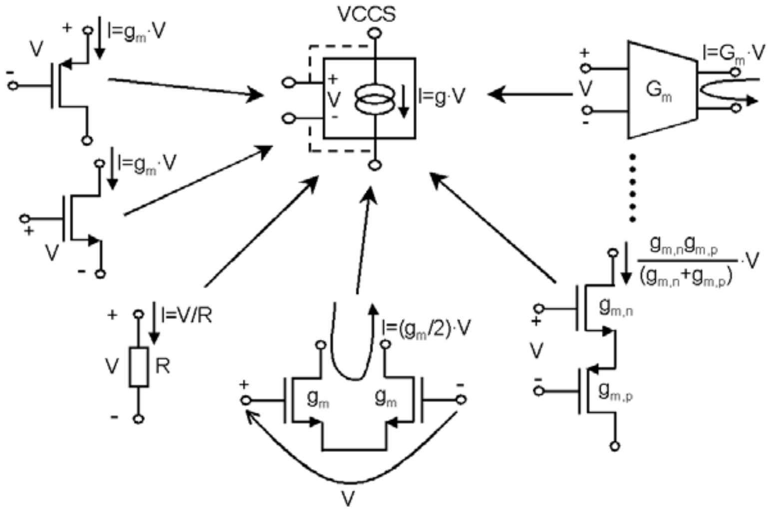


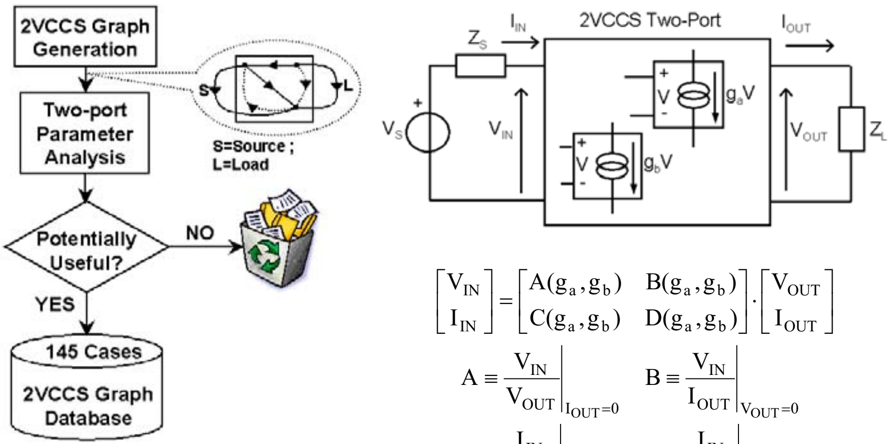

**Figure 2.1:** A VCCS can model a single MOSFET, a single resistor or any transconductor circuit.

## 2.2 The Systematic Generation Methodology

As previously mentioned, the aim of this chapter is to find all the potentially useful alternatives to well-known elementary wideband amplifiers by generating systematically all the two-port amplifiers that can be seen as circuits with 2 VCCSs. In previous work of Klumperink [3,4,5], all the graphs of potentially useful two-port circuits built by the interconnection of 2 VCCSs were systematically generated, classified in terms of their properties and stored in a database: the *2VCCS graph database*. This research starts from the fact that all the graphs of 2VCCS wideband amplifiers must be a sub-set of the 2VCCS database. In order to find them all, a systematic selection procedure will be described. In the next sub paragraph, the generation of the 2VCCS database and its properties are briefly reviewed. More details can be found in [3, 4, 5 and appendix D]. Following, the systematic selection of all the graphs of 2VCCS wideband amplifiers is described in detail.

### 2.2.1 2VCCS graphs database: generation and properties [3, 4 and 5]

The flow chart in figure 2.2a describes the steps leading to the generation of the 2VCCS graph database. In facing the problem of how to generate all the topologies of two-port circuits with 2 VCCSs a complexity issue pops up immediately. Since a VCCS has 4 terminals, a lot of circuits are possible interconnecting two of them (i.e. $VCCS_a$ and $VCCS_b$). This is evident even if one considers the simple case of a two-port connected between a voltage source $V_S$ with impedance $Z_S$ and load impedance $Z_L$ (figure 2.2b).




$$\begin{bmatrix} V_{IN} \\ I_{IN} \end{bmatrix} = \begin{bmatrix} A(g_a, g_b) & B(g_a, g_b) \\ C(g_a, g_b) & D(g_a, g_b) \end{bmatrix} \cdot \begin{bmatrix} V_{OUT} \\ I_{OUT} \end{bmatrix}$$

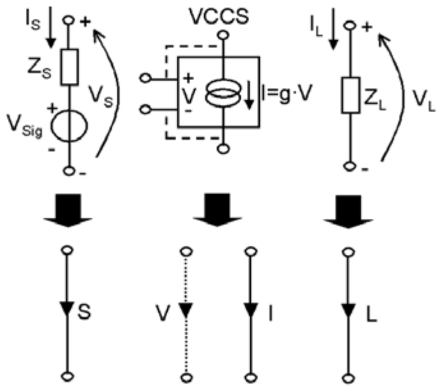
$$A \equiv \left.\frac{V_{IN}}{V_{OUT}}\right|_{I_{OUT}=0} \qquad B \equiv \left.\frac{V_{IN}}{I_{OUT}}\right|_{V_{OUT}=0}$$

$$C \equiv \left.\frac{I_{IN}}{V_{OUT}}\right|_{I_{OUT}=0} \qquad D \equiv \left.\frac{I_{IN}}{I_{OUT}}\right|_{V_{OUT}=0}$$

a) b)

**Figure 2.2:** a) Flow chart describing the steps leading to the generation of the 2VCCS database b) A 2VCCS two-port circuit described by {A, B, C, D} parameters. The latter are a function of the transconductances $g_a$ and $g_b$ of the 2 VCCSs (i.e. $VCCS_a$ and $VCCS_b$).

This issue was successfully solved [3, 4, 5] by considering that the connectivity among VCCSs can be efficiently studied representing the VCCS by a graph with a “V” and “I” branch as shown in figure 2.3a. The graphs of the source “S” and the load “L” are also shown. Graph theory could then be applied in order to generate systematically all the possible graphs of 2VCCS circuits avoiding to find the same one twice. This rendered 16000 2VCCS graphs! The small-signal properties of two-port circuits of these graphs were then analysed looking at their two-port parameters. To this purpose, {A, B, C, D} transmission parameters (see their definition in figure 2.2b) were preferred to other types of parameters because they are related to the transfers of a two-port: A=1/VoltageGain, B=1/Transconductance, C=1/Transimpedance and D=1/CurrentGain. If potentially useful 2VCCS graphs have at least *one non-zero* {A, B, C, D} parameter, we are left with only 145 graphs, which are stored in a database. Figure 2.3b gives an overview of the combinations of {A, B, C, D} parameters in the 2VCCS database, revealing a great deal of cases. Possible expressions for the {A, B, C, D} parameters as a function of the transconductances $g_a$ and $g_b$ of the 2 VCCSs and the number of graphs are indicated. In the next paragraph, the information in figure 2.3b will be used to select all graphs of wideband amplifiers in the 2VCCS database.




a)

| CASE | A | B | C | D | Nr. |
|---|---|---|---|---|---|
| {A} | 1 | 0 | 0 | 0 | 3 |
| {B} | 0 | $1/g_1$ | 0 | 0 | 37 |
| {D} | 0 | 0 | 0 | 1 | 2 |
| {AB} | 1 or $g_1/g_2$ | $1/g_3$ | 0 | 0 | 24 |
| {AD} | 1 | 0 | 0 | 1 | 6 |
| {BC} | 0 | $1/g_1$ | $g_2$ | 0 | 2 |
| {BD} | 0 | $1/g_1$ | 0 | 1 or $g_2/g_3$ | 24 |
| {ABC} | 1 or $g_1/g_2$ | $1/g_3$ | $g_4$ | 0 | 3 |
| {ABD} | 1 or $g_1/g_2$ | $1/g_3$ | 0 | 1 or $g_4/g_5$ | 24 |
| {ACD} | 1 | 0 | $g_1$ | 1 | 9 |
| {BCD} | 0 | $1/g_1$ | $g_2$ | 1 or $g_2/g_3$ | 4 |
| {ABCD} | 1 or $g_1/g_2$ | $1/g_3$ | $g_4$ | 1 or $g_5/g_6$ | 7 |

b)

**Figure 2.3:** a) The VCCS, the source $V_S$ and the load impedance $Z_L$ represented via graphs: “V” and “I” branch for the VCCS, “S” branch for the source and a “L” branch for the load b) Combinations of {A, B, C, D} parameters available in the 2VCCS database. Parameter expressions as a function of $g_a$ and $g_b$ and number of graphs (Nr.) are shown.

## 2.3 Functional Selection of All Elementary Wide-Band Amplifiers

This paragraph describes the basic idea exploited to select all the graphs of wideband amplifiers within the 2VCCS database. In general, the input impedance $Z_{IN}$, output impedance $Z_{OUT}$, forward voltage gain $A_{VF}$ and reverse voltage gain $A_{VR}$ of any linear two-port circuit is a function of the two-port parameters, the source impedance $Z_S$ and the load impedance $Z_L$. This is shown by the following two-port equations using {A, B, C, D} parameters:

$$Z_{IN} = \frac{Z_L A + B}{Z_L C + D} \qquad Z_{OUT} = \frac{Z_S D + B}{Z_S C + A}$$
$$A_{VF} \equiv \frac{V_{OUT}}{V_{IN}} = \frac{Z_L}{Z_L A + B} \qquad A_{VR} \equiv \frac{V_{IN}}{V_{OUT}} = \frac{AD - BC}{D + B/Z_S} \tag{2.1}$$

Equations (2.1) show that ports impedance (i.e. $Z_{IN}$, $Z_{OUT}$) and gains (i.e. $A_{VF}$ and $A_{VR}$) are univocally determined by the {A, B, C, D} parameters, $Z_S$ and $Z_L$ as shown in figure 2.4a.

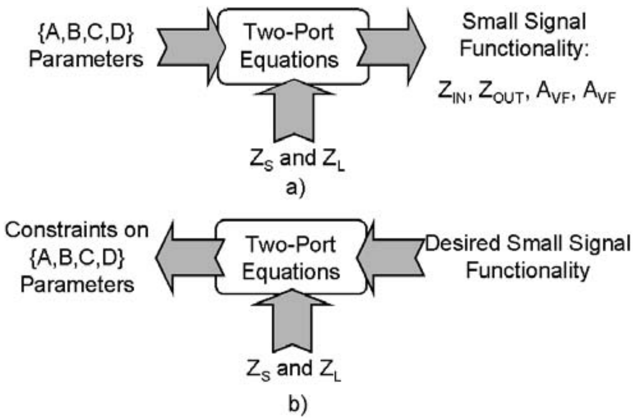



**Figure 2.4:** a) {A, B, C, D} parameters plus $Z_S$ and $Z_L$ determine the two-port small-signal functionality. b) Graphs of 2VCCS wideband amplifiers are selected using the reverse reasoning: the desired amplifier functionality is traduced into constraints on the {A, B, C, D} parameters upon assigned $Z_S$ and $Z_L$. These constraints are the criteria to select useful graphs within the 2VCCS database.

The procedure developed to select systematically all the graphs of 2VCCS wideband two-port amplifiers exploit the reverse reasoning indicated in figure 2.4b. In this case, the behaviour of a wideband two-port amplifier is first defined in terms of proper *functional* requirements, which are then translated into constraints for the {A, B, C, D} parameters of two-port circuits. To do so, equations (2.1) are exploited upon properly defined source and load impedance. The derived constraints are finally used as criteria to select graphs of wideband amplifiers in the 2VCCS database. This selection procedure has been implemented into the 4-step procedure described in the flowchart of figure 2.5.

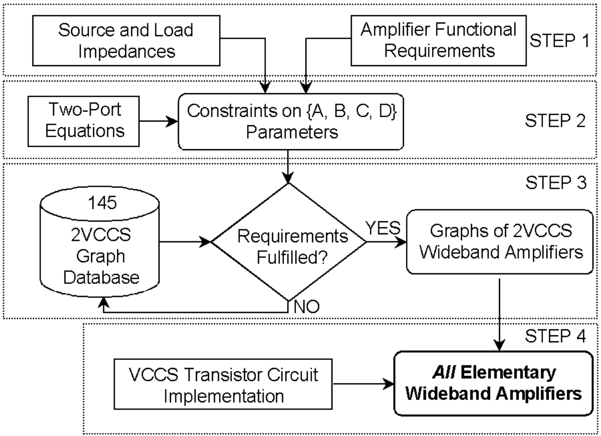



**Figure 2.5:** Flowchart of the systematic selection of all the elementary two-port amplifiers.

The procedure proceeds as follows:

**STEP1:** Amplifier high-level functional requirements and source/load impedances suitable for highly integrated CMOS receivers are defined.

**STEP2:** The information of STEP1 is translated into constraints for the {A, B, C, D} parameters of two-port amplifiers.

**STEP3:** Graphs of two-port circuits that meet these constraints are selected within the 2VCCS database.

**STEP4:** MOS transistor circuits of the selected graphs are provided.

In the next sections, the above steps are described.

## 2.3.1 STEP1: Source/load impedance and functional requirements

Source/load impedance and the amplifier functional requirements crucially determine the output of the generation methodology. For a wideband amplifier to be used in the receiver front-end of a modern communication system, the following assumptions about the source impedance $Z_S$ and load impedance $Z_L$ are made:

- The source impedance $Z_S$ is *real*: $Z_S=R_S$. This choice is motivated by the fact that the off-chip signal source represents either a coaxial cable terminated on its characteristic impedance or a discrete RF filter, which also provide a real output impedance (at least within a specified range of frequencies). Typical values of $R_S$ are 50Ω and 75Ω.
- The load impedance $Z_L$ is *capacitive*: $Z_L=1/(j\omega C_L)$. This choice is dictated by the realization of highly integrated receivers exploiting architectures with a minimum

number of external components. In this respect, zero-IF and low-IF receivers are the most indicated solutions [6, 7]. In these architectures, the front-end amplifier is directly loaded by the following on-chip frequency mixer (i.e. the external image rejection filter is not required). In principle, the choice of the input impedance of the mixer is a degree of freedom. In practice, commonly used active mixer circuits (i.e. the so-called Gilbert-type mixer) provide capacitive input impedance [6, 7].

The following requirements on the functionality of a wide-band amplifier are important:

- **Gain.** The amplifier must provide sufficient forward voltage gain: $|A_{VF}|>1$. This is required in order to boost a weak input signal above the generally high input noise-floor of the following frequency mixer. Moreover, the reverse gain $A_{VR}$ must be low enough to isolate the amplifier input from any undesired signal injected at its output.
- **Source impedance matching.** The amplifier input impedance must match the source impedance $R_S$: $Z_{IN}=R_S$[IV]. Incorrect termination of a coaxial cable leads to signal reflections that can cause destructive interference at the amplifier input. Incorrect termination of the RF filter preceding the amplifier leads to alterations of its transfer characteristics such as in-band ripples (even notches) and poorer out-band attenuation [8]. Signal reflections and in-band ripples degrade the receiver sensitivity while poorer out-band attenuation leads to receiver overloading.
- **Stability.** The amplifier must be stable at all the frequencies and upon all operating conditions. This includes (a) device parameter variations due to process-spread and temperature, (b) inaccurate or lacking modelling for the active devices, substrate underneath, IC package, and source/load impedances and (d) large signal operation. To cope with these issues, unconditional stability is typically required, which provides the safest degree of stability [9].
- **Frequency behaviour.** The frequency response of an amplifier is assumed wide-band if its transfer functions are frequency-independent in $[f_l, f_l+BW]$ and the ratio between the bandwidth BW and its middle frequency, $BW/(f_l+BW/2)$, can be as large as 2.

A step-up 1:n transformer with a resistive output termination equal to $n^2 \cdot R_S$ meets the above requirements (i.e. $Z_{IN}=R_S$, $A_{VF}=n$ and $A_{VR}=1/n$). However, transformers are not considered because they require a large area while their wide-band performance is typically poor, especially in CMOS processes, and anyhow at frequencies below one GHz.

[IV] A certain mismatch is tolerated. Typical values of $|\Gamma_{IN}|=|(Z_{IN}-R_S)/(Z_{IN}+R_S)|$ are from –8dB to –10dB.

### 2.3.2 STEP2: Constraints on the two-port {A, B, C, D} parameters

In this section, general constraints for the {A, B, C, D} parameters of two-port circuits are derived using the defined functional requirements and equations (2.1). Two types of constraints are distinguished: 1) on the allowed combinations of {A, B, C, D} parameters and 2) on the value of the non-zero {A, B, C, D} parameters.

**Allowed combinations of {A, B, C, D} parameters.** The two-port equations (2.1) suggest that not all the combinations of {A, B, C, D} parameters can be used to implement the functionality of a wideband amplifier. In table 2.1, expressions for the two-port input impedance $Z_{IN}$ and the forward gain $A_{VF}$ are given for all the combinations of {A, B, C, D} parameters. All two-ports with one non-zero transmission parameter and two-ports {AB} and {CD} are useless for our purposes because they render a $Z_{IN}$ that is either 0 or ∞. For the remaining cases, further selection is done analysing the qualitative behaviour of $Z_{IN}$ and $A_{VF}$ versus frequency due to $Z_L=1/(j\omega C_L)$ as shown in figures 2.6a and 2.6b. For instance, two-ports {AD} and {BC} are useless as their $Z_{IN}$ is imaginary and strongly frequency-dependent through $Z_L$ (i.e. integrative and derivative frequency behaviour, see also table 2.1). For the remaining two-port cases {{AC}, {AB}, {BD}, {ABC}, {ABD}, {ACD}, {BCD}, {ABCD}}, a wide range of frequencies [$f_l$, $f_l$+BW] can be found in figure 2.6a, where a real $Z_{IN}$ can be made equal to $R_S$. However, cases {{BD}, {BCD}} are rejected because their gain $A_{VF}$ has an integrative response (figure 2.6b). Case {ABD} is rejected because it leads to conflicting demands on $Z_{IN}$ and $A_{VF}$ (i.e. from table 2.1, a wideband $Z_{IN}$ is requires $|Z_L \cdot A| << |B|$ while a wideband $A_{VF}$ requires $|Z_L \cdot A| >> |B|$). Ultimately, wideband two-port amplifiers must have one of the following combinations of non-zero {A, B, C, D} parameters: {{AC}, {ABC}, {ACD}, {ABCD}}. Note as parameters "A" and "C" are always present. This is not surprising because a two-port with parameters {AC} represents the ideal model of the desired wideband amplifier: $Z_{IN}=A/C$, $A_{VF}=1/A$, $Z_{OUT}=0$ and $A_{VR}=0$ (figure 2.7). In this respect, two-ports {{ABC}, {ACD}, {ABCD}} are just approximation of {AC}.

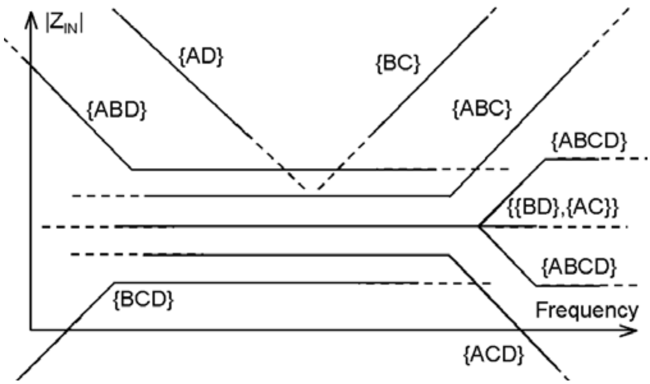
**Value of the non-zero {A, B, C, D} parameters.** Constraints on the value of {A, B, C, D} parameters are found from the gain and stability requirements. Using equations (2.1), the gain $A_{VF}$ of a two-port circuit with load impedance $Z_L=1/(j\omega C_L)$ can be written as:

$$A_{VF}=\frac{Z_L}{Z_L\cdot A+B} \quad \Rightarrow \quad |A_{VF}|=\frac{1}{|A+j\omega C_L B|}\leq\frac{1}{|A|} \quad ,\forall\omega \tag{2.2}$$

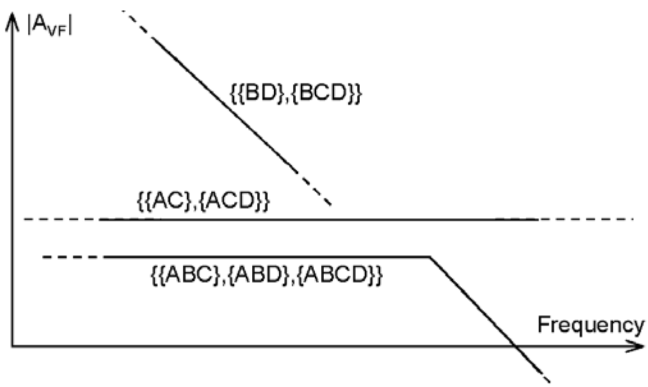
From (2.2), $|A_{VF}|>1$ requires a transmission parameter "A" such that $|A|<1$ holds.

| Case | $Z_{IN}$ | $A_{VF}$ | $Z_{OUT}$ | $A_{VR}$ | USEFUL |
|---|---|---|---|---|---|
| {A}, {B},{AB} | $\infty$ | - | - | - | NO |
| {C}, {D},{CD} | 0 | - | - | - | NO |
| {AC} | A/C | 1/A | 0 | 0 | YES |
| {AD} | $Z_L(A/D)$ | 1/A | - | - | NO |
| {BC} | $(B/C)/Z_L$ | $Z_L/B$ | - | - | NO |
| {BD} | B/D | $Z_L/B$ | - | - | NO |
| {ABC} | $(A/C)+(B/C)/Z_L$ | $1/(A+B/Z_L)$ | $B/(Z_SC+A)$ | $-Z_SC$ | YES |
| {ABD} | $(B/D)+Z_L\cdot(A/D)$ | $1/(A+B/Z_L)$ | - | - | NO |
| {ACD} | $(A/C)/(1+D/(Z_LC))$ | 1/A | $Z_S/(Z_SC+A)$ | A | YES |
| {BCD} | $B/(Z_L\cdot C+D)$ | $Z_L/B$ | - | - | NO |
| {ABCD} | $(A+B/Z_L)/(C+D/Z_L)$ | $1/(A+B/Z_L)$ | $(Z_SD+B)/(Z_SC+A)$ | $(AD-BC)/(D+B/Z_S)$ | YES |

**Table 2.1:** Two-port transfer functions for different combinations of non-zero {A, B, C, D} transmission parameters (notation {BD} refers to two-ports parameters {0, B, 0, D}). Expressions that are not useful to the selection process are indicated by '-'.




a)




b)

**Figure 2.6:** Qualitative behaviour of $Z_{IN}$ a) and $A_{VF}$ b) versus frequency for $Z_L=1/(j\omega C_L)$ and for different combinations of non-zero {A, B, C, D} parameters.

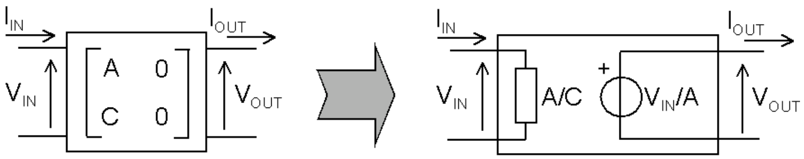



**Figure 2.7:** A two-port circuit with parameters {A, 0, C, 0}.

In RF and microwave amplifier design, it is a common practice to require the two-port stability to be unconditional [9]. The latter, means that the amplifier is stable for any value of the passive source and load terminations. Necessary and sufficient conditions for the unconditional stability of a linear two-port circuit are:

$$\Re\{Z_{IN}\} > 0 \quad \text{and} \quad \Re\{Z_{OUT}\} > 0 \qquad \forall\, Z_L \quad \forall\, \omega \tag{2.3-a}$$

Where $\Re$ is the real part of $\{\cdot\}$. Conditions (2.3a) are equivalent to [10]:

$$\Re\{Z_{IN}\} > 0 \quad \text{and} \quad \Re\{Z_{22}\} > 0 \qquad \forall\, Z_L \quad \forall\, \omega \tag{2.3-b}$$

Where $Z_{22}$ is the output impedance when the two-port input is left open. Relations (2.3b) can be rewritten in terms of {A, B, C, D} parameters as:

$$\begin{aligned} \Re\{Z_{IN}\} &= \Re\left\{\frac{Z_L A + B}{Z_L C + D}\right\} > 0 \\ \Re\{Z_{22}\} &= \frac{D}{C} > 0 \qquad \forall Z_L \quad \forall\omega \end{aligned} \tag{2.4}$$

It can be shown (see appendix A) that necessary and sufficient conditions to meet relations (2.4) are that *all the {A, B, C, D} parameters must share the same sign*.

We observe that the unconditional stability requirement constraints the product of the forward gain and the reverse gain, $|A_{VF}A_{VR}|$. The latter can be written as:

$$|A_{VF}A_{VR}| = \frac{1}{|A + j\omega C_L B|} \cdot \left| \frac{AD - BC}{D + \dfrac{B}{R_S}} \right| \le \left| \frac{D - \dfrac{BC}{A}}{D + \dfrac{B}{R_S}} \right| \quad \forall\omega \tag{2.5}$$

For $Z_{IN} \approx A/C = R_S$ and knowing that the {A, B, C, D} parameters must have the same sign, equation (2.5) yields the following inequality:

$$\left|A_{VF}A_{VR}\right| \le \left|\frac{D - \frac{B}{R_S}}{D + \frac{B}{R_S}}\right| \le 1 \quad \forall\omega \tag{2.6}$$

Equation (2.6) says that the product of the forward and reverse gain of an unconditionally stable matched-input two-port amplifier is lower or equal than one. In practice, a condition more stringent than (2.6) may be desired because:

- The amplifier can be considered unilateral, which means better stability [9] and lower leakage of the local oscillator signal to the amplifier input.
- The sensitivity of the input impedance to variations of the load is lower.

An important remark is that the derived constraints on the {A, B, C, D} parameters were obtained without referring to the specific nature of the two-port circuit. This means that they identify wide-band amplifiers made by any other proper set of generating elements.

### 2.3.3 STEP3: 2VCCS graphs database exploration

In this section, graphs of wideband amplifiers are extracted from the 2VCCS database according to the previously defined constraints on the {A, B, C, D} parameters. The table in figure 2.3b provides all the combinations of non-zero {A, B, C, D} parameters that can be realized as 2VCCS two-port circuits. However, we are interested in graphs of 2VCCS circuits according to the allowed combinations and values of non-zero transmission parameters. This selection process is outlined in table 2.2. Starting from an initial set of 145 2VCCS graphs (see appendix D), only 19 of these correspond to graphs of two-port cases: 3 {ABC}, 9 {ACD} and 7 {ABCD}. Notice that no graphs of two-port with parameters {AC} are available in the 2VCCS database. This presumably means that more than 2 VCCSs are needed to realise their functionality. The 19 graphs are then checked to verify if their {A, B, C, D} parameters can fulfil the gain and stability requirements. This possibility depends on the expression of the {A, B, C, D} parameters as a function of the transconductances $g_a$ and $g_b$ of the 2 VCCSs as indicated in table 2.2. For instance, all the 9 graphs of {ACD} two-ports have A=1 (i.e. they provide no gain), so they are rejected. Among the remaining 10 graphs (i.e. 3 {ABC} and 7 {ABCD}), only *1 {ABC} and 3*

*{ABCD} graphs* ultimately meet all the requirements. The latter are *all* the graphs of wide-band two-port amplifiers in the 2VCCS database and they are shown in figure 2.8. In the next subparagraphs, their transistor level implementations will be discussed.

### 2.3.4 STEP4: Transistor circuits implementation

The transistor level implementation of the graphs of 2VCCS wideband amplifiers shown in figure 2.8 depends on the orientation of the "V" and "I" branch of the VCCS and their mutual interconnection [3, 4, and 5]. Figures 2.9 shows this dependence when the V" and "I" branch share the same orientation (i.e. both arrows point to or from the same connection node). A graph with no connection between its "V" and "I" branch corresponds to a general 4-terminal VCCS element with separate input and output ports (i.e. nodes 1, 2, 3, and 4 are not connected). The latter can be implemented with a MOSFET differential pair (e.g.: n-type, p-type or complementary) or any 4-terminal transconductor circuit. If one connection exists between the "V" and "I" branch, a 3-terminal VCCS can be used. This can be implemented by a single MOSFET (either n-type or p-type depending on the arrow) or again with any 4 terminal transconductor with one of its terminals connected to one other (i.e. node 2 connected to 4). If the "V" and "I" branch are connected to each other at both ends, the 2-terminals VCCS can be implemented with a single resistor or a so-called diode-connected MOSFET. The orientation of the "V" and "I" branch also impacts the transistor implementation. For instance, reversing the orientation of both the "V" and "I" branch of a VCCS with 3 nodes its "g" is not changed while the transistor circuit changes from n-type to p-type or vice versa.

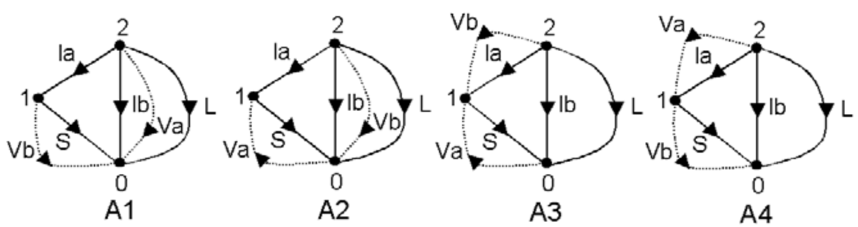



**Figure 2.8:** *All* the graphs of 2VCCS wideband amplifiers: A1-A4 (The symbol S, I, L over the continuous line indicates the branch of the input voltage source, the output current source of the VCCS and the load impedance $Z_L$ respectively while the black arrows indicates the direction of the current). They are all based on the same KCL graph S+I+(I//L) described in [2,3,4] (i.e. + indicates the series connection between two branches while // a parallel one), with their "V" (i.e. the input voltage of the VCCS) branches connected to different pair of nodes (node 0: reference).

| Useful Cases | Database Cases | Database Nr. | Graph | Transmission Parameters A | Transmission Parameters B | Transmission Parameters C | Transmission Parameters D | $\lvert A \rvert<1$ & T.P same sign? | Condition |
|---|---|---|---|---|---|---|---|---|---|
| {AC} | NO | - | - | - | - | - | - | - | - |
| {ABC} | {ABC} | 3 | **S+I+(I//L), [$V_a$=$V_2$, $V_b$=$V_1$]** | **-ga/gb** | **-1/gb** | **-ga** | **0** | **Y** | **gb>ga** |
| | | | S+I+(I//L), [$V_a$=$V_2$, $V_b$=$V_2$-$V_1$] | 1+ga/gb | 1/gb | -ga | 0 | N | - |
| | | | (S//I)(I//L), [$V_a$=$V_2$, $V_b$=$V_2$-$V_1$, $S_{ref}$=0] | 1 | 1/gb | ga | 0 | N | - |
| {ACD} | {ACD} | 9 | S//(I+I)//L, [$V_a$=$V_2$, $V_b$=$V_2$-$V_1$] | 1 | 0 | -gagb/(ga+gb) | 1 | N | - |
| | | | S//(I+I)//L, [$V_a$= $V_2$-$V_1$, $V_b$=$V_2$] | 1 | 0 | gagb/(ga+gb) | 1 | N | - |
| | | | S//I//I//L, [$V_a$= $V_1$, $V_b$=$V_1$] | 1 | 0 | (ga+gb) | 1 | N | - |
| | | | S//(I+I)//L, [$V_a$=$V_1$, $V_b$=$V_2$] | 1 | 0 | -ga | 1 | N | - |
| | | | S//(I+I)//L, [$V_a$=$V_1$, $V_b$=$V_2$-$V_1$] | 1 | 0 | -ga | 1 | N | - |
| | | | (S//I//L)(I), [$V_a$=$V_1$, $V_b$=$V_2$] | 1 | 0 | ga | 1 | N | - |
| | | | (S//I//L)(I), [$V_a$=$V_1$, $V_b$=$V_2$-$V_1$] | 1 | 0 | ga | 1 | N | - |
| | | | (S//I//L)(I), [$V_a$=$V_2$, $V_b$= $V_2$-$V_1$] | 1 | 0 | ga | 1 | N | - |
| | | | (S//I//L)(I), [$V_a$=$V_2$-$V_1$, $V_b$= $V_2$] | 1 | 0 | -ga | 1 | N | - |
| {ABCD} | {ABCD} | 7 | **S+I+(I//L), [$V_a$=-$V_1$, $V_b$=$V_2$]** | **gb/ga** | **1/ga** | **gb** | **1** | **Y** | **ga>gb** |
| | | | **S+I+(I//L), [$V_a$=-$V_1$, $V_b$=$V_2$-$V_1$]** | **gb/(gb+ga)** | **1/(gb+ga)** | **gagb/(gb+ga)** | **ga/(gb+ga)** | **Y** | **-** |
| | | | **S+I+(I//L), [$V_a$=$V_2$-$V_1$, $V_b$=$V_1$]** | **-ga/(gb-ga)** | **-1/(gb-ga)** | **-gagb/(gb-ga)** | **-ga/(gb-ga)** | **Y** | **$\lvert gb-ga \rvert$>ga** |
| | | | S+I+(I//L), [$V_a$=$V_2$-$V_1$, $V_b$=$V_2$] | 1+gb/ga | 1/ga | gb | 1 | N | - |
| | | | S//I//(I+L), [$V_a$=$V_1$, $V_b$=$V_2$-$V_1$] | 1 | 1/gb | ga | 1+ga/gb | N | - |
| | | | S//I//(I+L), [$V_a$=$V_2$, $V_b$=$V_2$-$V_1$] | 1 | 1/gb | ga | 1 | N | - |
| | | | (S//I)(I//L), [$V_a$=$V_1$, $V_b$=$V_2$-$V_1$, $S_{ref}$=0] | 1 | 1/gb | ga | ga/gb | N | - |

**Table 2.2:** Selection of *all* the graphs of wideband 2VCCS amplifiers (T.P. are {A, B, C, D}).

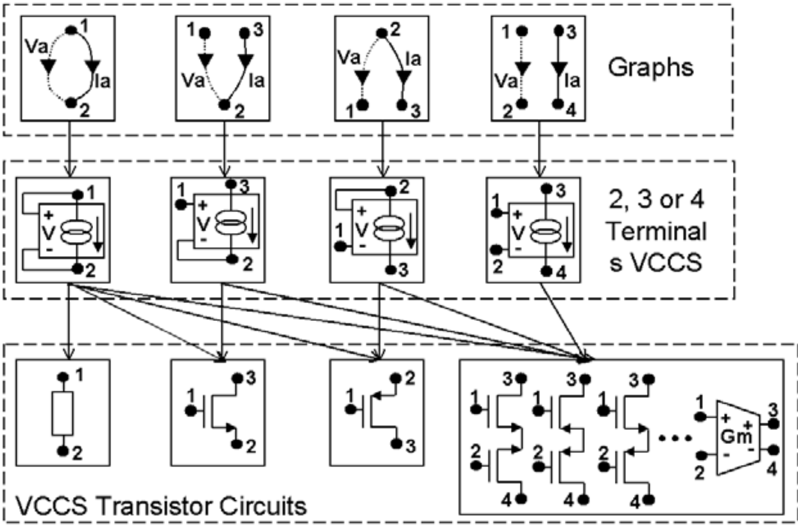



**Figure 2.9:** Relations among graph, VCCS and MOST implementation (biasing not shown).

On the other hand, if the "V" or "I" branch is reversed, "g" is negative. In such case, a complex circuit is required even for a 2-terminal VCCS. However, this case does not occur for the graphs in figure 2.8. In figure 2.10, the graphs of the generated 2VCCS wide-band amplifiers are draw as 2VCCSs circuits. From this figure, the conclusions are:

- Since all the VCCSs have one or even two terminals in common between the "V" and "I" port, they can be implemented using a single MOSFET (either a n-type or p-type MOSFET biased in saturation) or with a resistor (i.e. 2-terminal VCCS). These elementary amplifier implementations are shown in figure 2.11, where a generalized symbol for the MOSFET with two back-to-back arrows is used in order to cover both the n-type and the p-type MOSFET options. This means that each topology in figure 10 has 4 possible single-transistor circuit implementations: N-N, P-P, N-P and P-M where P indicate PMOS and N indicate NMOS. This corresponds to 16 different circuits. From figure 2.11, it can be seen that amplifiers A2 and A4 are well-known circuits: the common-gate and common-source shunt-feedback amplifier stages [6, 7]. The fact that well-known circuits are found using this generation methodology is not a surprise because *all* the wideband two-port amplifiers that can be modelled as circuits with 2 VCCSs have been generated. In contrast, A1 and A3 are alternative wideband amplifiers, which to the best of our knowledge are new. In [11], a circuit topology resembling A1 is proposed as a low-voltage V-I and I-I converter. However, the role of the input and output nodes was swapped, with the input signal injected into node 2 instead of node 1 (see figure 2.11).

- According to the guidelines in figure 2.9, the 2VCCS amplifiers in figure 2.10 can be implemented at transistor level in a number of different ways, each of them with specific strong and weak points. This provides more design freedom, thus potentially enhancing the quality of the design. For instance, figure 2.12 shows the amplifiers A1 and A3 where a differential pair (either n-type or p-type) replaces each VCCS. An advantage of these circuits is the absence of 2nd order distortion due to the odd-symmetry of the V-I transfer of the differential-pair.

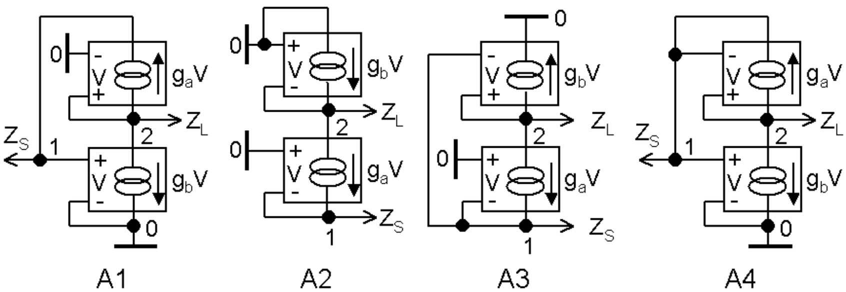



**Figure 2.10:** Implementations of A1-A4 using VCCS elements (biasing not shown).

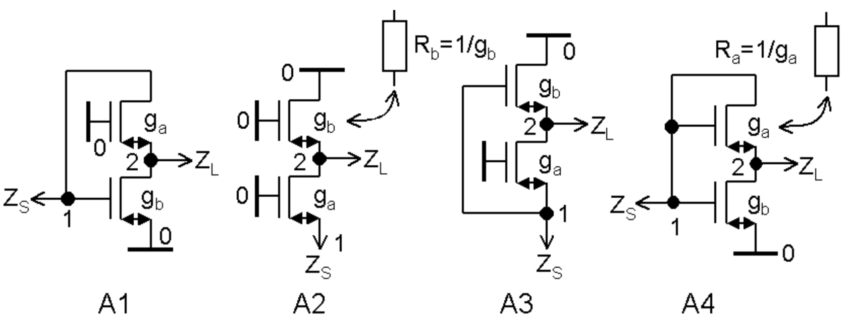



**Figure 2.11:** Implementation of A1-A4 with MOSFETs or resistors (biasing not shown).

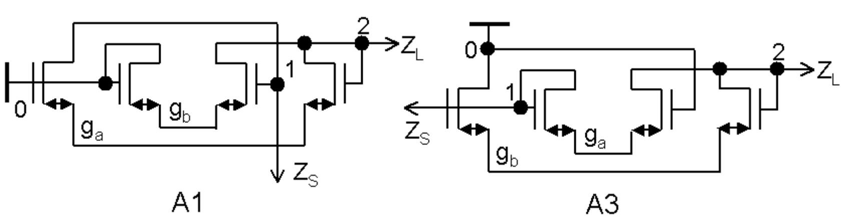



**Figure 2.12:** Amplifiers A1 and A3 with MOS differential pairs (biasing not shown).

## 2.4 Conclusions

In this chapter, alternatives to elementary wide-band amplifiers were investigated using a methodology that generates *all* the graphs of wide-band two-port amplifiers that can be seen as circuits with 2 VCCSs. This is done selecting from a previously generated graph database [3, 4, and 5] all the graphs of 2VCCS circuits that behave as wide-band amplifiers according to properly defined *functional requirements* and source/load impedance suitable for highly integrated receivers. This yielded 4 graphs of 2VCCS wideband amplifiers (figure 2.8). Examining the 2VCCS circuits in figure 2.10, it was found that:

- Replacing each VCCS element with a single MOSFET renders four elementary 2-Transistor amplifiers. Two are well-known circuits (A2 and A4, figure 2.11) while the others (A1 and A3, figure 2.11) are believed to be -at the present time- novel wide-band amplifier topologies.
- Alternative circuit implementations of these amplifiers involving more devices are also possible, each with specific strong and weak points. This provides the designer with an increased number of design options, thus potentially improving the design quality.

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