Optimum Hybrid Design

National Semiconductor
Application Note 397
Harry Holt
October 1999

Optimizing the interface between the phone line and a modem, can significantly improve modem performance. An increase of 6 dB in transmitted tone rejection can often be achieved. Depending on the modem design this can provide a similar or greater improvement in dynamic range.

The analysis described in this article uses the properties of conformal mappings to produce a solution which is valid for an entire locus of circuits, rather than a single one as is generally the result of circuit analyses.

PART I: PRACTICAL CONSIDERATIONS

Most low speed, full duplex modems use the phone line for transmitting and receiving signals simultaneously. A large part of the circuitry in a Bell 103 modem is devoted to separating the transmitted from the received signals. The telephone line hybrid performs some of this function. By subtracting the transmitted from the received signal some transmitted signal component in the receive path can be eliminated. The receive filter removes much of the remaining transmitted tone but is incapable of removing modulation sidebands and harmonic distortion products of the transmitter. Most receive filters have limited dynamic range specifications, so optimizing the hybrid allows maximum signal to be presented to the receive filter and thus optimizes the overall modem dynamic range.

The analysis presented in this article is performed at two frequencies, 1 kHz and 3 kHz. This was done due to the availability of data on the phone line input impedance at these frequencies. The format of the analysis is general, however, and can be applied to any available data.

A block diagram of the phone line, data access arrangement (D.A.A.) and hybrid is shown in *Figure 1*. The D.A.A. provides interfacing between the phone line and the hybrid. A circuit of a typical D.A.A. is shown in *Figure 2*. Many of its components do not affect the A.C. performance of the system, being included to draw line current, provide on/off hook control and perform other similar functions. The hybrid performs two to four wire conversion.

The most common hybrid circuit is shown in *Figure 3*. This circuit is the one used in National Semiconductor's MM74HC942 and MM74HC943 single chip 300 baud modems. Analysis of this circuit reveals it nulls the transmitted signal only for the case where the D.A.A. input impedance is 600Ω. The phone line input impedance, and thus the D.A.A. input impedance varies from line to line, and this ideal case is rare.

By optimizing the hybrid circuit, performance improvements can be achieved. For modems for the consumer market the extra component cost may not justify the performance improvements. For the industrial market however, the performance improvements may outweigh the cost.

The variety of phone line impedances are demonstrated in *Figures 4, 5*. As can be seen the impedance varies over a wide range, and 600Ω is not a good approximation of the value. The data for these graphs is from Gresh(2).

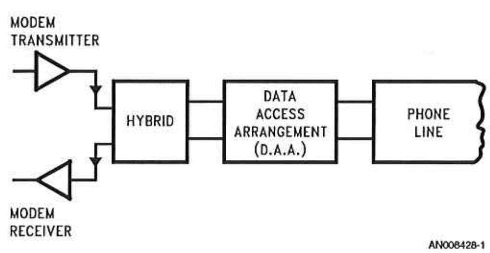

FIGURE 1. Hybrid, D.A.A. and Phone Line

PrintDate=1999/10/12 PrintTime=07:11:29 57586 an008428_p Rev. No. 1 cmserv Proof Seq=1

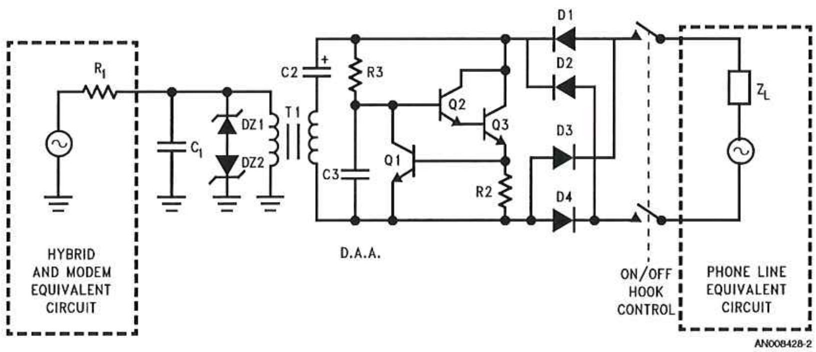

FIGURE 2. D.A.A. Typical Circuit

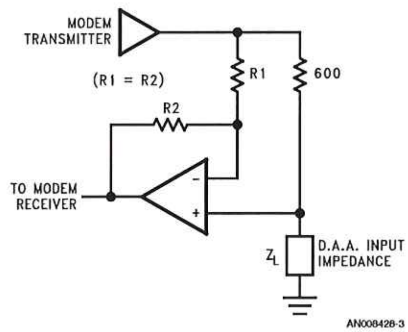

FIGURE 3. Common Hybrid Circuit

Improved Hybrid Topology

A common variation of the circuit of *Figure 3* is to replace R2 with an RC network. This does allow the hybrid to be optimized, but causes the circuit to have a non-flat frequency response from the phone line to the hybrid output. This causes little change in actual performance, but does cause the modem's carrier amplitude detect circuit to trip at different points depending on the mode of the modem (Answer or Originate). This is undesirable.

An improved hybrid circuit is shown in *Figure 6*. This circuit has fixed gain from the phone line to the modem output, and achieves good performance after optimum selection of the components.

This article includes a computer program which optimizes the component values of this circuit. It is possible to use this program without fully understanding the details of its operation, however some of its operation must be understood.

The Hybrid Design Problem

The aim of the hybrid is to minimize the hybrid gain G from the transmitter output to the modem input. Generally, a value Gmax will be chosen that is the maximum tolerable gain. Phase shift does not affect modem performance so the gain G can be a complex number. Thus the modem design goal can be expressed by the equation.

$$|G| < G_{max} \quad (1)$$

Obviously minimizing Gmax would also be a benefit. This equation is the equation of a circle. The range of values of G in complex space is called the "gain space".

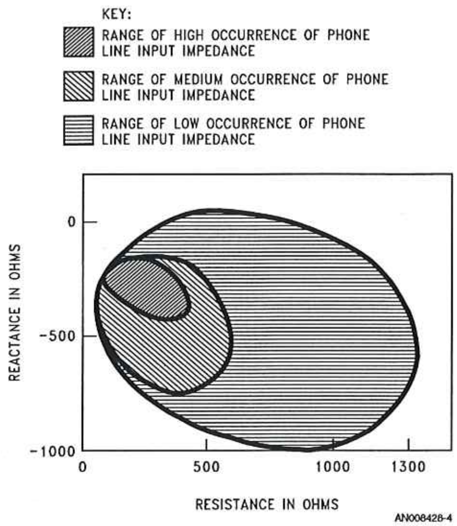

FIGURE 4. Input Impedance of Phone Line at 3 kHz

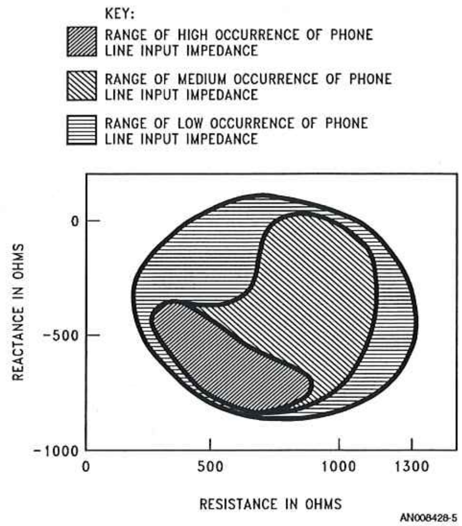

FIGURE 5. Input Impedance of Phone Line at 1 kHz

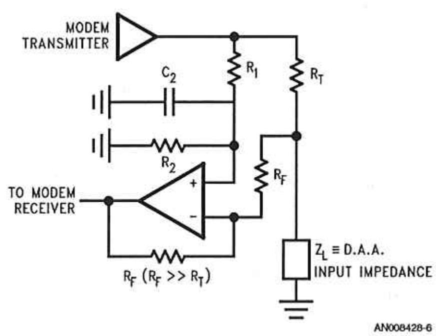

FIGURE 6. Improved Hybrid Topology

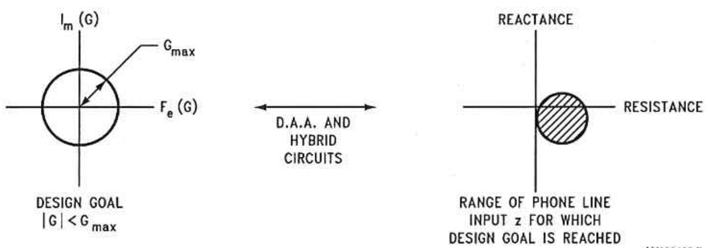

FIGURE 7. Design Solution Space

Due to some mathematics described in Part 2 of this article, for any hybrid or D.A.A. design the range of phone line impedances for which *Equation (1)* is satisfied falls inside a circle. This means this hybrid design meets its design goal for all the impedances enclosed by this circle. This is illustrated in *Figure 7.*

As the circle of impedances for which the design goal is met depends on the hybrid design, this design may be altered to move the circle of phone line impedances for which the design goal is satisfied. This is to some extent a reverse way of looking at the problem. A hybrid design is chosen, and analysis of its performance shows it meets its design goal for a cir-

PrintDate=1999/10/12 PrintTime=07:11:30 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=3

cular disk or phone line impedances. This circular range of impedances may not include many of the possible phone line input impedances. In this case it is necessary to adjust the hybrid design until the circle of impedances for which the design goal is met is a reasonable approximation of the range of phone line impedances.

In practice it is easier to solve the problem in a more direct manner. Since the design will meet its goal for a range of impedances in the form of a circle, as the first step of the hybrid design this circle may be chosen. For the range of impedances described by this circle the hybrid will show a range of gain values which will be a circle, but may not be of the form of *Equation (1)*, the design goal. The hybrid may then be adjusted until, for the range of phone line impedances chosen, the gain is of the form of *Equation (1)*. At this point the radius of the circle Gmax, is evaluated. This gives the best possible design goal based on the range of impedances of the analysis.

The design problem is thus one of choosing R1, R2 and C2 so the circle of impedances for which *Equation (1)* is satisfied encloses the areas of phone line impedances of interest. The constraints applying to the choice of the circle representing the phone line is discussed in the worked example.

The Effect of the D.A.A.

Before the circuit can be optimized the effect of any circuitry between the hybrid and the phone line must be taken into consideration. This is not difficult because, just as the hybrid generated a circular range of impedances for which the design goal was satisfied, the D.A.A. input impedance, for a circular range of load impedances, will cover a circular range.

Understanding exactly the relation between the phone line input impedance and the D.A.A. input impedance is a difficult task. This task is sidestepped by evaluating the effect of the D.A.A. at three points for each frequency of analysis. These points are chosen to provide all the necessary data on the effect of the D.A.A. This is demonstrated in the example and explained fully in Part 2.

HYBRID DESIGN EXAMPLE

This example covers the complete design of a hybrid. The design example uses a MIDCOM 671-0017 transformer, but the technique is applicable to any D.A.A. circuit.

Step 1: Designing the D.A.A. Input Impedance

It is necessary that the final circuit, when measured from the phone line, have an input impedance of 600Ω ±10% to meet F.C.C. specifications. This impedance should be resistive. Several components of the D.A.A. affect the final circuit's input impedance. These must be identified and the necessary components adjusted until the design meets its goal.

From *Figure 2* it can be seen that few components of the D.A.A. affect the A.C. performance of the system. The resistor R3 is usually very large and can be ignored. The transistors Q1, Q2 and Q3 form a current source which does not have any effect on A.C. The diodes DZ1 and DZ2 are for surge suppression and may also be ignored. Thus the only components which affect the A.C. performance of the D.A.A. are the transformer, the capacitor C_1, the hybrid output impedance R_1, and the phone line input impedance Z_L.

By adjusting R_1 and C_1 it is possible to adjust the input impedance of the circuit to meet the specification. This may be done using the simplified circuit shown in *Figure 8*. It should be done at about 2 kHz so optimum performance is achieved across the 300 kHz–3 kHz band of the phone line.

Some modem designers find the value of R_1 simply by measuring the D.C. resistance of the transformer and subtracting it from 600Ω. This will not compensate for incomplete coupling between transformer windings, or a transformer with an unequal number of turns on the primary and secondary sides. Thus optimum designs can only be achieved with an impedance analyzer and actual measurements of circuit performance.

The values of R_1 and C_1 should consist of "preferred" values for ease of manufacture of the finished circuit. The value of R_1 in *Figure 8* consists of the parallel value of R_T and R_F of the improved hybrid circuit of *Figure 6*. At this point R_F can be chosen, the only real constraint being that it be much greater than 600Ω so it has minimal effect on the rest of the circuit. A value of 20 kΩ is suitable for most applications.

By trial and error it was found that the value of the capacitor C_1 required for the MIDCOM 671-0017 transformer is 0.01 µF. This brings the phase of the transformer input impedance to less than 1 degree. A resistor R_1 of value 601Ω (20k in parallel with 620Ω) gave an input impedance of the network of 603Ω. It could be argued that these adjustments are unnecessary, as a 600Ω resistor and no capacitor will provide an input impedance which is within the F.C.C. specifications. However, some transformers, particularly low quality miniature ones, will cause the final design to fall outside of F.C.C. specifications if these adjustments are not included. They were thus included for completeness.

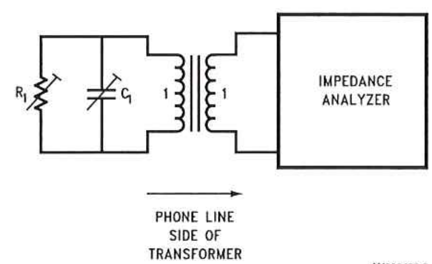

FIGURE 8. Designing D.A.A. Input Impedance

Step 2: Characterizing the Phone Line

The range of impedances seen looking into the phone line must be defined. Since the final circuit works for a circular range of impedances, this range of phone line impedances must be chosen. This is chosen by drawing a circle on a plot of phone line input impedances. This circle is chosen to enclose most values in an efficient manner. This is demonstrated in *Figure 9*.

At this point some engineering discretion must be applied. As a small circle represents a small range of phone line input impedance variation, it is intuitive that an optimized design should have high performance, and the measure of hybrid performance. Gmax will be small, indicating high transmitter rejection. Thus the circle chosen should be small. On the other hand, the smaller the circle, the smaller the percentage of possible phone line input, impedances enclosed by it, and the less meaningful the final design becomes.

Phone line input impedance circles should be chosen at both 1 kHz and 3 kHz, the two frequencies at which data is available.

PrintDate=1999/10/12 PrintTime=07:11:32 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=4

Three points on the perimeter of each of these circles are then chosen. As three points define a circle, these six points define the range of phone line impedances at the two frequencies. These points contain all the information of the circles which were drawn. The values chosen by the author from the data of *Figure 9* are given in *Table 1*, together with R and C combinations which produce these impedances.

Combinations of resistors and capacitors are then selected to simulate these impedances. These RC networks are used as a crude phone line simulator in the proceeding analysis as shown in *Figure 10*.

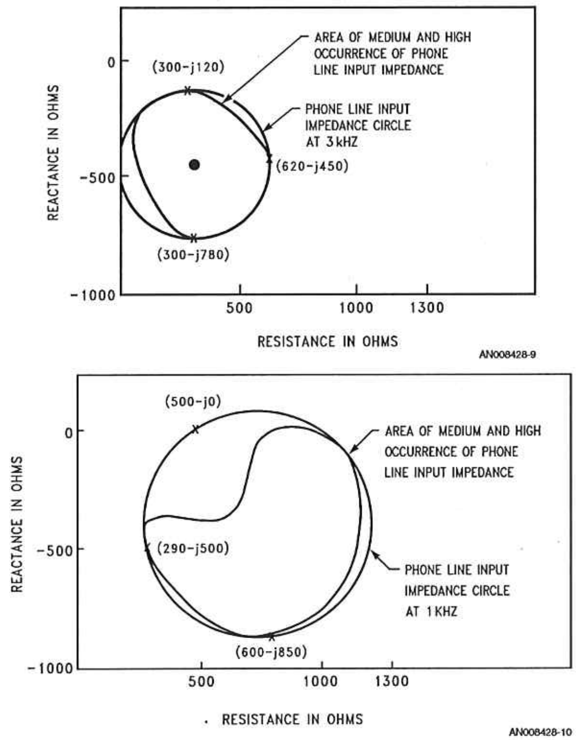

FIGURE 9. Phone Line Input Impedance Circles

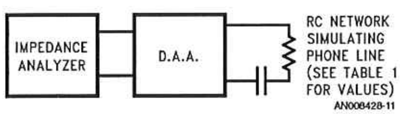

FIGURE 10. Characterizing the D.A.A.

Step 3: Characterizing the D.A.A.

The RC networks simulating the phone line are placed on the phone line side of the D.A.A. The input impedance of the D.A.A. is then measured for each RC network at the relevant frequency. This is illustrated in *Figure 10*. The six impedance values measured at this point now completely specify the D.A.A. and phone line. These values are used as inputs for the hybrid optimization program.

TABLE 1. Phone Line and D.A.A. Characterization Impedances

Freq.	Z_{PL}	R	C	Z_{DAA}
1 kHz	290-j 500	290	0.33 µF	419-j 564
1 kHz	800-j 850	800	0.18 µF	970-j 870
1 kHz	500	500	0	594-j 10
3 kHz	300-j 120	300	0.44 µF	390-j 115
3 kHz	300-j 780	300	0.68 nF	344-j 812
3 kHz	620-j 450	620	0.12 µF	651-j 511

Step 4: Running the Optimization Routine

The program included in Part 2 can now be run. This program is written in HP Basic (3). This code used in this program is very similar to FORTRAN so if users do not have ac-

PrintDate=1999/10/12 PrintTime=07:11:32 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=5

cess to a machine capable of running HP Basic, translation to FORTRAN should be straightforward. The author has been running the program on the HP98XX series desktop computers. An example of the program output is provided as a guide. The program provides all the necessary prompts. The steps are:

1. Enter the program and begin execution.
2. Enter the value of the resistor R_T of *Figure 6* as determined in the section "Designing the Hybrid Input Impedance".
3. Enter the real and imaginary parts of the 6 measurements from "Characterizing the D.A.A." So long as the values are entered for the correct frequency class the order is unimportant. These are echoed by the program, including the center and radius of the circle defined by them.

The program will then print the transmitter gain for the hybrid circuit which has been optimized for a 600Ω load. This is the "Transmitter rejection for A = 0.25". In the example given this was 11 dB at 1 kHz and only 5 dB at 3 kHz.

The program then also prints the "Best transmitter rejection". This is the optimum performance which can be achieved under the worst conditions within the range chosen. Most loads within the range will show better performance than this. As can be seen from the example this is considerably more rejection than provided by the simple circuit, providing an extra 6 dB at 1 kHz and 7.5 dB at 3 kHz.

The "Optimized A Value" refers to the gain to the non-inverting input of the op-amp for optimum performance.

The "Gain Circle Center" and "Gain Circle Radius" refer to the circle of *Equation (1)*. These values were calculated inside the program and demonstrate that the final solution has the form of *Equation (1)*: a circle centered at the origin.

1. Enter a value for R_1 of *Figure 6*. This value is arbitrary, but will affect the final values of R_2 and C_2. 20 kΩ is usually suitable.

The program will then return optimum values of R_2 and C_2 for each frequency. A compromise depending on the actual final design is chosen. For example, suppose the modem was "Originate only", then high frequency performance is more important than low, as the modem receives on the high frequency band. Thus resistor and capacitor values should be chosen to optimize performance at high frequencies. For an "Answer or Originate" modem, the values should be chosen for the frequency at which performance is poorest, as this can least be compromised. At this point component values should be rounded off to "preferred values".

The program will then print the actual performance based on the final chosen values. As can be seen in the example the effect of the compromise is not great, as the final values are worse by approximately 2 dB at 1 kHz and 0.2 dB at 3 kHz than the best possible.

Step 5: The Final Circuit

Figure 11 shows the final hybrid circuit while *Figure 12* shows a complete modem circuit with an optimized hybrid and employing the MM74HC943 single chip modem. As can be seen the additional circuitry required to provide an optimized hybrid is small.

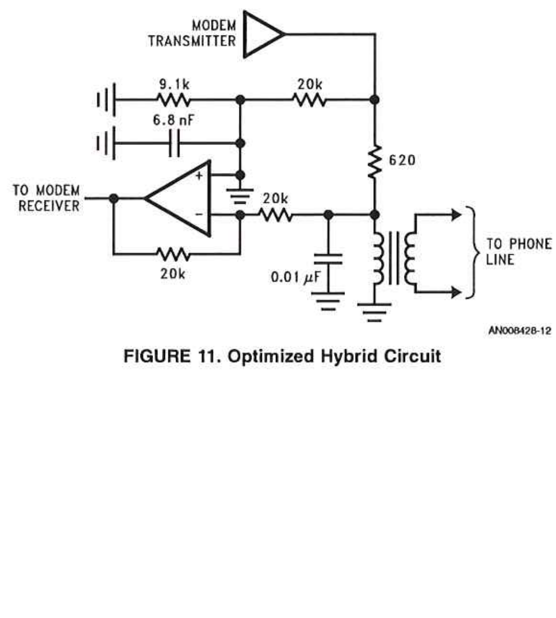

FIGURE 11. Optimized Hybrid Circuit

PrintDate=1999/10/12 PrintTime=07:11:33 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=6

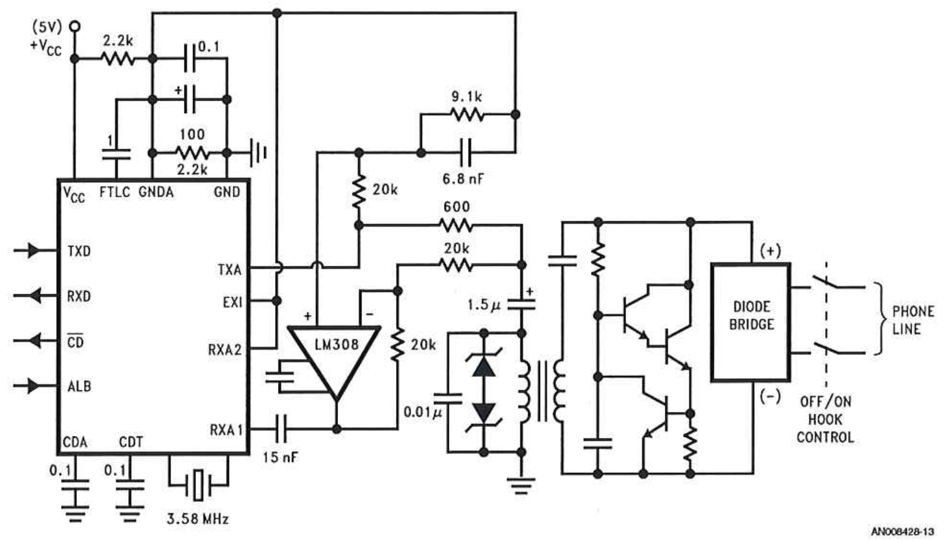

FIGURE 12. Complete Stand Alone Modem With Optimized Hybrid

PART 2: PROBLEM ANALYSIS

This presents the analysis of the hybrid design problem, and discusses the techniques to optimize the design. The analysis proceeds by first evaluating a performance criterion for a given hybrid design. Then, using a computer program, this performance is optimized.

A block diagram of the functions from the phone line to the modem is shown in *Figure 1*. The analysis of the hybrid optimization problem consists of four parts:

1. Stating the Design Goal
2. Analyzing the Hybrid, D.A.A. and Phone Line Interaction
3. Optimizing the Hybrid Design
4. Realizing the Optimizing Hybrid Design

1. The Design Goal

From *Figure 6*, assuming $R_F \gg R_T$ the gain from the transmitter output to the hybrid output is:

$$G = 2.0 \times A - \frac{Z_L}{Z_L + R_T} \qquad (2)$$

$$\text{where } A = \frac{R_2}{R_1 + R_2 + sR_1R_2C_2} \qquad (3)$$

is the non-inverting gain from the transmitter to the op-amp, Z_L is the Thevenin equivalent input impedance of the D.A.A. and s is the Laplace Transform variable.

Note that the transmitter signal is completely rejected in the case $R_T = Z_L = 600$, $A = 0.25$. This is the case of the resistive hybrid designed for an "ideal" phone line.

Since the purpose of the hybrid is to reject transmitted tones, a figure of merit of the hybrid is the transmitter rejection, the reciprocal of the hybrid gain. The task of optimizing the hybrid design is to minimize G for the entire locus of Z_L. For this locus of Z_L there will exist Gmax, a scalar equal to the absolute value of the worst case gain of the hybrid. As G may be a complex number the design goal may now be written

$$| G | < \text{Gmax} \qquad (4)$$

(This is *Equation (1)* of Part 1 and is repeated here for completeness). The locus of G satisfying this equation will lie inside the circle.

$$| G | = \text{Gmax} \qquad (5)$$

The goal of the hybrid design is to find the value of A such that Gmax is minimized, and *Equation (4)* is satisfied for the entire locus of the hybrid load Z_L.

Mathematical Tools

Before the hybrid can be optimized the mathematics of the problem must be further defined.

The relationship *Equation (2)* states that for fixed A, for each load Z_L, there exists a gain G satisfying *Equation (2)*. This equation may be considered a transform mapping the Load Space onto the Hybrid Gain Space.

This transform is of a very clearly defined nature. It is a Linear Fractional Transformation, which is a special case of a Conformal Mapping (1). Conformal Mappings have the following properties.

1. They map circles onto circles
2. They have inverses
3. Their inverses are Conformal Mappings
4. The combination of two conformal mappings is a conformal mapping

Many relationships between various aspects of linear networks are conformal mappings. For example, the relationship between the input impedance of a linear two-port and the termination impedance of the two-port is a conformal mapping.

The mapping of a circle by a conformal mapping may be characterized by evaluating its affect on three arbitrary points on the perimeter of the circle. These points will lie on the perimeter of the circle to which this circle is mapped. The center and radius of the new circle may then be found using simple algebra. This is illustrated in *Figure 13*.

PrintDate=1999/10/12 PrintTime=07:11:34 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=7

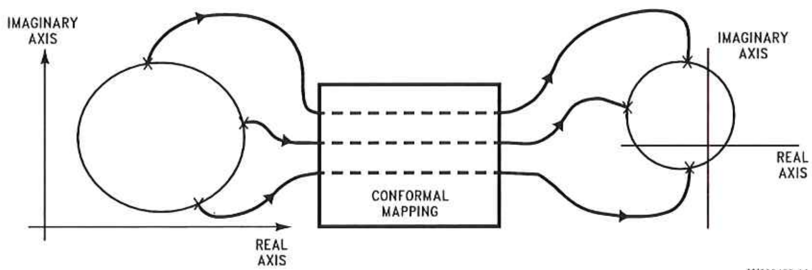

FIGURE 13. The Conformal Mapping of a Circle

The Hybrid, D.A.A. and Phone Line Interaction

The information available to the hybrid designer consists of:

1. The hybrid topology is known. Only one complex number A is required to define the hybrid electrical characteristics at a given frequency.
2. The electrical characteristics of the D.A.A. can be measured. The D.A.A. design is based on phone-line interface constraints. Once these are met the D.A.A. can be characterized.
3. The locus of the phone line input impedance is available (2).

From this information the analysis proceeds by:

1. The locus of D.A.A. input impedances is evaluated. This is done by sidestepping the complex problem of fully analyzing the D.A.A. The final form of the design goal is in the form of a circle. As the hybrid may be represented by a conformal mapping, and the D.A.A. is a linear network, the relation between its input impedance and the phone line input impedance is a conformal mapping. Thus by Conformal Mapping Property No. 4 the locus of phone line input impedances for which the hybrid meets its design goal will be a circle.

The range of phone line input impedances for which the hybrid will be optimized may be chosen. The basic tradeoffs made in this task are discussed in the section "Characterizing the Phone Line".

Once these circles have been chosen the effect of the D.A.A. is evaluated to find the locus of D.A.A. input impedances. The final form of this locus for the purposes of this analysis is a circle. This circle may be found by terminating the D.A.A. with three impedances, these impedances having been chosen to lie on the perimeter of the circles of phone line input impedance. With each of these impedances on the D.A.A., its input impedance is measured. The three input impedances will lie on a circle, and this circle will define the locus of D.A.A. input impedances. This second circle may be evaluated for its center and radius using simple algebra. This procedure is repeated at each frequency for which impedance data is available.

Thus the problem of characterizing the D.A.A. has been reduced to measuring its affect on three points at each frequency of analysis. These points were carefully chosen to contain all the information necessary for the problem solution so detailed D.A.A. circuit analysis is not necessary.

Maximum Hybrid Gain

Once the circles representing the loci of loads have been defined the maximum hybrid gain may be calculated for the given hybrid parameters. The three points of possible loads defining each load circle are transformed to Gain Space using *Equation (2)* and *Equation (3)*. The three points in Gain Space now define the circle of possible hybrid gain.

Thus the entire range of circuit gains for the entire range of phone line input impedances have been evaluated. This was performed by the two conformal mappings, one from the phone line to the D.A.A. input impedance via the D.A.A. and the second from the D.A.A. input impedance to the hybrid gain via *Equation (2)* and *Equation (3)*.

Once the points defining the circles of possible hybrid gain have been found, they may be solved for their centers and radii. The maximum hybrid gain may be evaluated. By inspection of *Figure 14* the maximum transmit path gain is

$$G_{max} = | C_x + jC_y | + R \qquad (6)$$

The analysis thus yields a unique number characterizing the hybrid at each frequency. This number is the worst possible performance for the entire locus of loads selected for the analysis.

Optimizing the Hybrid

As the performance of a hybrid can now be evaluated for any amplifier gain the problem remains to choose the value of A which optimizes hybrid performance. This is done using a simple numerical search algorithm.

First a value of amplifier gain is arbitrarily chosen. Four points around this value are then chosen. The distance between the central point and the outer points is arbitrary. The hybrid performance is then evaluated at each of these five points. Based on the behavior at each of these points a search routine may be implemented. This is illustrated in *Figure 15*.

It the best value of A is found to be one of the outer four points, this point is chosen as the central point for another matrix of gain values.

If the best value of A is the central point, the best possible hybrid is inside the area defined by the outer points, so the search increment A_{inc} is halved. This allows greater resolution for the search. The search then continues using the new value of A_{inc}.

PrintDate=1999/10/12 PrintTime=07:11:35 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=8

This process is repeated until the value of A_{inc} is so small that the optimum value for A is known to be inside a precisely defined area. At this point A is known to within the required accuracy.

Although the optimization routine minimizes Gmax, the final form of the solution is of the form of *Equation (4)* and *Equation (5)*. i.e., the range of hybrid gains for the range of loads is a circle with its center at the origin. Intuitively this is reasonable as the optimum hybrid design will be one that makes most efficient use of the gain space. A proof of this is beyond the scope of this analysis.

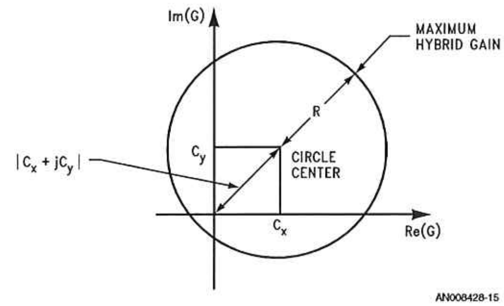

FIGURE 14. The Maximum Hybrid Gain

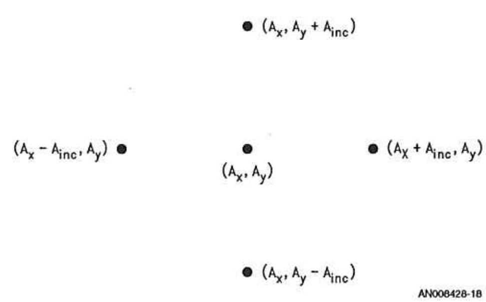

FIGURE 15. Matrix of Points for Numerical Search

Designing the Hybrid

The final problem to be solved is to find a circuit which has the optimum gains A at each of the frequencies of the analysis. The circuit used in Part 1 was found to give sufficient accuracy for engineering purposes. Solving this circuit at one frequency for a necessary gain is straightforward. However, this circuit is not capable of realizing arbitrary gains at each frequency. For this reason a compromise is made. The circuit components for optimum performance may differ for each frequency. This is due to the complex nature of the phone line input impedance. The circuit performance degradation from choosing fixed values for these components is small as was demonstrated in the example. If desired, a more complex hybrid circuit, capable of realizing the optimum gain at each frequency could be designed. This would not be a difficult task. However, the extra performance may not justify the increased complexity.

```
          HYBRID OPTIMIZATION ANALYSIS
          ----------------------------
Transformer termination resistance   620
Load circle points at 1 kHz.
 X = 419  Y = -564
 X = 970  Y = -870
 X = 594  Y = -10
Load Circle Center at X= 869.603733515 Y= -401.698832789
Load Circle Radius       478.941952156
```

Thus, by utilizing a combination of complex number analysis, computer programming and engineering discretion, an apparent intractable problem has been reduced to a simple procedure for optimum hybrid design.

REFERENCES

1. W.R. Derrick "Introductory Complex Analysis and Applications" Academic Press 1972.
2. P.A. Gresh "Physical and Transmission Characteristics of Customer Loop Plant" Bell Syst. Tech. Journal, Dec. 1969.
3. "Basic Language Reference with Extensions 2.0 for the HP Series Desktop Computers", Hewlett Packard Desktop Computer Division, 3404 East Harmony Road, Fort Collins, Colorado 80525.

PrintDate=1999/10/12 PrintTime=07:11:36 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=9

```
Transmitter rejection for A=0,25 = -11.2550722066 dB
Best transmitter rejection -17.19882266 dB
Optimized A value .285309791565  -.0578956604004 j
Gain circle center X= 8.19033644646E-7 Y= -8.34107354335E-7
Gain circle radius    .138055969327
--------------------------------------------------------------
Lead circle points at 3 kHz.
 X = 390   Y = -115
 X = 344   Y = -812
 X = 651   Y = -511
Load Circle Center at X=  298.967509106  Y= -459.010050816
Load Circle Radius        355.850852831
Transmitter rejection for A=0.25 = -4.96739666758  dB
Best tranamitter rejection -12.4830101726  dB
Optimized A value  .193202972412    -.153240203857  j
Gain circle center X= -7.65881406104E-8  Y=  2.89917098934E-7
Gain circle radius    .237601371549
--------------------------------------------------------------
 Optimum hybrid component values at  1000  Hz.
 R1 =  20000
 R2 =  8451.85356886
 C2 =  5.43598278096E-9
 Optimum hybrid component values at  3000  Hz.
 R1 =  20000
 R2 =  9186.276873
 C2 =  6.6844698044E-9
 Chosen values ; R2= 9100  C2 =  6.8E-9
 At 1 KHz
 A value for chosen components  .291873289127  -.0779940607259  j
 Transmitter rejection          -14.8780162632  dB
At 3 KHz
 A value for chosen components  .19037172402  -.152612770919  j
 Transmitter rejection          -12.2735391061  dB
100 !                         HYBRID DESIGN PROGRAM
110 !                         ----------------------
120 !                                                        P.S. Sept '83
130 !
140 ! This program finds a value of the gain A in the non inverting path of
150 ! a hybrid for optimum operation of the hybrid. The hybrid is optimized
160 ! for an entire locus of loads.
170 !   The locus of loads is assumed to be enclosed by a circle. Three points
180 ! on the perimeter of the circle are used as inputs and these points define
190 ! the circles. This is performed at two frequencies, 1 and 3 kHz.
200 !
210 ! This program is written in HP (Hewlett Packard) Basic 2.0.
220 !   The following variable conventions are used
230 !
240 ! First letter Z : a lead point (Z-space)
250 ! First letter A : the gain to the non-inv. input of the op-amp (A-space)
260 ! First letter G : a hybrid gain point (G-space)
270 ! Subscript    x : Real part of a complex variable.
280 ! Subscript    y : Imaginary part of a complex variable.
290 !
300     REAL Ax(3),Ay(3)
310     COM /Z/ REAL Z1x(1:3,1:3),Z1y(1:3,1:3),K
320     COM /Circle/ Cx,Cy,R
330     COM /Rtermc/ Rterm
340     !
350     PRINT "          HYBRID OPTIMIZATION ANALYSIS "
360     PRINT "          ---------------------------- "
370     !
380     INPUT "Enter transformer termination resistance",Rterm
390     PRINT " "
400     PRINT " Transformer termination resistance",Rterm
410     PRINT " "
420     !
430     ! Read load circle values
```


PrintDate=1999/10/12 PrintTime=07:11:37 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=10

```
440    CALL Readz (Z1x("),Z1y("),Rterm)
450    !
460 FOR K=1 TO 3 STEP 2 ! Step through two frequencies
470    PRINT "Load circle points at ";K;" KHz."
480    PRINT " "
480    FOR K3-1 TO 3
500        PRINT " X = ";Z1x(K,K3);" Y ";Z1y(K,K3)
510    NEXT K3
520    CALL Cir (Rx,Ry,R,Z1x(K,1),Z1y(K,1),Z1x(K,2),Z1y(K,2),Z1x(K,3),Z1y(K,3))
530    PRINT "Load Circle Center at X= ";Rx;" Y= ";Ry
540    PRINT "Load Circle Radius       ";R
550    PRINT " "
560    CALL Gmax(Gohl,.25,0.,Gohdb)
570    Gohldb=20,*LGT(Gohl)
580    PRINT "Transmitter rejection for A=0.25 = ";Gohdb;" dB"
590    PRINT " "
600    CALL Search (Gmin,Ax(K),Ay(K))
610    CALL Gmax(Goh,Ax(K),Ay(K),Gohb)
620    PRINT "Best transmitter rejection ";Gohdb;" dB"
630    PRINT "Optimized A value ";Ax(K) ;" ";Ay(K);" j"
640    PRINT " "
650    PRINT "Gain circle center X= ";Cx," Y= ";Cy
660    PRINT "Gain circle radius     ";R
670    PRINT "-----------------------------------------------------"
680    PRINT " "
690 NEXT K
700    !
710    CALL Pllrc(Ax(1),Ay(1),Ax(3),Ay(3))
720 END
730   !
740   SUB Search(Gmin,Acenx,Aceny)
750   !
760   ! Search in amplifier gain space (A-space) for
770   ! the amplifier gain constant yielding
780   ! optimum hybrid performance.
790   !   The amplifier gain at this point is
800   ! (Acenx,Aceny) and the hybrid gain is Gmin
810   ! at the worst point
820   !
830    REAL Gs(1:5),Ax(1:5),Ay(1:5)
840   !
850    Acenx=3. ! Choose arbitrary value to begin search
860    Aceny=0. ! Arbitrary y value
870    Ainc =.5 ! Gain increment: sets size of search area
880   !
890    FOR J=1 TO 1000 ! Dummy loop for search.
900                Ax(1)=Acenx ! Center of pattern of points
910       Ay(1)=Aceny
920       Ax(2)=Acenx+Ainc  ! These statements
930       Ay(2)=Aceny       ! create the matrix
940       Ax(3)=Acenx-Ainc  ! of points of
950       Ay(3)=Aceny       ! Figure 13.
960       Ax(4)=Acenx       !
970       Ay(4)=Aceny+Ainc  !
980       Ax(5)=Acenx       !
990       Ay(5)=Aceny-Ainc  !
1000      !
1010      FOR K=1 TO 5 ! Evaluate performance at points of matrix
1020        CALL Gmax(Gs(K),Ax(K),Ay(K),Gsdb)
1030      NEXT K
1040      !
1050      Gmin=MIN(Gs(1),Gs(2),Gs(3),Gs(4),Gs(5)) ! Find best point
1060      !
1070      IF (Gmin=Gs(1)) THEN ! Center point is best
1080         IF (Ainc<1.0E-6) THEN Finish ! Search accuracy is O.K.
1090         Ainc=Ainc/2.0 ! Increase search accuracy
1100         !
```


PrintDate=1999/10/12 PrintTime=07:11:38 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=11

```
1110      ELSE ! Find which point is best
1120         FOR L=2 TO 5 ! Loop thru perimeter points of matrix
1130            IF (Gmin=Gs (L)) THEN ! Best point located
1140               Acenx=Ax(L)
1150               Aceny=Ay(L)
1160            END IF
1170          NEXT L
1180      END IF
1190   NEXT J
1200 Finish: !
1210 SUBEND
1220  !
1230  !----------------------------------------
1240  !
1250 SUB Gmax(Goh,Ax,Ay,Gohdb)
1260  !
1270  COM /Circle/ Cx,Cy,R
1280  COM /Z/ Z1x(*),Z1y(*),Khz
1290  !
1300  ! This sub finds the maximum gain of hybrid with gain Ax,Ay
1300  ! for the locus of loads defined by Z1x1,Z1y1 ...
1320  !
1330   CALL Z1tog(Ax,Ay,Z1x(Khz,1),Z1y(Khz,1),Gx1,Gy1) ! Find points in Gain
1340   CALL Z1tog(Ax,Ay,Z1x(Khz,2),Z1y(Khz,2),Gx2,Gy2) ! space for each load
1350   CALL Z1tog(Ax,Ay,Z1x(Khz,3),Z1y(Khz,3),Gx3,Gy3) ! for given A value.
1360  !
1370   CALL Cir(Cx,Cy,R,Gx1,Gy1,Gx2,Gy2,Gx3,Gy3) ! Find circle in G space
1380   Goh=R+SQR(Cx^2+Cy^2)  ! Evaluate maximum gain
1390   Gohdb=20.”LGT(Goh)
1400   !
1410   SUBEND! ----------=-----------------------------------------------
1420   !
1430   SUB Cir(Cx,Cy,R,X1,Y1,X2,Y2,X3,Y3)
1440   ! Solves for circle passing thru (X1,Y1)... for center Cx,Cy and radius R
1450   !
1460   Var1=X2^2-X1^2+Y2^2-Y1^2
1470   Var2=X3^2-X2^2+Y3^2-Y2^2
1480   M11=2.*(X2-X1)
1490   M12=2.*(Y2-Y1)
1500   M21=2.*(X3-X2)
1510   M22=2.*(Y3-Y2)
1520   Mdet=M11*M22-M12*M21
1530   Cx=(M22*Var1-M12*Var2)/Mdet  ! Circle center
1540   Cy=(M11*Var2-M21*Var1)/Mdet  ! Circle center
1550   R=SQR((X1-Cx)^2+(Y1-Cy)^2)   ! Circle radius
1560 SUBEND!-----------------------------------------
1570   !
1580 SUB Z1tog(Ax,Ay,Z1x,Z1y,Gx,Gy)
1590   !
1600   COM /Rtermc/ Rterm
1610   !   This calculates the gain from the transmitter to the hybrid output.
1620   ! Ax and Ay are the real and imaginary parts of the gain to the non-inv
1630   ! input of the op-amp. The value of the line transformer terminating
1640   ! resistor is the variable rterm, passed through common.
1650   !
1660   ! Compute inverting gain
1670   Rden=Z1x+Rterm
1680   Iden=Z1y
1690   Absden=Rden^2+Iden^2
1700   Gxi=(Z1x*(Z1x+Rterm)+Z1y^2)/Absden
1710   Gyi=Rterm*Z1y/Absden
1720   !
1730   Gx=2.0*Ax-Gxi ! Sum non inverting and inverting
1740   Gy=2.2*Ay-Gyi ! gains
1750 SUBEND!------------------------------------------------
1760   !
1770   SUB Readz(Z1x(*),Z1y(*),Zterm) ! Reads impedance values from user
```


PrintDate=1999/10/12 PrintTime=07:11:38 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=12

```
1780    INPUT "Enter 1 Khz impedance no 1 ",Z1x(1,1),Z1y(1,1)
1790    INPUT "Enter 1 Khz impedance no 2 ",Z1x(1,2),Z1y(1,2)
1800    INPUT "Enter 1 Khz impedance no 3 ",Z1x(1,3),Z1y(1,3)
1810    INPUT "Enter 3 Khz impedance no 1 ",Z1x(3,1),Z1y(3,1)
1820    INPUT "Enter 3 Khz impedance no 2 ",Z1x(3,2),Z1y(3,2)
1830    INPUT "Enter 3 Khz impedance no 3 ",Z1x(3,3),Z1y(3,3)
1840  SUBEND!------------------------------------------------
1850  !
1860  SUB P11rc(A1,B1,A3,B3) ! Handles choice of R<&amp>C in non-inv. path
1870  !
1880  COM /Z/ Z1x(*),Z1y(*),Khz
1890  INPUT " Enter input resistor value",R1
1900  !
1910  CALL Rc(A1,B1,1000.,R1,R2,C2)
1920  CALL Rc(A3,B3,3000.,R1,R2,C2)
1930  !
1940  INPUT " Enter desired values of R2,C2 ",R2,C2
1950  PRINT " Chosen values : R2= ";R2;" C2 = ";C2
1960  FOR Khz=1 TO 3 STEP 2
1970   ! Khz is passed through common
1980   PRINT " "
1990   PRINT "At ";Khz;" KHz"
2000   CALL Eval (R1,R2,C2,1000.*Khz,A,B)
2010  NEXT Khz
2020  !
2030  SUBEND !------------------------------------------------------
2040  !
2050  SUB Rc(A,B,F,R1,R2,C2) ! Finds R2,C2 to give gain A+jB at F Hz.
2060  !
2070  Denom-A^2+B^2
2080  Theta=A/Denom
2090  Phi=-1.0*B/Denom
2100  !
2110  R2=R1/(Theta-1)
2120  C2=Phi/R1/2./PI/F
2130  !
2140  PRINT " "
2150  PRINT " Optimum hybrid component values at ";F;" Hz."
2160  PRINT " R1 = ";R1
2170  PRINT " R2 = ";R2
2180  PRINT " C2 = ";C2
2190  !
2200  SUBEND !-------------------------------------------------------
2210  !
2220  SUB Eval (R1,R2,C2,F,A,B) ! Evaluates hybrid of R1,R2,C2 at F
2230  !
2240  Theta=R1/R2+1.
2250  Phi=F*2*PI*C2*R1
2260  Denom=Theta^2+Phi^2
2270  A=Theta/Denom
2280  B=1.0*Phi/Denom
2290  PRINT " A value for chosen components ";A;" ";B;" j"
2300  CALL Gmax(Goh,A,B,Gohdb)
2310  PRINT " Transmitter rejection         ";Gohdb;" db"
2320  !
2330  SUBEND !-----------------------------------------------------
```

Book Extract End

PrintDate=1999/10/12 PrintTime=07:11:39 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=13

Notes

LIFE SUPPORT POLICY

NATIONAL'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT AND GENERAL COUNSEL OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

National Semiconductor Corporation
Americas
Tel: 1-800-272-9959
Fax: 1-800-737-7018
Email: support@nsc.com

www.national.com

National Semiconductor Europe
Fax: +49 (0) 1 80-530 85 86
Email: europe.support@nsc.com
Deutsch Tel: +49 (0) 1 80-530 85 85
English Tel: +49 (0) 1 80-532 78 32
Français Tel: +49 (0) 1 80-532 93 58
Italiano Tel: +49 (0) 1 80-534 16 80

National Semiconductor Asia Pacific Customer Response Group
Tel: 65-2544466
Fax: 65-2504466
Email: sea.support@nsc.com

National Semiconductor Japan Ltd.
Tel: 81-3-5639-7560
Fax: 81-3-5639-7507

PrintDate=1999/10/12 PrintTime=07:11:39 57586 an008428_p Rev. No. 1 cmserv **Proof** Seq=14