Understanding and Designing Sequence Asymmetric Polyphase Networks

The functioning of Polyphase networks described, a
spreadsheet macro to design them and useful tips
to get an optimum result

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1 Introduction.

Sequence Asymmetric Polyphase networks can be used as the quadrature processing network in a phasing type of SSB transmitter or receiver. These networks were patented by M.J. Gingell in the late 1960's.[1, 2] and are usually just called Polyphase networks. Thorough analyses of these networks have been published but the mathematics used is of a high level and the accompanying programs are written in FORTRAN which is not readily available for most Radio Amateurs[3].

The interest from the Radio Amateur community in the 70's and 90's[4, 5, 6, 7, 8, 9] of last century recently revived with the publication of Direct Conversion receivers and transmitters using the commutating (Tayloe) detector[10, 11, 12, 13, 14, 15]. A block diagram of such a receiver using a commutating detector and a Polyphase network is shown in Figure 1.
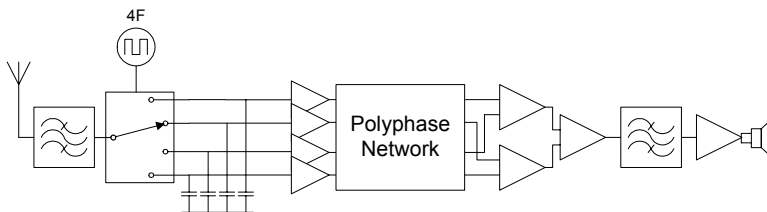

Figure 1. Block diagram of a receiver using a commutating (Tayloe) detector and a Polyphase network.

Reversing the signal flow, rearranging the Polyphase network connections and omitting the 4 capacitors will turn this circuit into a SSB transmitter, see Figure 2
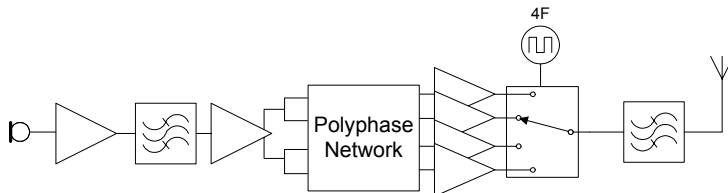
Figure 2, Block diagram of a transmitter using a commutating (Tayloe) detector and a Polyphase network.

Using basic electronics theory this article explains the functioning of a Polyphase network. For designing Polyphase networks a spreadsheet macro is presented. This macro not only plots the unwanted sideband rejection ratio but also insertion loss, input-impedance and output-impedance. Finally some general design rules for Polyphase networks are listed.

2 Polyphase networks and Polyphase signals.

Polyphase networks come in different shapes and forms[1,2].The most commonly used one by Radio Amateurs is an eight port and has 4 identical nodes per segment. Each node has one Resistor and one Capacitor and the electrical diagram of it is shown in Figure 3. These networks are mainly used by Radio Amateurs for audio quadrature processing. However they function just as well on RF[16,17].

Figure 3. A 4 node, 1 segment Polyphase network. x is n or p depending on the phase sequence of the Polyphase signal applied to the inputs 1, 2, 3 and 4

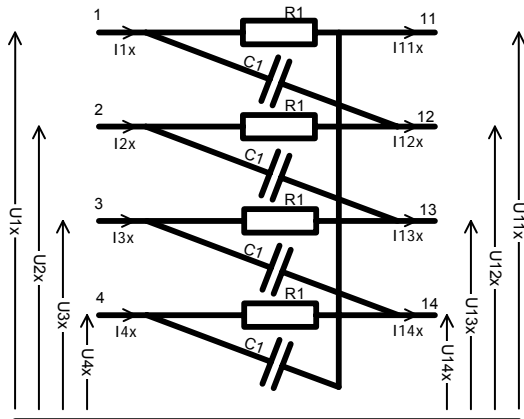In 1918 C.L. Fortesque published the general theory analyzing n-phase systems.[18] His theory is used mainly for 3 phase AC power systems. It is also applicable to 4 phase systems which are used with Polyphase networks. The Polyphase signals defined and used in the next paragraphs are a subset of his general n-phase theory.

For this discussion, let us define a Polyphase signal as:

- A set of n vectors, each of which corresponds to a voltage
- The vectors are of equal magnitude
- The vectors are uniformly distributed over 360°.

A Polyphase signal with n=4 will have 90° phase difference between the vectors and is therefore useful in a phasing type of SSB exciter/detector.

Now let's take a set of 4 voltages as shown in Figure 4.a. It is a Polyphase signal as defined above and 1p is leading 2p by 90º, 2p is leading 3p etc. We can call this a Polyphase signal with a positive phase sequence. To emphasize this, vectors are drawn in red and the suffix p is added to the identification of each vector.

It will not be a surprise that you can also define a Polyphase signal with a negative phase sequence. Here 1n is lagging 2n by 90º; 2n is lagging 3n by 90º, etc. To emphasize the negative phase sequence the voltage vectors are drawn in blue in Figure 4.b and the suffix n is added to the identification of each vector.
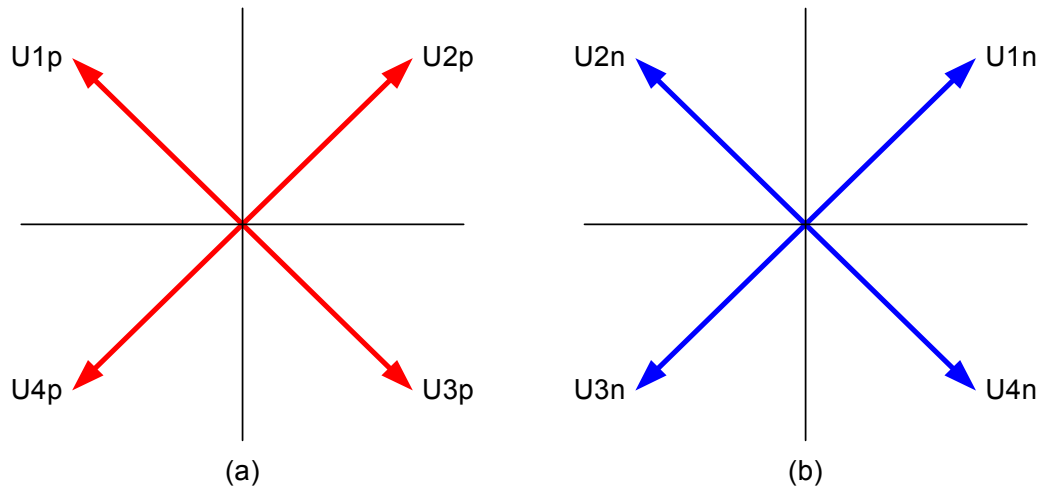
Figure 4. Two Polyphase signals. (a) has a positive phase sequence, (b) has a negative phase sequence.

When we connect the Polyphase signal of Figure 4.a to the inputs 1, 2, 3 and 4 of the unterminated Polyphase network of Figure 3 the relation between the input and output voltages is:

$$U_{Sp} = U_{1Sp} . \frac{1 + j.\omega.R.C}{1 - \omega.R.C} \quad {}_{\substack{S=1,2,3,4 \\ \omega=2.\pi.f}} \quad \text{Eq. 1}$$

Paragraph 10.2 explains how to get to this formula and the next one.

If $\omega RC=1$ we will have **no** output voltage. For other frequencies U_{1Sp} will be a fraction of U_{Sp}.

Now let's connect a Polyphase signal with a negative phase sequence to the inputs of the Polyphase network of Figure 3. Then the relation between input and output voltages is:

$$U_{Sn} = U_{1Sn} . \frac{1 + j.\omega.R.C}{1 + \omega.R.C} \quad {}_{\substack{S=1,2,3,4 \\ \omega=2.\pi.f}} \qquad \text{Eq. 2}$$

With this signal applied to the inputs we will **always** have an output voltage, irrespective of the frequency. Figure 5 shows the Gain of the network for the two Polyphase signals with a different phase sequence.
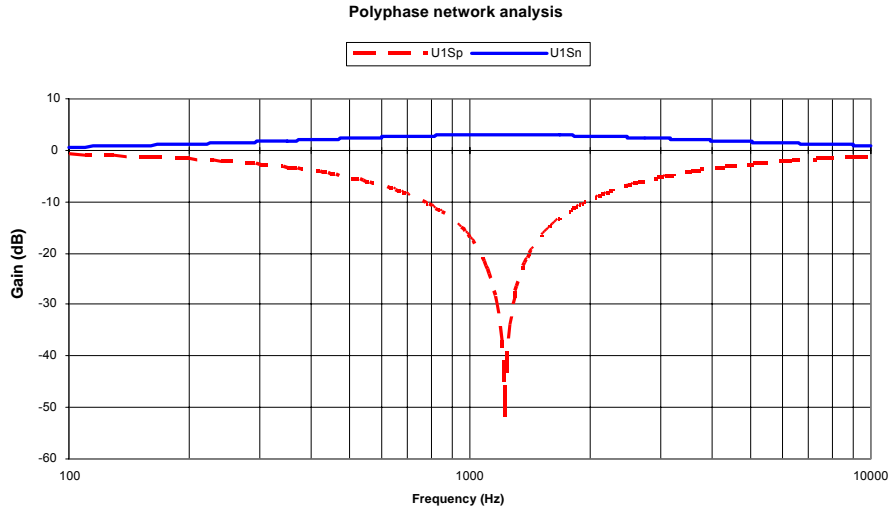
Figure 5. Gain of a Polyphase network for a Polyphase signal with a positive (U_{1Sp}) and negative (U_{1Sn}) phase sequence.

3   Going from Push-Pull to Polyphase

Now it's all good and well that we can change the attenuation of the Polyphase signal through the Polyphase network by selecting the phase sequence, but we want to generate a Polyphase signal, not attenuate it. So let's see what happens when we apply both Polyphase signals at the same time to the input of the Polyphase network. The voltages at pin 1, 2, 3 and 4 can be determined by vector addition of both Polyphase signals. The result will depend on the phase difference between the two Polyphase signals and will often result in 4 different voltages at the input to the network. For one angle however something interesting happens, see Figure 6
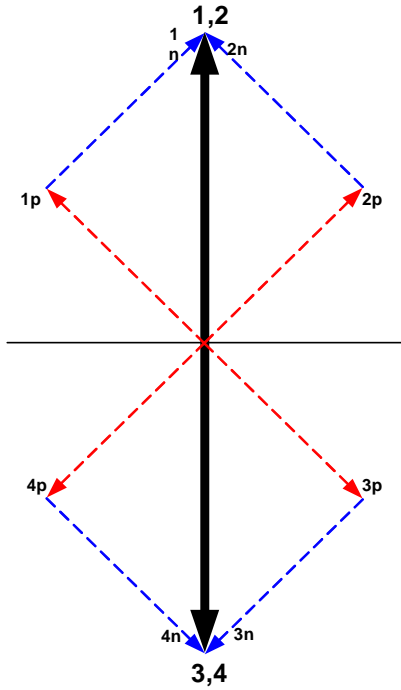
Figure 6. Determining the resulting input voltages for pin 1, 2, 3 and 4 when a Positive and Negative phase sequence Polyfase signal are applied at the same time

The result is a symmetrical set of four voltages or phasors.

But it is not a Polyphase signal! The 4 resulting voltages are not evenly distributed over a full circle anymore. The phase difference between 1 and 2 and 3 and 4 is 0º but between 1 and 3 and 2 and 4 it is 180º. However since the voltages have 180º phase difference between them they can easily be generated with a simple inverting and non-inverting op-amp circuit.

We have applied the sum of the two Polyphase signals to the inputs of the Polyphase network. Identical to determining the resulting input voltages the voltages at the output pin's 11, 12, 13, 14 can also be determined by vector addition. See Figure 7
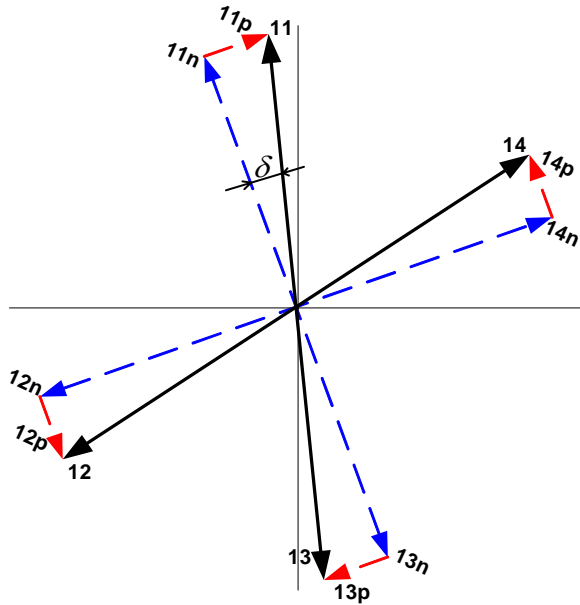
Figure 7. The voltages at the output can be determined by vector addition of the resulting voltages of the two Polyphase signals.

If $\omega RC=1$ vectors 11p, 12p, 13p 14p will disappear because of Eq. 1. At pin 11, 12, 13 and 14 we will then have a Polyphase signal with a negative phase sequence while we started with a push-pull signal at the input.

So we are getting somewhere, at $\omega RC=1$ we will have perfect quadrature signals at the output of the network. However, it only works perfectly at one frequency. As soon as $\omega RC \neq 1$ the output signals are not exactly in quadrature anymore. For the frequency range of the human voice between 300 and 3000 Hz we need something more.

4 Cascading Polyphase network segments.

Figure 6 and Figure 7 show that a single segment Polyphase network can convert a push-pull signal into a Polyphase (or quadrature) signal. But it does it only perfect for one frequency. To cover the range of say 300-3000Hz we can cascade Polyphase network segments and accept some errors (Figure 7. For a cascade of for example 4 segments we will get a circuit as shown in Figure 8
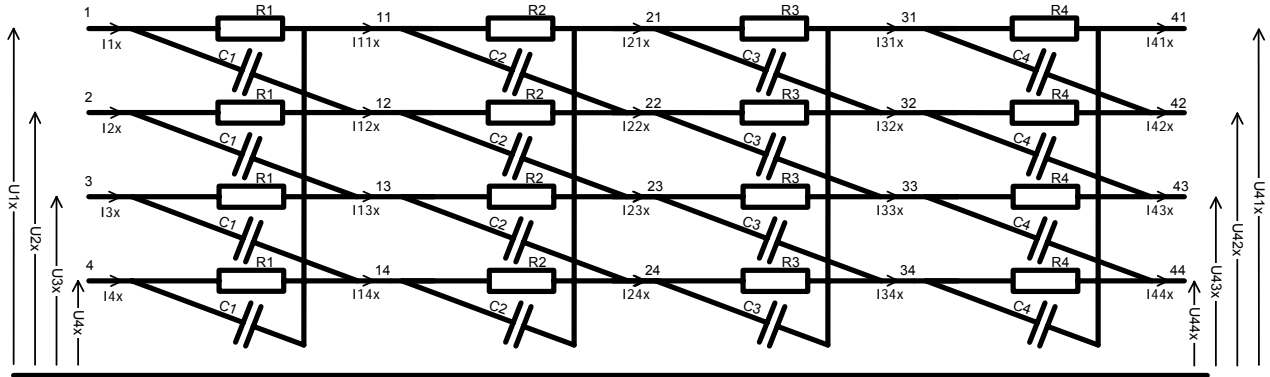
Figure 8. A 4 segment Polyphase network. By selecting different RC values for each segment nearly perfect Quadrature signals can be generated over a certain frequency range.

5 Design parameters for a Polyphase network.

Ok so we will have to accept some errors in the quadrature output of the Polyphase network. Now what are the consequences of these errors? If we know that we can accept a certain quality of SSB signal or design a better Polyphase network.

In a phasing type of SSB exciter or receiver the rejection of the unwanted sideband is mainly determined by the accuracy of the audio phase shift network. Not only the amplitude balance has to be correct but also the two audio signals have to be exactly in quadrature. If either amplitude or phase is not correct the unwanted sideband will come up.

The same is true for the RF phasing circuit part of the exciter or receiver. But, due to the limited frequency range or the use of digital circuits this is a lot easier to achieve.

Note that Amplitude and Phase errors are orthogonal in a phasing type of SSB exciter. This means that a phase error can not be trimmed out by adjusting amplitudes and vice versa. The amplitude balance can be kept under control by using precision components or a potentiometer somewhere in the circuit to trim it[19].

5.1 *Phase error*

The phase error will be determined for a large part by the design of the Polyphase network. If we call the deviation from quadrature, or 90° degrees, the phase error δ, the ratio between the two sidebands *S* in a phasing type of exciter is given by[4,19].

$$S = -20\log\left(tg\left(\frac{1}{2}\delta\right)\right) \quad \text{Eq. 3}$$

The phase error δ, or the suppression ratio S, is the most important parameter for a Polyphase network.
If we design a Polyphase network which has a phase error δ of 1º the unwanted sideband S will be 41 dB below the wanted sideband. Or, if we want a network where S is 50 dB the phase error δ must be smaller then 0,18º.

5.2 *Normalized Phase Angle*

If you design a Polyphase network for different values of rejection of the unwanted sideband the phase error δ varies over a quite large range. For S = 30 dB the phase error δ equals 3.6º. For S = 60 dB δ is only 0.11º. I therefore defined the Normalized Phase error P as:

Eq. 4

$$P = \frac{\delta}{2.arctg(10^{-\frac{Sdesign}{20}})}$$

Sdesign is the minimum rejection for which you are designing the Polyphase network. If P is between +1 and -1 for the required frequency range the design is fulfilling the requirements. The Normalized phase error shows in one curve how good the designed network meets the rejection design criteria. If the curve goes outside the +/-1 range you are not meeting the rejection criteria. If it stay's close to 0 you have used to many segments in the Polyphase network. The unwanted sideband rejection curve shows the same data as the Normalized Phase error curve. However due to the tangent and log functions it has the nasty habit of going to infinity at the RC points. The normalized phase error curve does just go to zero and allows for easier visual optimization of the design.

5.3 *Insertion Loss*

In an exciter a bit of loss in the audio path is not so much of an issue. When used in a receiver excessive insertion loss of the audio quadrature network can affect receiver performance. The Insertion loss, or negative gain, of a Polyphase network is therefore also an important parameter.

5.4 *Other parameters.*

Phase error and insertion loss are the most important parameters of a Polyphase network. But since we are designing a network we would also like an answer to the following questions:

- What are the input and output impedances of the final network
- What are the influences of driving and loading resistances of the network

Answering all these questions and calculating these parameters is a perfect job for a computer who can make some graphs to visualize it all.

6 Reducing an eight-port Polyphase network to a two-port.

A four node Polyphase network like in Figure 3 can be called an eight-port network. It has four inputs and four outputs. Calculating the performance of the network of Figure 8 using eight-port

theory gets rather complicated as Schmidt[3] shows. For calculating the parameters of two-port systems much simpler chain or ABCD matrices can be used.

Now don't get afraid of this!

You probably know how to calculate the total gain of two cascaded amplifiers. If you do this properly and take care of input and output impedances you are already using all the elements of ABCD matrices. ABCD matrices are especially useful for cascaded two-port systems like RC filters or amplifiers[20]. When you cascade two two-port systems you multiply the ABCD matrices of each individual system with each other to get the ABCD matrix of the cascaded system.

Now let us see if we can still use somehow ABCD-matrices for determining the response of a multi segment Polyphase network.

Let's go back to the definitions of the Polyphase network and the Polyphase signal. In a single segment Polyphase network all Resistors and Capacitors are equal. In a Polyphase signal all voltages have equal amplitude and an equal phase difference between them. So, if you know the value of one Resistor you know the value of all other Resistors. If you know how one output is loaded you know how the other three outputs are loaded. The same is true for the Capacitors, Input voltages etc. In parallel with basic transistor h-parameter theory, you can view the Polyphase network of Figure 3 as a circuit with one input, one output and with "dependable" R's, C's and voltage sources interconnected[4]. The resulting diagram is shown in Figure 9. The fact that voltage sources and impedances inside the two-port depend on what is connected to the two-port is emphasized by making these components grey.
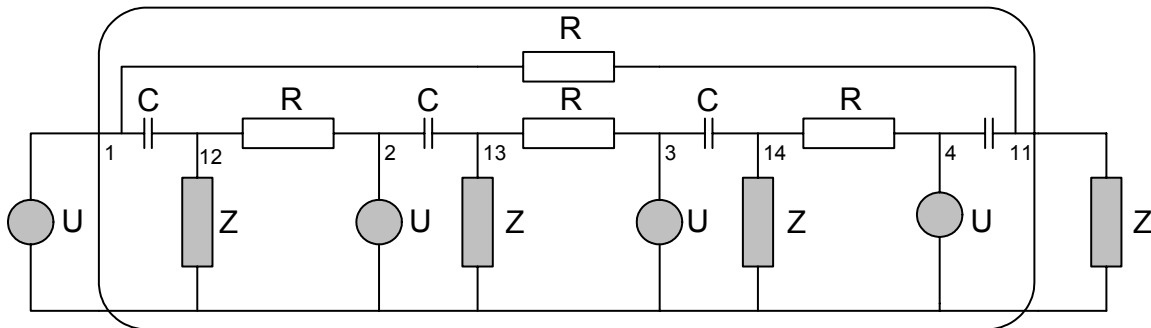
Figure 9. A one segment Polyphase network redrawn as a two-port with dependable components.

By applying the two Polyphase signals from Figure 4a and Figure 4b to the Polyphase network it can be shown that the ABCD matrix for the positive phase sequence Polyphase signal is[4]:

$$\begin{pmatrix} U_{Sp} \\ I_{Sp} \end{pmatrix} = \frac{1}{1-\omega RC} \cdot \begin{pmatrix} 1+j.\omega.R.C & R \\ 2.j.\omega.C & 1+j.\omega.R.C \end{pmatrix} \cdot \begin{pmatrix} U_{1Sp} \\ I_{1Sp} \end{pmatrix}_{S=1,2,3,4} \quad \textbf{Eq. 5}$$

For the negative phase sequence Polyphase signal it is:

$$\begin{pmatrix} U_{Sn} \\ I_{Sn} \end{pmatrix} = \frac{1}{1+\omega RC} \cdot \begin{pmatrix} 1+j.\omega.R.C & R \\ 2.j.\omega.C & 1+j.\omega.R.C \end{pmatrix} \cdot \begin{pmatrix} U_{1Sn} \\ I_{1Sn} \end{pmatrix}_{S=1,2,3,4} \quad \textbf{Eq. 6}$$

Paragraph 10.1 and 10.2 explains how to get to these equations but in the mean time look carefully at them. Eq. 5 and Eq. 6 are caused by the two different phase sequences and the only difference between them is the factor with which the matrices are multiplied. (Hence the words "sequence asymmetric" in the official name of these networks). U_{1Sp} will be zero at $\omega RC=1$ independent of the load of the network. Also connecting another Polyphase segment with its own R and C values will not influence the frequency for which the first segment will produce a Polyphase signal. Now if we cascade a few Polyphase network segments with their individual RC values spread over the audio voice spectrum we will end up with a network which produces a nearly perfect quadrature signal for the voice spectrum.

If we want to know the ABCD-matrices for a 2 segment Polyphase network all we have to do is multiply the ABCD-matrices of each individual segment with each other. The result of this will be another set of two A-matrices. When we add another segment we just multiply the ABCD-matrices for the 2-segment network with the ABCD-matrices of the new segment to get the ABCD-matrices for the 3-segment Polyphase network. And of course this process can be repeated for every segment added. But, even calculating the output voltage for only one frequency becomes a tedious and error prone job.

7 Designing a Polyphase network with a spreadsheet Macro

Calculating the ABCD-matrices elements of a multi segment Polyphase network for a single frequency is already quite a job. If you want to cover the 300-3000 Hz. frequency range in 10Hz steps it becomes a nightmare. So that's were the computer comes in. I wrote the very first version of this program way back in 1978[4]. Recently I converted this program to a Macro for Excel. Computer performance has increased tremendously since 1978 and calculation time is down to seconds now on a standard desktop PC. I therefore also implemented Jan Verduyn's idea to calculate the data for two Polyphase networks so that comparing different networks is easily done.[21] As the signal source for the Polyphase network the signal of Figure 6 is assumed. The Excel macro contains a few nested For-Next loops in which it calculates all the matrix elements for a specified frequency range. There is a possibility to take in account the effect of the signal source impedances and load impedances of the network. Then it calculates phase error, gain, input impedance, output impedance and the normalized phase error.

7.1 *Using the Macro*

The complete spreadsheet with embedded macro can be found on the Internet[22]. In the cells with a Gray background data can be entered. Resistor and Capacitor values for two networks go in the upper left area of the main sheet. Below that is a possibility to enter source and terminating resistance for the networks. If nothing is entered there it is assumed that the network is driven by ideal voltage sources and that the outputs are not terminated. Then press on the Gray pushbutton bar as indicated in the spreadsheet. Within a few seconds the plot of the rejection vs. frequency will appear, see Figure 10. Within a few iterations of changing values, you end up with a Polyphase network meeting your design specifications. To get started, below the Gray "Click here to calculate" cell, there is a library of Polyphase network designs published by various people over the last 30 years. Additional information on where the design was published is in the comment field of the header of the individual design.
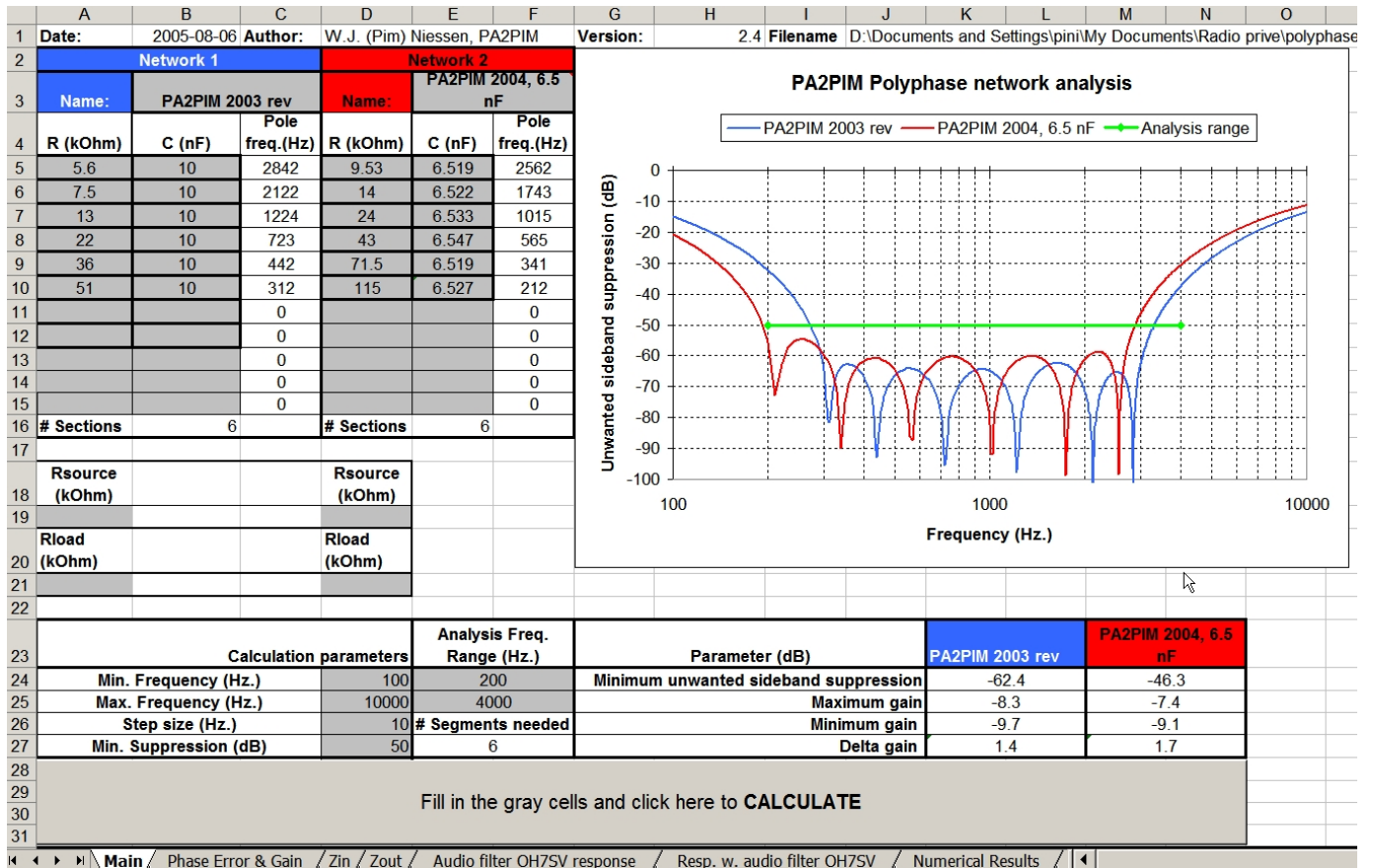
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Date:	2005-08-06	Author:	W.J. (Pim) Niessen, PA2PIM			Version:		2.4	Filename	D:\Documents and Settings\pini\My Documents\Radio prive\polyphase				
2		Network 1			Network 2										
3	Name:	PA2PIM 2003 rev		Name:	PA2PIM 2004, 6.5 nF										
4	R (kOhm)	C (nF)	Pole freq.(Hz)	R (kOhm)	C (nF)	Pole freq.(Hz)									
5	5.6	10	2842	9.53	6.519	2562									
6	7.5	10	2122	14	6.522	1743									
7	13	10	1224	24	6.533	1015									
8	22	10	723	43	6.547	565									
9	36	10	442	71.5	6.519	341									
10	51	10	312	115	6.527	212									
11			0			0									
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15			0			0									
16	# Sections	6		# Sections	6										
17															
18	Rsource (kOhm)			Rsource (kOhm)											
19															
20	Rload (kOhm)			Rload (kOhm)											
21															
22															
23		Calculation parameters		Analysis Freq. Range (Hz.)			Parameter (dB)				PA2PIM 2003 rev		PA2PIM 2004, 6.5 nF		
24	Min. Frequency (Hz.)		100	200			Minimum unwanted sideband suppression				-62.4		-46.3		
25	Max. Frequency (Hz.)		10000	4000			Maximum gain				-8.3		-7.4		
26	Step size (Hz.)		10	# Segments needed			Minimum gain				-9.7		-9.1		
27	Min. Suppression (dB)		50	6			Delta gain				1.4		1.7		
28															
29															
30				Fill in the gray cells and click here to **CALCULATE**											
31															

Main / Phase Error & Gain / Zin / Zout / Audio filter OH7SV response / Resp. w. audio filter OH7SV / Numerical Results /
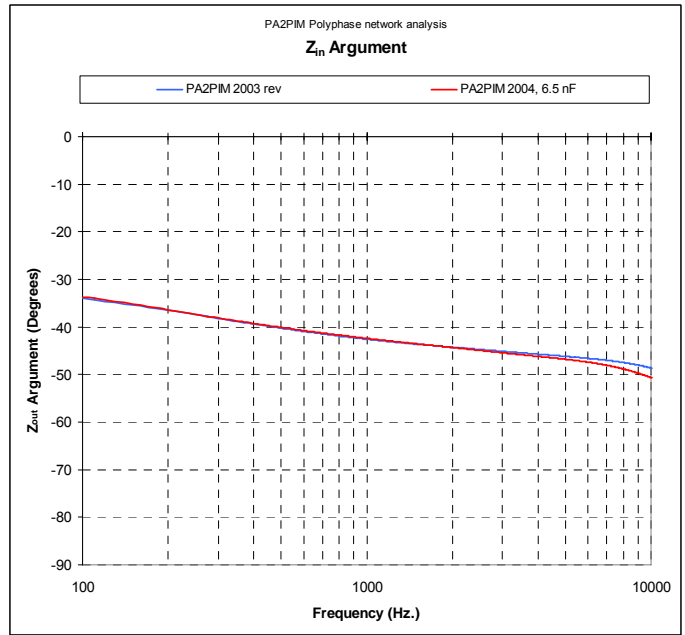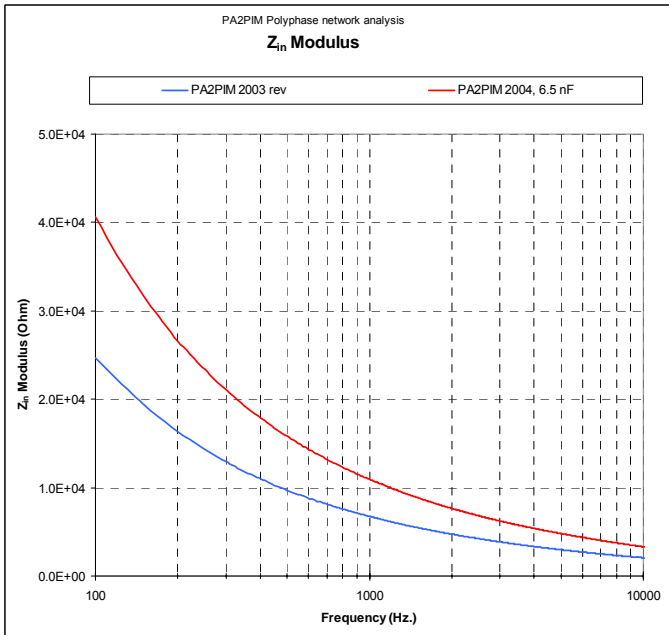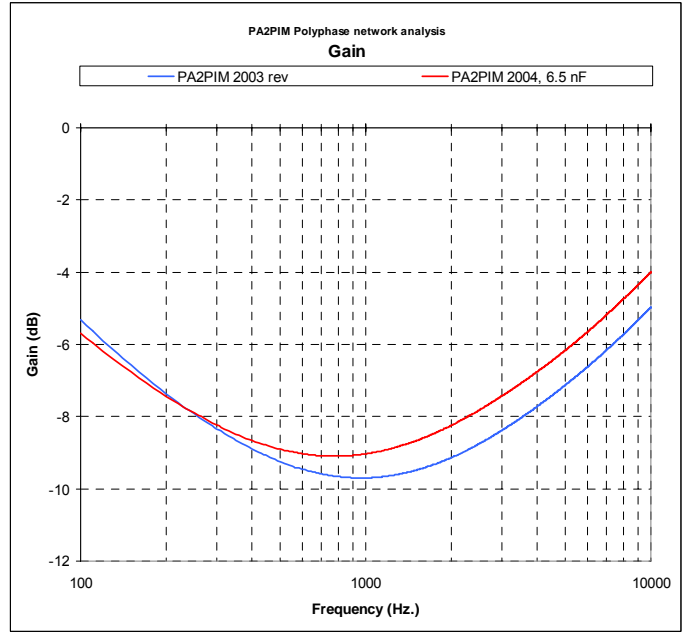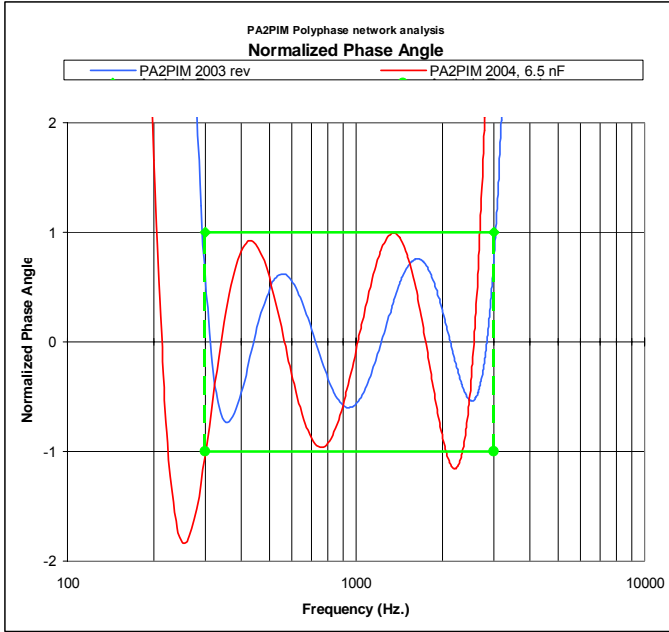
Figure 10. Main sheet of the Spreadsheet with the unwanted sideband suppression plotted for two different Polyhase networks.

Figure 11 shows the other graphs produced by the spreadsheet:

- Normalized Phase error
- Gain
- Input-impedance (Modulus and Argument)
- Output-impedance (Modulus and Argument)

The green lines in the Normalized phase error curve are an aid in determining if the network meets the design criteria for the unwanted sideband suppression. If the plotted curves stay in between the green solid lines the design criteria is met.
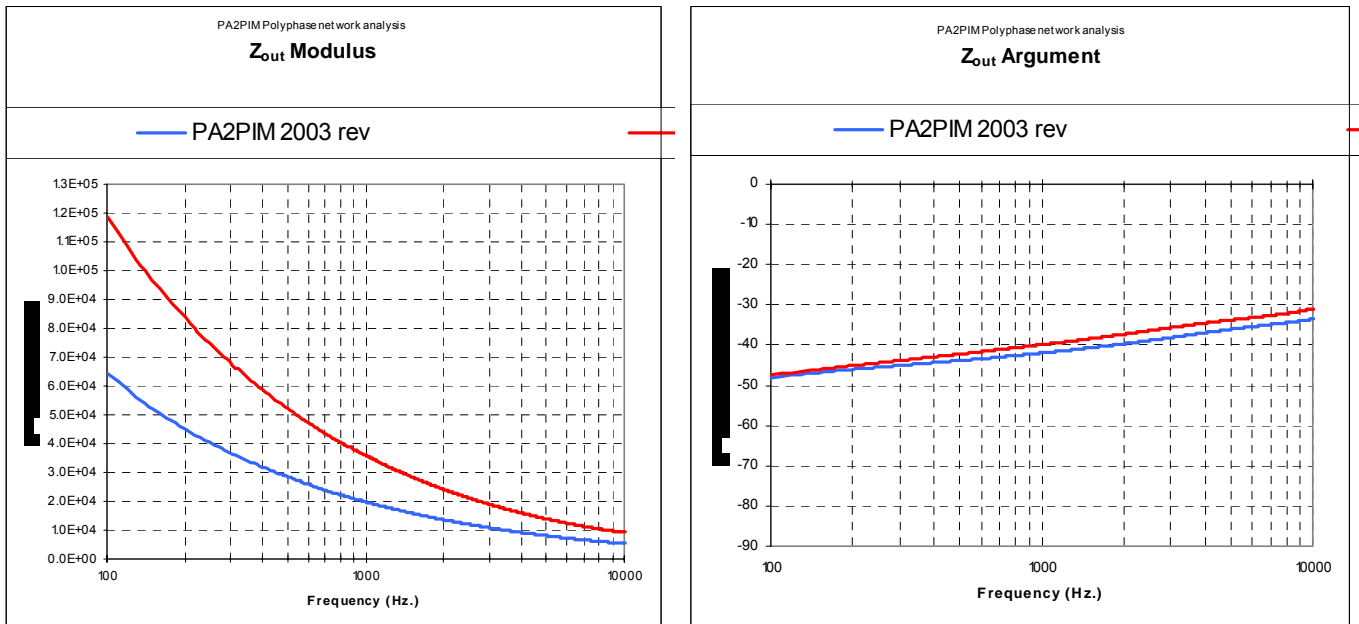
PA2PIM Polyphase network analysis
Normalized Phase Angle

PA2PIM Polyphase network analysis
Gain

PA2PIM Polyphase network analysis
Z$_{in}$ Modulus

PA2PIM Polyphase network analysis
Z$_{in}$ Argument

Figure 11. Various other parameters of the designed Polyphase networks are produced by the spreadsheet.

8 Ten tips for designing Polyphase networks

When designing and implementing Polyphase networks quite a number of choices have to be made. The 10 most important ones are listed below.

8.1 *How many segments to use.*

From various publications[3, 4, 23] a rule of thumb for the number of sections can be derived.

- For a frequency range of 1 to 10 you will need one segment for every 10 dB of unwanted sideband suppression, i.e. 5 sections will give you 50 dB suppression over the 300-3000 Hz range.
- Every doubling of frequency range requires an additional segment, i.e. 6 sections will give you 50 dB suppression over the 300-6000 Hz. range.

In formula form this can be written as:

$$N = Log_2\left(\frac{F_{max}}{10 * F_{min}}\right) + \frac{M}{10} \qquad \text{Eq. 7}$$

N = Number of segments of the Polyphase network
Log_2 = Log function with Base 2
$Fmax$ = Maximum frequency for the network
$Fmin$ = Minimum frequency for the network
M = Minimum suppression of the unwanted sideband

This formula is used to calculate the number of needed segments listed at cell F27 of the spreadsheet.

8.2 *Selecting RC values for segments*

Kevin Schmidt (W9CF)[3] provides in his QEX publication the optimum values for the RC points. (Chebyshev). An approximation is to put the RC point's equidistance between F_{min} and F_{max} on a logarithmic scale[4]. Start by putting the first RC point at F_{min}.

In formula form this can be written as:

$$Rx.Cx = \frac{\left(\sqrt[N-1]{\frac{F_{max}}{F_{min}}} \right)^{(1-x)}}{2.\pi.F_{min}} \quad x = 1,2...N \quad \text{Eq. 8}$$

N = Number of segments of the Polyphase network
Fmax   = Maximum frequency for the network
Fmin   = Minimum frequency for the network

Calculate the *Rx* en *Cx* values using the above formula and then move the first and last RC point 5-10% inside the frequency range of the network. That will result in a rather good approximation of the ideal Chebyshev values.

A pragmatic approach would be to have a look at the library of designs in the main sheet of the spreadsheet.

8.3 *Place the most accurate components at the output*

A Polyphase network is self correcting for phase errors which occur near the input of the network. Figure 7 shows that a phase error is caused by a residual Polyphase signal with a positive phase sequence. Network segments further in the signal path will still attenuate this positive phase sequence signal. A Polyphase signal with a positive phase sequence and a frequency of half the $\omega RC=1$ frequency of a segment still gets attenuated by 6 dB. Obviously, this effect does not occur at the last segment of the network and that is why the most accurate components have to be placed at the output. Actual RC values for any segment of a Polyphase network are of secondary importance. It is more important that the components per segment are matched to each other.

8.4 *Insertion loss depends on the signal direction.*

The insertion loss of a Polyphase network depends on the signal direction through the network:

- o For a network with the same Resistors in each section the Insertion loss will be minimum when the smallest Capacitors are put at the output of the network. I.e. the smallest RC product must be put at the output.
- o For a network with the same Capacitors in each section the insertion loss will be minimum when the largest Resistors are put at the output of the network. I.e. the largest RC product must be put at the output.

- o The RC products for each section must either increase or decrease from input to output for minimizing the Insertion loss.

Figure 12 shows what happens to the insertion loss when not obeying these rules: Reversing a Polyphase network will result in a difference in Insertion loss of 9-10 dB.
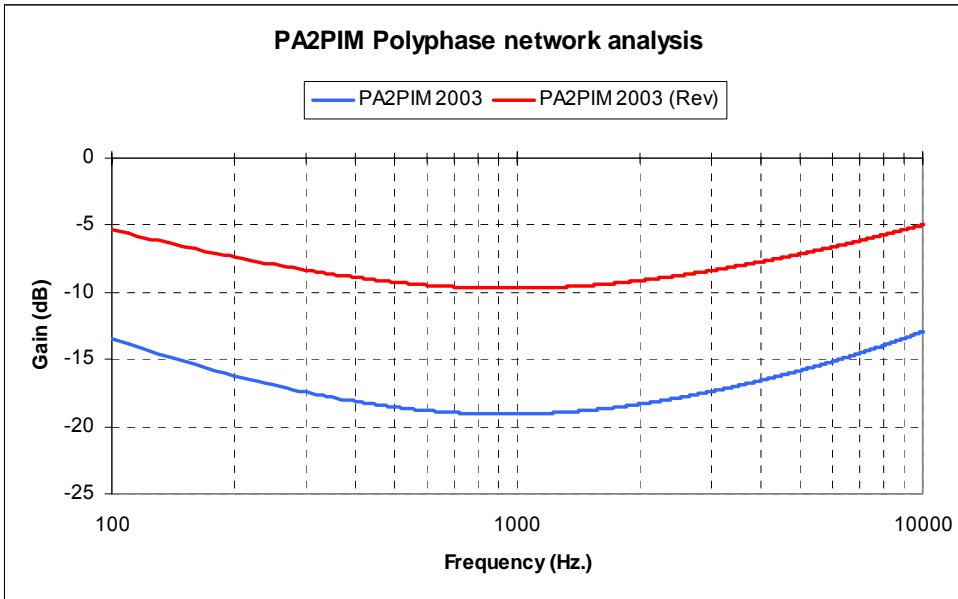

Figure 12. The insertion loss of a Polyphase network with equal Capacitors depends on the signal direction through the network

8.5 *Use the same Capacitors for each segment*

This is a more practical then technical tip. Unlike low tolerance Capacitors low tolerance Resistors are readily available and affordable. Therefore design a network using the same Capacitor value in each segment and obtain a more then sufficient amount of them. Measure the values and put the four capacitors with the least spread among them at the output of the network[5,24]. From the remaining capacitors select again the four with the least spread and put these at the one but last segment of the network. Repeat this step working your way to the input segment of the network.

8.6 *Match audio filter and Polyphase network performance*

The unwanted sideband suppression rapidly decreases outside the design frequencies of the Polyphase network. However, there is also an audio filter which suppresses the unwanted sideband! The overall unwanted sideband suppression of the SSB receiver/transmitter is determined by both circuits. The unwanted sideband suppression of the Polyphase network of Figure 13 is not ideal. Look at the blue curve, below 300 Hz and above 3000 Hz the unwanted sideband comes up rapidly.
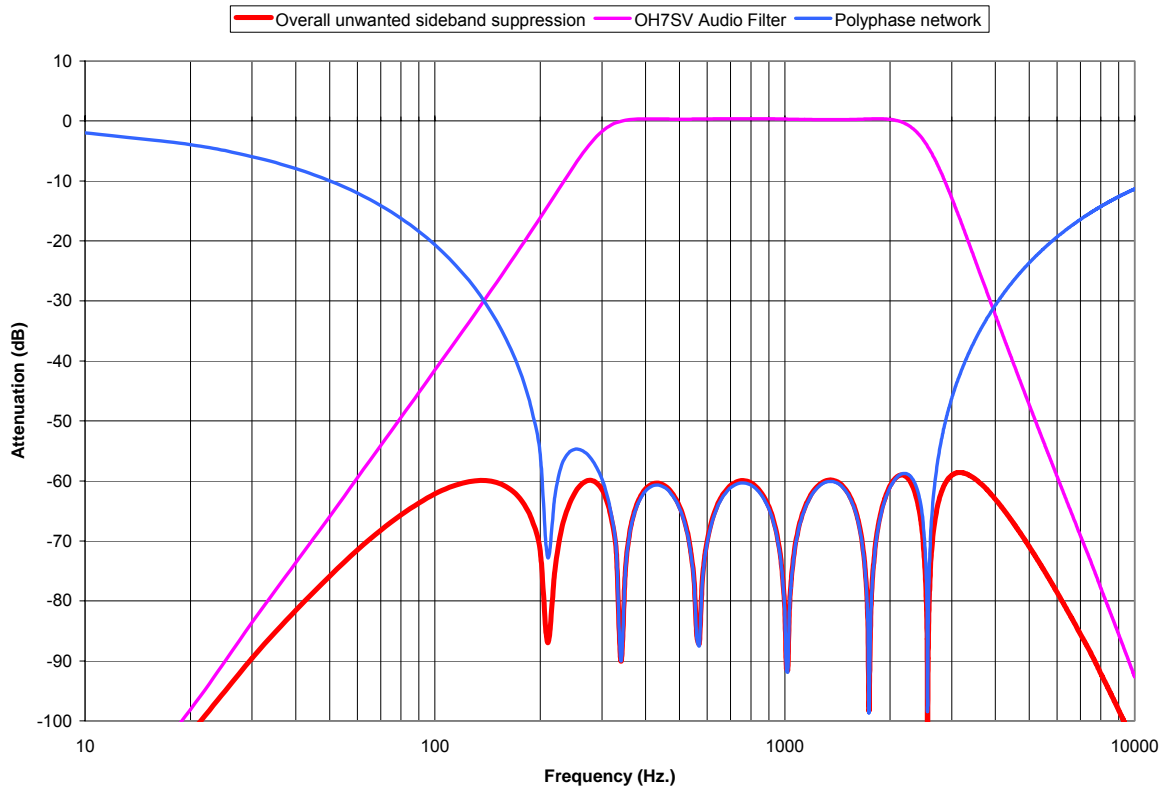
Figure 13. Overall unwanted sideband attenuation is determined by the Polyphase network and the Audio filter

The response of an audio filter designed by OH7SV[14] is shown in the Purple curve. Both circuits together produce the red curve, an unwanted sideband suppression of > 59 dB over the whole frequency range.

8.7 *Keep the design and the implementation symmetrical*

The Polyphase network has four inputs and four outputs. Using only two of the four outputs will unbalance the network.

When building the Polyphase circuit take care that the physical layout is also symmetrical, see Figure 14.
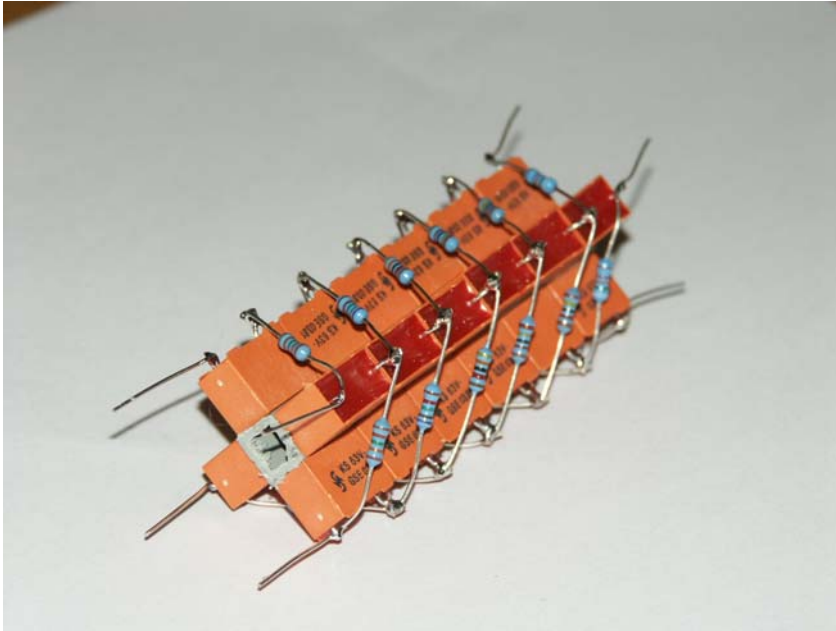
Figure 14. "Corncob" construction style provides a symmetrical implementation of a Polyphase network.

This is one way of keeping the parasitic capacity identical for each input and output. Especially when using the JA1KO design with its high Resistor values and small Capacitors this can be an issue.

8.8 *Avoid using coupling- and decoupling Capacitors.*

A rule of thumb in Electronics is to choose coupling- and decoupling Capacitors so that at the lowest frequency the impedance is ten times lower then the load of that Capacitor.

Assume now that:

- The value of a decoupling Capacitor in the audio circuit was chosen using the above rule of thumb
- This coupling Capacitor, present in both audio paths, deviates by +/- 10%. For electrolytic Capacitors with -20/+50% tolerance this is a realistic assumption.

This capacity difference will introduce a phase difference between the two audio signals. Assuming there are no other errors in the whole exciter or receiver, this 10% spread in decoupling Capacitor value alone will be responsible for an unwanted sideband suppression of only 46 dB[4]. Coupling- and decoupling Capacitors can not always be avoided. However, choose their value at least ten times larger then normal.

8.9 *JA1KO design requires very high terminating impedances*

Polyphase networks designed using the method of JA1KO use component values spread over several decades. The result is a 0 dB insertion loss for an unterminated network. Terminating the outputs of these networks with say 1 MΩ will result in a high pass filter response. With the rather

small Capacitors used in these designs, parasitic capacity can also be an issue for high performance circuits.

8.10 *Be realistic*

As stated in paragraph 5 the unwanted sideband level is not only determined by the phasing errors of the Polyphase network. It is therefore not very useful to design a Polyphase network for 80 dB of unwanted sideband suppression. The requirements for component tolerance to obtain this are unachievable in practice. With careful construction and proper component selection 60 dB of unwanted sideband suppression is achievable[14,16].

9 Conclusion

This document explains the functioning of Polyphase networks and how they can be used in phasing type of SSB circuits. The Excel Macro presented enables one to design a Polyphase network within a few minutes. The design tips will lead to a successful implementation of the designed network. Choosing the right signal direction through the network will minimize the insertion loss, a fact overlooked in some published designs.

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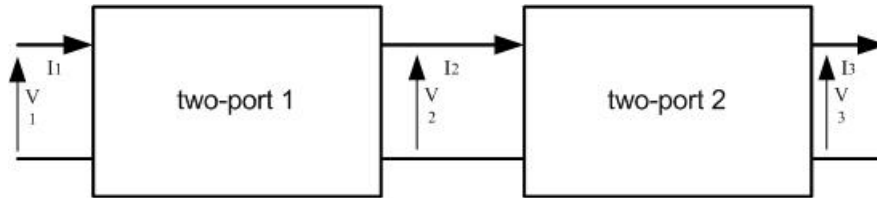
10 Appendix

10.1 *ABCD matrices*

Figure 15. Two cascaded two-ports.

For the two cascaded two-ports of Figure 15 we can write down the following equations:

$$V_1 = A_1.V_2 + B_1.I_2$$

Eq. 9

$$I_1 = C_1V_2 + D_1.I_2$$

Eq. 10

$$V_2 = A_2.V_3 + B_2.I_3$$

Eq. 11

$$I_2 = C_2.V_3 + D_2.I_3$$

Eq. 12

Entering Eq. 9 and Eq. 10 in Eq. 11 and Eq. 12 and grouping the result we get

$$V_1 = (A_1.A_2 + B_1.C_2).V_3 + (A_1.B_2 + B_1.D_2).I_3$$

Eq. 13

$$I_1 = (C_1.A_2 + D_1.C_2).V_3 + (C_1.B_2 + D_1.D_2).I_3$$

Eq. 14

Eq. 9 and Eq. 10 can also be written very compact using matrix notation:

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \cdot \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}$$

Eq. 15

Doing the same for Eq. 11 and Eq. 12 results in:

$$\begin{pmatrix} V_2 \\ I_2 \end{pmatrix} = \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} \cdot \begin{pmatrix} V_3 \\ I_3 \end{pmatrix}$$

Eq. 16

A_1, B_1, C_1, D_1 and A_2, B_2, C_2, D_2 are the elements of the ABCD matrices of two-port 1 and two-port2
The ABCD matrix is a complete electrical description of a two-port. Now matter how complex the circuit inside the two-port, if you know the ABCD matrix of it you know how it will behave under all (electrical) circumstances.

Mathematicians have formulated a lot of things you can do with matrices, one of them is multiplying them with each other[25].
The result of multiplying two (ABCD) matrices with each other is a new 2 by 2 matrix:

$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} = \begin{pmatrix} A_1.A_2 + B_1.C_2 & A_1.B_2 + B_1.D_2 \\ C_1.A_2 + D_1.C_2 & C_1.B_2 + D_1.D_2 \end{pmatrix}$$

Eq. 17

The elements in the resulting matrix in Eq. 17 are exactly the factors with which V_3 and I_3 in Eq. 13 and Eq. 14 are multiplied to calculate V_1 and I_1.

From this follows that the ABCD matrix for two cascaded two-ports is calculated by multiplying the ABCD matrices of the individual two-ports with each other.

10.2   *Determining ABCD matrix elements*

The values of the individual matrix elements of the ABCD matrix are quite easy to determine. If we make $I2{=}0$ by removing the load of the network then $A1$ is the ratio between V_2 and V_1, see Eq. 9. Mathematicians write this down as follows:

$$A_1 = \frac{V_1}{V_2}\bigg|_{I_2=0}$$

Eq. 18

B_1 can be determined by shortening the output of the two-port, applying an input voltage V_1 and measuring the current through the short.

$$B_1 = \left. \frac{V_1}{I_2} \right|_{V_2=0}$$

Eq. 19

Using the same method we find for C_1 and D_1:

$$C_1 = \left. \frac{I_1}{V_2} \right|_{I_2=0}$$

Eq. 20

$$D_1 = \left. \frac{I_1}{I_2} \right|_{V_2=0}$$
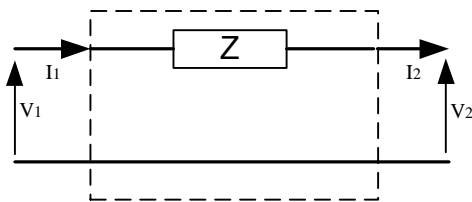
Eq. 21

Figure 16. A simple two-port

Using Eq. 18 through Eq. 21 we find Eq. 22, the ABCD matrix for the simple two-port of Figure 16. A simple two-port:

$$\begin{pmatrix} 1 & Z \\ 0 & 1 \end{pmatrix}$$

Eq. 22

Determining the ABCD matrix of the Polyphase network of Figure 9 is also done with Eq. 18 through Eq. 21. Determining the matrix elements is a bit more complicated because of the dependable components inside the two-port.
For example for determining B the output has to be shorted. Because all four outputs of a Polyphase network are loaded identical this will result in 3 shorts inside the two-port. Also applying one input voltage will result in 3 additional voltage sources inside the two-port. The phase difference between the input voltage and these voltage sources changes if you are determining the matrix for the positive- or the negative phase sequence input voltage system.
The result is Eq. 5 and Eq. 6.

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