Matching Networks and Phasing

W.C. Alexander
Crawford Broadcasting Company
Denver, Colorado

Abstract

Any AM antenna system consists of the antenna itself, some sort of transmission line to convey the RF energy from the transmitter to the antenna, and some sort of impedance matching network. Directional antenna systems consist of multiple radiating elements, transmission lines and matching networks. In this paper, we will examine in building-block fashion the components that make up such systems. In addition to the theory behind them, we will discuss practical aspects of network design and construction.

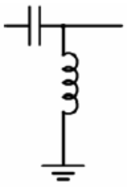
1.00 Matching Networks

A vertical radiator, whether it is a simple non-directional radiator or an element of a multi-tower directional array, presents a complex impedance to the source feeding it. Transmission lines are used to couple the RF from the transmitter output to the antenna, and coaxial transmission lines have a characteristic impedance based upon, among other things, the diameter and spacing of the inner and outer conductors. The modern coaxial transmission lines commonly used in AM antenna systems typically have a characteristic impedance of 50 ohms.

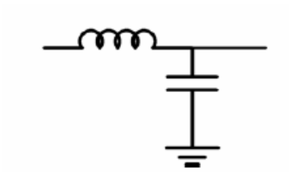
To properly and efficiently couple RF from the transmission line to the antenna, the impedance of the load must be transformed or "matched" to the impedance of the transmission line. In the simplest of situations, wherein the resistance of the antenna is 50 ohms, all that may be needed is a reactive component of an equal value and opposite sign of the antenna reactance to "tune out" the reactance of the antenna. This would leave only the resistive component of the antenna impedance, thus presenting a "match" to the transmission line.

Seldom do such situations occur, however. A typical radiator will exhibit a complex base or driving point impedance that has a resistance of some value other than 50 ohms along with a reactance. It is thus necessary to use a matching network to transform the resistance to 50 ohms and eliminate the reactance. This can be done with any of several types of networks: L, Tee or Pi. Pi networks are seldom used in AM antenna systems. L networks are well-suited to use in non-directional antennas where the phase shift through the network is not important. Tee networks are useful where control of phase is necessary in addition to impedance transformation.

A matching network will either advance (lead) the phase of the current through it or retard (lag) it. The configuration of leading and lagging L networks is shown below:



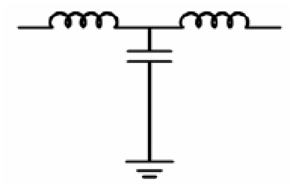
Leading L Network



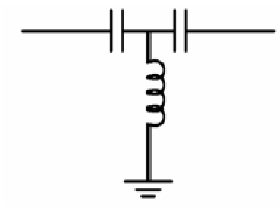
Lagging L Network

Notice that the identifying characteristic of a leading L network is a capacitor on the input. Conversely, the identifying characteristic of a lagging L network is an inductor on the input.

The configuration of leading and lagging Tee networks is shown below:



Lagging Tee Net



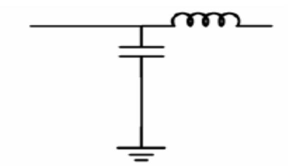
Leading Tee Net

Notice that in its simplest form as shown here, the identifying characteristic of a leading Tee network is capacitors in the series elements. Conversely, inductors in the series elements of a Tee network denote a lagging configuration. In many cases, however, for the purpose of canceling inductive reactances in the load or input or for other reasons, there may be a combination of inductors and capacitors in the series arms of a practical Tee network. As such, it can be hard to identify whether such a network is a leading or lagging net by the series elements alone. A simpler, sure-fire way of identifying a Tee network is by the components in its shunt arm: If there is a capacitor in the shunt arm, the network is lagging, the series elements notwithstanding. If there is no capacitor in the shunt arm, the network is leading.

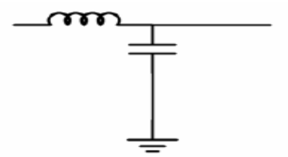
1.01 L Networks

The value of phase shift through an L network is determined solely by the ratio of resistances to be matched.

The configuration of an L network is dependent upon whether or not the load resistance is higher than the input resistance or vice versa. The parallel (shunt) reactance always goes on the side of the network with the higher resistance.



Lagging L Net
Higher R on Input



Lagging L Net
Higher R on Output

Another consideration when using an L network is the filtering properties of such networks. By nature, a leading L network exhibits high-pass properties; conversely, a lagging L network exhibits low-pass properties.

The leg reactances of an L network are calculated as follows:

$$X_P = \frac{R_1}{\sqrt{\frac{R_1}{R_2} - 1}}$$

$$X_S = R_2 \sqrt{\frac{R_1}{R_2} - 1}$$

where: R_1 is always the larger of the resistances to be matched
R_2 is always the smaller of the resistances to be matched
X_P is the parallel (shunt) reactance in ohms
X_S is the series reactance in ohms

These equations deal only with the matching of pure resistances. Should there be any reactances to be tuned out, a reactive component of equal but opposite value is inserted into the series arm of the network on the side where the reactance exists. For example, an L network matching an antenna with a capacitive reactive component to a transmission line would require an inductor of equal (but opposite) reactance to the antenna reactance between the L network and the antenna.

1.02 Tee Networks

By far, the most common matching network in use in AM antenna systems, especially directional antenna systems, is the Tee network. The advantage of the Tee network is that the phase shift can be set independently of the transformation ratio. As a result, the Tee network can be used as a phase shift network in a directional system, a matching network or both. Tee networks can be configured for phase lead or phase lag, and they exhibit high/low-pass properties similar to L networks.

In the case of a Tee network where the phase shift is chosen to be ±90°, the calculation of leg reactances is very simple: all legs are of equal reactance, calculated as follows:

$$X_1 = X_2 = X_3 = \sqrt{R_{IN} R_{OUT}}$$

where: X_1, X_2 and X_3 is the reactance in ohms for the series and shunt legs
R_{IN} is the characteristic impedance of the transmission line
R_{OUT} is the load resistance

In the same way that an L network will only accommodate resistance transformation, a Tee network will accommodate only resistance transformation. If there is a reactance component in the impedance to be matched, a component of equal but opposite reactance is inserted in the output leg of the network. In many cases, the same objective can be achieved simply by adjusting the value of the output leg component. For example, if the calculated value of the output leg of a Tee network is +j100 ohms and the load already has an X_L of 20 ohms, then the component in the output leg should be adjusted to +j80 ohms. The overall leg reactance would be the sum of the load reactance plus the leg reactance, or +j100 ohms.

A 90° Tee network will exhibit the same characteristics as a 90° section of transmission line. An infinite impedance on the output will appear as a very low impedance on the input and vice versa. This property of the 90° tee network can be a significant factor when adjusting a directional antenna phasing and coupling system.

In the case of a Tee network where the phase shift is chosen to be other than ±90° (which is usually the case), the legs are not necessarily of equal reactance. The individual leg values are calculated as follows:

$$X_1 = \frac{R_1}{\tan\beta} - X_3$$

$$X_2 = \frac{R_2}{\tan\beta} - X_3$$

$$X_3 = \frac{\sqrt{R_{IN}\, R_{OUT}}}{\sin\beta}$$

where: X_1 *is the input,* X_2 *is the output and* X_3 *is the shunt leg reactance*
R_{IN} *is the input resistance (typically the characteristic impedance of the transmission line)*
R_{OUT} *is the resistance of the load*
β *is the desired phase shift in the network*

2.00 Practical Considerations for Matching Networks

In addition to the values of X for the individual legs, there are some other important considerations for practical networks. The most important of these are the voltage and current in the network legs.

Currents and voltages in a network are calculated quite simply using Ohm's Law. For a Tee network, they are calculated as follows:

$$I_1 = \sqrt{\frac{P_{IN}}{R_{IN}}} \qquad E_1 = I_1\, X_1$$

$$E_2 = I_1 \sqrt{R_{IN}^{\;2} + X_{IN}^{\;2}} \qquad I_2 = \frac{E_2}{X_2}$$

$$I_3 = \sqrt{\frac{P_{IN}}{R_{LOAD}}} \qquad E_3 = I_3\, X_3$$

where: I_1*,* I_2 *and* I_3 *are the currents in* X_1*,* X_2 *and* X_3*, respectively*
E_1*,* E_2 *and* E_3 *are the voltages in* X_1*,* X_2 *and* X_3*, respectively*
P_{IN} *is the power applied to the network*
R_{IN} *is the input resistance to the network*
R_{LOAD} *is the load resistance*

The above equations yield RMS voltage and current. For the purpose of selecting components to construct a network, however, the RMS voltage and current are merely starting points. The very nature of alternating current tells us that in the case of capacitor ratings, we must pay attention to *peak* voltage rather than RMS. It is the instantaneous peak voltage that will cause the dielectric material to arc through if it is not of a sufficient thickness and dielectric constant. Peak voltage can be calculated by simply multiplying the RMS voltage by the square root of 2, or roughly 1.414.

In the real world of AM broadcasting, we must go beyond even peak voltage, however, in our choice of components with the proper rating. An AM carrier modulated 125% positive will, on peaks, have 2.25 times the voltage of the unmodulated carrier. Peak *modulated* voltage can thus be calculated by multiplying the RMS voltage by 3.18 (1.414 x 2.25).

When it comes to current in a coil or capacitor under modulation, the situation is a little more complicated. A multiplier of

1.335 for 125% positive modulation is derived as follows:

	Voltage	Power
Carrier Vector	1.000	1.000
Upper Sideband	0.625	0.3906
Lower Sideband	0.625	0.3906
Total (Sum)	1.250	1.7813

$I_{MAX} = \sqrt{1.7813}$ which rounds to 1.335.

Seldom are matching networks in the real world set to their theoretical leg reactances and forgotten. In the real world, factors such as stray and distributed capacitances, stray inductances and changing environmental conditions often cause the *adjusted* network values to depart significantly from the calculated values. In a directional system, the phase shift of a network is often changed ±20° from the design value, the driving point impedances of the array elements can vary considerably, and the power distribution among array elements can also vary. Since we know these variances are bound to happen, the best approach to network design will take them into consideration. As such, it is often prudent to allow for a network phase shift ±20°from design value, 0.5 - 1.5R, X±30 ohms, and 1.5 power. Of course there are judgment calls to be made in each case and such allowances do not always need to be made.

Real-world networks utilize an adjustable inductor in the inductive legs and a fixed capacitor in series with an adjustable inductor in the capacitive legs. In some cases, a vacuum variable capacitor may be used in a capacitive leg, but this is relatively rare because of the high cost of such components. Air variable capacitors are never used. Variable inductors can consist of either roller inductors which are adjusted by turning a knob, or tapped coils wherein unused turns in a coil are bypassed by clipping a jumper onto the turn of the coil that produces the desired inductance.

In some cases, the bandwidth of an antenna or array element can be improved considerably by “slope matching” the reactance of the antenna or element with fixed capacitor-variable inductor combination in the output leg of the matching network. There is no hard and fast rule for slope matching; each situation must be individually examined.

3.00 Phase Shifting Networks

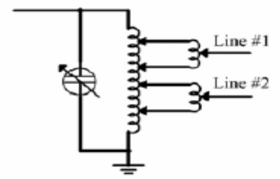
As mentioned earlier, a Tee network is ideally suited as a phase shifting network. Such a network can be designed with a 1:1 transformation ratio (for 50 ohms in and out) and the desired amount of nominal phase lead or lag. By using roller inductors in the input and output legs and ganging the shafts of both inductors together with an insulated coupler, an adjustable phase shift can be produced while maintaining a relatively constant unity transformation ratio throughout the adjustment range.

Occasionally, a zero phase shift is called for in a design, yet it is desirable to have some amount of phase “trim.” This can be achieved by using a relatively low-reactance, series-resonant L-C combination. Typically, a fixed capacitor with an X_C of about 50 ohms is put in series with a roller inductor that has a maximum X_L of about 100 ohms. With the roller inductor adjusted to its midpoint, the circuit is series resonant and has a zero phase shift. As the inductance is decreased, the net reactance becomes capacitive and the network exhibits a slight phase lead. As the inductance is increased, the opposite happens. One caveat about zero phase shift networks, however: As with all series-resonant circuits, their impedance increases rather steeply on either side of resonance. Adjusting such a circuit very far off the zero point will result in a considerable drop in power to that branch of the directional array.

4.00 Power Dividers

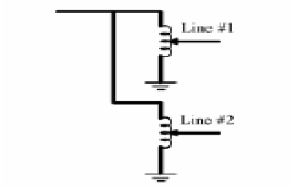
As the name implies, the purpose of a power divider is to distribute power from a transmitter to the elements of a directional array in the proper ratio. In most cases, the power divider controls are adjustable from the front panel of the phasor, giving the engineer a degree of control over the power distribution in the array.

All sorts of power divider schemes have been used over the years in phasing and coupling systems. Some offer low component count and high-reliability at the expense of adjustability. Others offer adjustment range at the expense of component count and reliability. The three major types of power divider commonly in use today are tank (sometimes called "series"), tee-network and shunt.



Tank-Type Divider

Tank-type power dividers are among the worst for bandwidth. The power divider circuit is, as its name implies, itself a tank circuit that stores energy. As with any parallel-resonant circuit, the slopes are steep on either side of resonance and this has a very detrimental effect on the sideband impedances.



Shunt Divider

The tee-network power divider/phase shifter combination offers a lower component count and good adjustability, but it operates on the principal of an impedance mismatch. While bandwidth is generally acceptable, there are unwanted reactances in such a system.

The shunt-type (sometimes called "Ohm's Law") power divider is probably the best choice for providing adjustability and producing optimum bandwidth. Virtually all current phasor designs use the shunt-type power divider.

Ideally, as the roller coil tap is moved up and down between ground and the common point bus, the amount of power delivered to the line would change with very little phase shift. In the real world, however, there is often considerable phase shift. The lower the tap setting on the power divider coil, the more phase lag that is introduced. The degree to which this effect occurs is largely a function of coil design and mutual coupling. In small, ribbon-type inductors, the effect is less pronounced because there is greater mutual coupling between turns of the inductor. It is most evident in large, tubing inductors where the turns are widely spaced and there is less mutual coupling between turns.

One disadvantage of the shunt-type power divider is that in large arrays (more than four towers), the common point bus impedance tends to become quite low. This low impedance can often be raised by placing a capacitor across the power divider bus. The improvement sometimes comes at the expense of bandwidth and/or load symmetry, so the use of a bus resonating capacitor must be evaluated on a case-by-case basis.

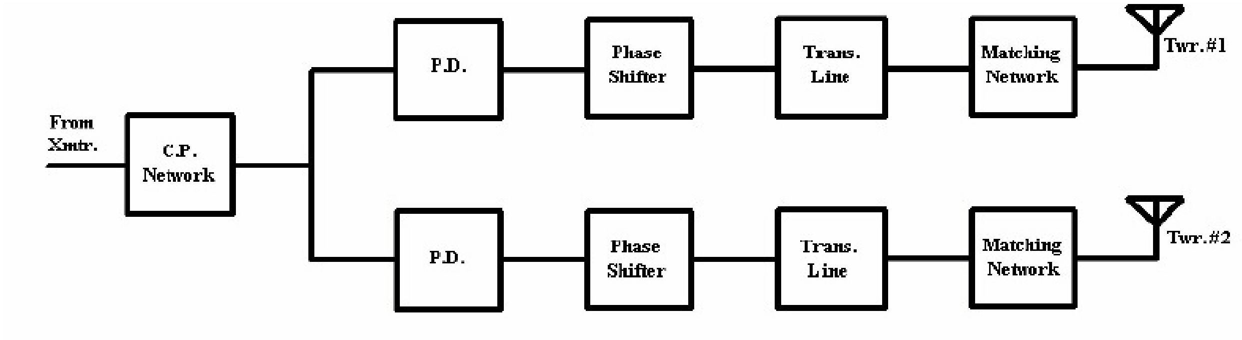
5.00 Phase Budget:

The goal in a phasing and coupling system design is to produce the desired current ratio at the proper phase relationship in each array element. The current is controlled by the power divider while the phase relationships are controlled by the total amount of phase shift in each branch of the system. The total phase shift in the reference tower is the starting point. As in all the branches of the system, it consists of the phase shift in the power divider, phase shifter, transmission line and matching network. The difference between the total amount of phase shift in the branches and the total phase shift in the reference tower determines the phase relationship between each tower in the array and the reference tower.

One of the first questions the designer must answer is, what should the phase budget be? Some parts of this are, to some degree, fixed. Transmission line lengths, for example, are often a function of transmitter building location, trenching routes and the like. With a little thought, it is easy to see that there is a near infinite number of possible phase budgets for a given system, even with some parts of the budget fixed.

It is here that some judgment calls must be made. Practical factors must be considered. For example, Tee networks work best for phase shifts between 60 and 120 degrees. Phase shifts outside this range can be problematic. Another practical consideration is that leading networks are generally more costly than lagging networks because they usually have one more capacitor. This not only affects the initial cost but also repair and maintenance costs as the added capacitor is one more possible point of failure. Yet another consideration is that zero phase shift networks have a limited adjustment range and a significant effect on power either side of resonance.

Below is an example of some possible phase budgets for a two-tower array.



DA Block Diagram

```
==============================================================================
No.   Pwr-Div     Phasor       Line        ATU     Twr-Ph     Error
------------------------------------------------------------------------------
Mode Reference Tower Number 1
 Mode[ 1 ]           ?                     ?
  1      +0.0      -94.3     -149.3      -94.3       +0.0      -4.3
  2     -11.9      -85.1     -148.9      -85.1       +7.0      +4.9
    Point of Origin +337.9 Degrees, High Error    +5 Low Error   -4
 Mode[ 2 ]           ?                     ?
  1      +0.0       +0.0     -149.3      -99.2       +0.0      -9.2
  2     -11.9       +0.0     -148.9      -80.8       +7.0      +9.2
    Point of Origin +248.5 Degrees, High Error    +9 Low Error   -9
 Mode[ 3 ]           ?                     ?
  1      +0.0      +85.7     -149.3      -94.3       +0.0      -4.3
  2     -11.9      +94.9     -148.9      -85.1       +7.0      +4.9
    Point of Origin +157.9 Degrees, High Error    +5 Low Error   -4
 Mode[ 4 ]           ?                     ?
  1      +0.0       +0.0     -149.3      +80.8       +0.0      -9.2
  2     -11.9       +0.0     -148.9      +99.2       +7.0      +9.2
    Point of Origin  +68.5 Degrees, High Error    +9 Low Error   -9
 Mode[ 5 ]           ?                     ?
  1      +0.0      +85.7     -149.3      +85.7       +0.0      -4.3
  2     -11.9      -85.1     -148.9      -85.1       +7.0      +4.9
    Point of Origin  -22.1 Degrees, High Error    +5 Low Error   -4
 Mode[ 6 ]           ?                     ?
  1      +0.0       +0.0     -149.3       +0.0       +0.0      +0.0
  2     -11.9      +90.9     -148.9      -89.1       +7.0      +0.9
    Point of Origin +149.3 Degrees, High Error    +1 Low Error   +0
```

In the final design, Mode 1 was selected because it provides for all lagging networks with phase shifts close to 90°. This resulted in lower cost, greater reliability and efficiency.

In some cases, it may be prudent to make adjustments to the transmission line lengths to achieve a better phase budget. If the transmitter building location can be moved, for example, more favorable transmission line lengths may result. Another possibility, especially in lower power systems, is adding length to one or more transmission lines to achieve greater phase delay in those branches. There is nothing wrong with burying a coil of line if it helps achieve a better design. The caveat is that the excess line must be in the same environment as the rest of the line so that temperature effects will be uniform.

6.00 Common Point Network Design

The common point network design process is usually quite simple. Leg reactances are calculated for a 50-ohm input and a specified range of output impedance values. Typically this range is 0.5 to 1.5 R and X ±30 ohms. It is not necessary, however, to allow for 1.5 times the nominal power. Some allowance for phase shift adjustment should be made to permit load symmetry optimization.

The input leg of the common point matching network is typically a front-panel adjustment for reactance. The shunt leg is typically the resistance adjustment. In higher power designs, it may be better to use a vacuum variable capacitor in one or the other of these legs than a fixed vacuum in series with a roller inductor (i.e. the cost of a vacuum variable by itself may be equal to or less than a fixed vacuum capacitor - large roller inductor combination).

As mentioned above, it is entirely possible to produce a common point bus impedance so low that it cannot be matched with an economical common point Tee network. In these cases the use of a common point bus resonating capacitor may be indicated. In extreme cases, it may be necessary to “two-step” the CP matching process, using an L-network between the CP bus and Tee network.

7.00 Power Divider Design

The goal in power divider design is to use the smallest inductor possible consistent with an acceptable common point bus impedance and adjustment range. A typical power divider inductor value is 22 uH, although both smaller and larger values are often used.

Smaller values produce less phase shift but tend to load the common point bus. They also have more adjustment sensitivity, producing a larger change in branch power for a given control rotation than larger coils. They do tend to produce less change with temperature variation, however.

Larger values produce more phase shift but lighter loading on the common point bus. Finer adjustment is possible with larger inductor values, but temperature effects are more pronounced.

Current in a power divider inductor is calculated using Ohm’s laws for series and parallel circuits. Compensation for peak modulated current should be applied and allowances made for out-of-balance power distribution. It is entirely possible for a lightning-damaged array, for example, to upset the power balance so that the transmitter stays on the air but with one or more branches carrying 150% of their design power.

8.00 Phase Shifter Design

Designing a phase shifter network is a simple matter. Calculate the leg values for 50 ohms in and out at the desired phase shift. Do the same thing at the desired phase shift plus and minus 20 degrees. Calculate peak modulated voltages and currents at all the above phase shifts at 1.5 times the nominal branch power. Select components based on the worst-case values. This will insure that the installed network has sufficient adjustment range and that it can handle out-of-balance power situations.

As mentioned previously, zero nets are simply series-resonant L-C combinations. The are typically designed with a fixed capacitor having a nominal reactance of close to 50 ohms. A variable inductor having a maximum reactance of close to 100 ohms is used. Current and voltage are calculated using Ohm’s law for series circuits, applying the appropriate constants for peak modulated conditions. Components are typically selected so that they can handle 1.5 times the nominal branch power.

9.00 Matching Network Design

The design of a matching network must take into account known and unknown factors. If a phasing and coupling system is being designed for a new directional antenna, the designer will be working from a set of *predicted* driving point impedances. These impedances will likely be in the ballpark, but some room must be allowed for real-world variations. The typical range should be 0.5 to 1.5 R and X ±30 ohms.

If the design is for an existing antenna, the designer will be working from a *known* set of driving point impedances. With these values in hand, the design can be much narrower. Still, some adjustment range should be allowed in R, X and phase shift to accommodate variations due to installation and changing environmental conditions.

One other factor that comes into play in matching networks feeding towers using lighting chokes is that a capacitor should be used in the output leg of the network, even if it is a lagging network. A large value capacitor, such as 0.01 uF, will have a fairly low reactance that can be easily compensated in the output leg inductor. The idea is to eliminate any path to ground back through the matching network, transmission line and phasor for 60 Hz AC should one side of the lighting choke short to the tower (which is not an uncommon occurrence). Also, stray 60 Hz AC currents can affect base current and antenna monitor indications.

10.00 Multi-Mode Systems

Many directional antennas have more than one mode of operation. For example, there may be different patterns for day, night and critical hours. There may also be one or more non-directional modes. The phasing and coupling system must be designed to accommodate all modes of operation.

There are different approaches to multi-mode operation, but the most economical is to share network components wherever possible, using RF contactors to switch between coil taps and to switch components in and out of the circuit. The overall design process often becomes iterative as the designer tries to achieve a balance between the different modes. For example, a less-than-optimum phase budget may be selected for one mode of operation because doing so provides options for the other mode of operation.

One important consideration for multi-mode system design is maintenance and reliability. Using separate networks for the different modes is more costly, but it provides a degree of redundancy. An example might be a blown capacitor in the day matching network for a particular tower. If the network is common to both day and night modes of operation, the station will likely be off the air until repairs can be made. If, however, separate networks are in place for day and night, the station can simply switch to the night mode and continue to operate until repairs can be made. Depending upon layout, repairs might even be possible with reduced power operation without going off the air.

One other important consideration is tower maintenance. To safely accommodate workers on the towers, excitation must be removed or power reduced to the value specified in OET Bulletin No. 65 for the frequency and electrical height of the tower. During the design process, it is beneficial to note what the OET-65 maximum power is with respect to power distribution in the array. If there is one tower in the array in any mode of operation that is driven with less that the OET-65 maximum, that tower can be safely climbed while on the air. A good strategy is to design a non-directional mode of operation using that tower as the ND radiator. In that way, the ND tower can be safely climbed during DA operation. To work on the other towers, the ND mode is selected and excitation is removed from all the other towers, making them safe to climb. If there is no tower in the system driven with a power level below the OET-65 maximum, a good option may be to design in two ND modes using different towers.