Electrical Tech Note — 516

Biosystems & Agricultural Engineering Department
Michigan State University

Analog Signal Filtering

A transducer that is continuously measuring a quantity such as temperature, pressure, voltage, or any other desired quantity can be exposed to unwanted interference in the form of other signals also present on wires or when the signal is transmitted wireless. An example may be a continuous measurement of temperature that is expected to change slowly but the signal received is constantly changing by a small amount making it impossible to determine the actual temperature. A small dc voltage can be produced by galvanic activity where the electrodes of the measuring system are chemically reacting with the material being measured. This introduces a small dc voltage bias to the measurements resulting in some cases an inaccurate measurement. If there is a frequency difference between the quantity being measured and an unwanted signal, that unwanted signal can be reduced to insignificant level by a process known as filtering. This Tech Note is about the basic concept of analog signal filtering such as how to minimize all frequencies above or below a particular frequency. Or, minimize all frequencies above or below a particular frequency. Another concern is to minimize only one particular frequency while allowing all other frequencies above or below that frequency to pass and be received. Terminology such as high pass, low pass, band pass, and band reject will be discussed. The components that will accomplish these tasks discussed in this Tech Note are capacitors, inductors, and resistors.

The Perfect Filter: Figure 516.1 illustrates several types of "perfect" filters where the change from receiving a frequency while eliminating a group of frequencies or a single frequency is desired, but in the real world those results can only be approximated. Sometimes signal distortion can occur close to the transition point so even though the concept seems quite easy, in a particular case the task may be quite difficult. An undesirable effect is that the components used for filtering can reduce unfiltered signal power.

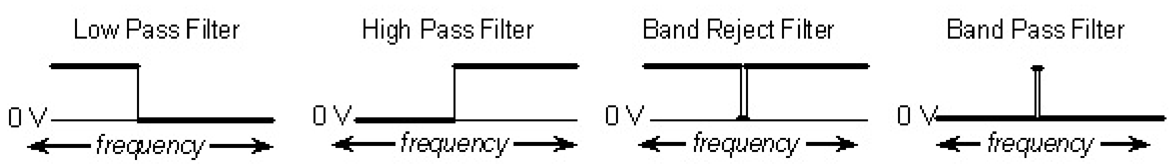

***Figure 516.1** Examples of "perfect" filters that pass all frequencies above a particular frequency, reject all frequencies above a particular frequency, pass all but one particular frequency, or reject all but one particular frequency.*

Value Changes as Frequency Changes: The value of a resistor does not change as the frequency of a circuit changes, but that is not the case for a capacitor or inductor. As the frequency increases the reactance of a capacitor in ohms decreases. In the case of an inductor the inductive reactance in ohms increases as the frequency increases. This is illustrated in Figure 516.2. If a capacitor and an inductor are in the same circuit there is a frequency at which the reactance (ohms) of a capacitor and an inductor have the same value. This frequency is known as the resonant frequency. At a frequency of zero Hertz the reactance of a capacitor is considered infinite. The relationship of an inductor with respect to change in frequency is linear. At zero frequency (direct current) inductive reactance is zero and the value of capacitive reactance is extremely large. This means a capacitor will block the flow of direct current once the plates of the capacitor are fully charged. In the case of an inductor it theoretically does not block the flow of direct current, but since an inductor is a coil of wire the wire will act as a resistor. With respect to frequency the value of resistance is a constant.

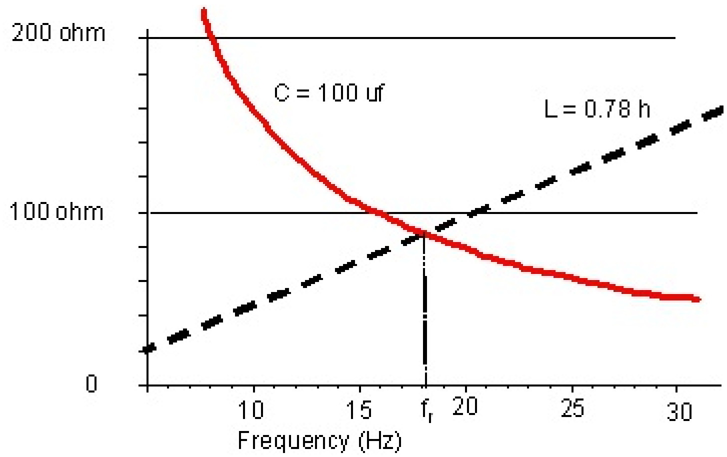

Figure 516.2 *The solid line is capacitive reactance and the dashed line is inductive reactance. The frequency at which the two lines cross is known as the resonant frequency and the capacitor and inductor have the same reactance value.*

Figure 516.3 illustrates the reactance value of a capacitor at three different capacitor values. It takes about two decades of frequency for the reactance to change from an extremely high value to a small value. Because of this dramatic reactance value change over a range of frequencies a capacitor value can be chosen that will block frequencies below a particular value and pass frequencies above a particular value. There is a band of frequencies over which there is a transition from blocking to passing current flow. This effect can be observed for three different values of capacitor in Figure 516.3.

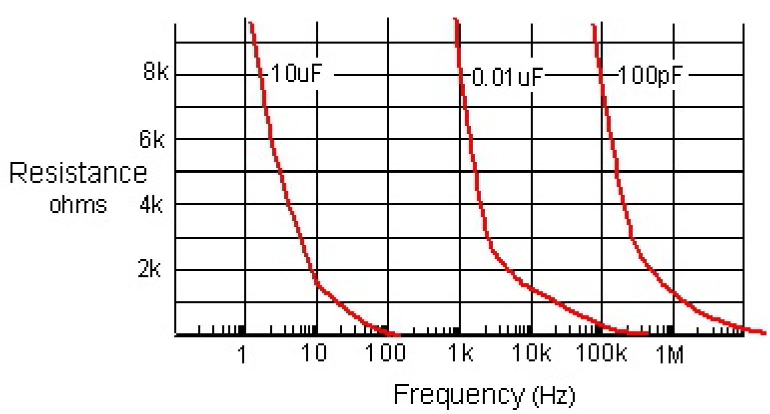

Figure 516.3 *The reactance value of a capacitor changes from extremely high to very low over a range of frequencies of about two decades.*

The reactance of an inductor is linear with respect to frequency but with the log scale horizontal axis the inductive reactance (dashed line) is a curved line as shown in Figure 516.4. A value of inductor can be selected that can reduce the power of an analog signal over a small range of frequencies and at higher frequencies a signal is considered blocked. This diagram also shows that an inductor will have the opposite effect as a filter than a capacitor. A capacitor blocks lower frequencies and passes higher frequencies while the inductor has the opposite effect.

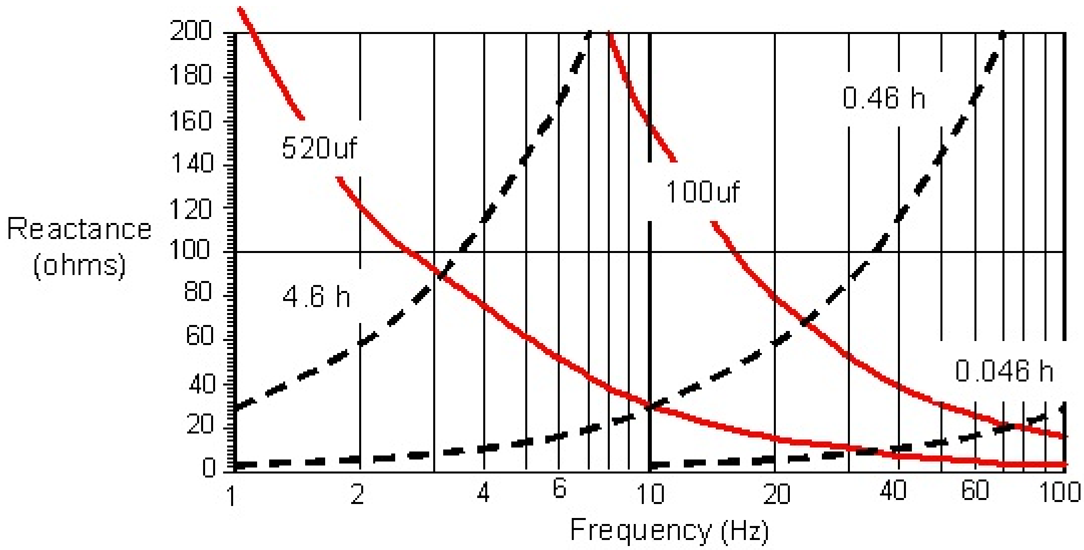

***Figure 516.4** The dashed lines are inductive reactance over a two decade frequency range. Inductive reactance increases as frequency increases. The solid curves are capacitive reactance which decrease as frequency increases.*

Bode Diagrams: The power of a signal is frequently expressed in decibels (dB) which are tents of a common log. You may want to review Tech Note 502 and Tech Note 504. Hendrik Bode in the 1930's developed a method of graphing signal strength or gain verses frequency. Signal power (strength) usually in decibels on the vertical axis verses frequency on the horizontal axis as a common log. An analog signal is frequently plotted as signal power on the vertical axis and frequency on the horizontal axis. The horizontal scale is the common log of frequency. The value of signal strength (power) is plotted on the vertical axis as a common log of the signal power in units of decibels (dB). Figure 516.5 is a Bode plot for a “low pass” filter that allows the signal to pass with minimal impedance up to a particular frequency beyond which signal power experiences a steady reduction, usually shown as negative units in decibels (-dB).

For a Bode plot a frequency called “cut off” is the point at which the unencumbered frequency experiences a power reduction of 50%. A decibel (dB) is one-tenth of a common log. For every three dB reduction in signal power the previous power level is reduced by 50%. The object of a filter is to reduce unwanted signals that are present with the primary signal to a power level so that the primary signal is clearly recognizable. Filtering can be difficult when the signal frequency and unwanted frequencies are nearly the same value. The left diagram in Figure 516.1 is an ideal low pass filter. Figure 516.5 is an example of an actual low pass filter. Assume the power level of the signal to be 0 dB. If signal power is reduced by -3 dB the signal power has been reduced to 50% (100 to 50). If the signal power is reduced to -6 dB the signal power at -3 dB has been reduced by an additional 50% (50 to 25 or total 100 to 25 overall).

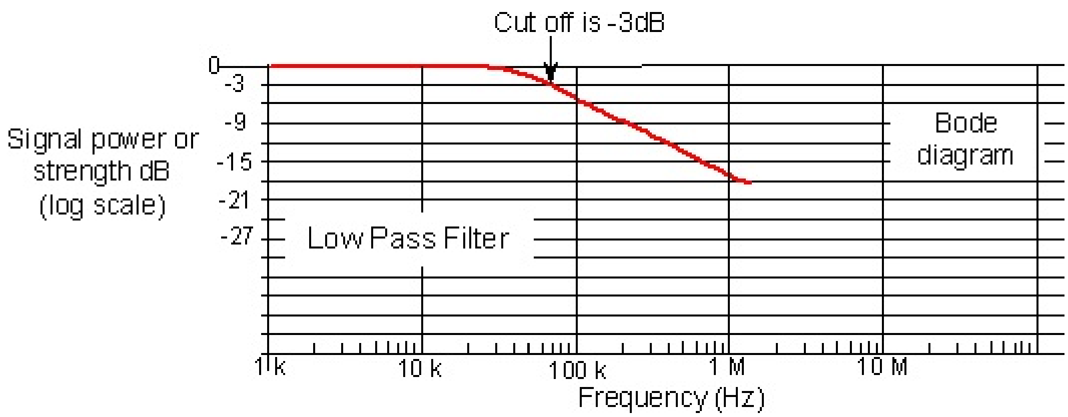

Figure 516.5 *All signals with a frequency above the cut off frequency have reduced power compared with frequencies below the cut off frequency.*

Voltage, Current, and Cut Off: Power is the product of voltage and current. Other ways to express power is the square of the current times resistance or the square of the voltage divided by the resistance. If the power of a signal has been reduced to 50% the original value, the ratio of the original power to power at minus 3 dB is 0.5. If power is proportional to the square of the voltage than when the square of the voltage has been reduced to minus 3 dB the ratio compared to the original voltage squared is 0.5. But the power ratio of 0.5 is approximately 0.7 when comparing the original voltage to the voltage at minus 3 dB. The value 0.7 is the approximate square root of 0.5 so a power reduction to 50% is a voltage reduction to approximately 70% the original value. The same is true of the current since the square of the current is proportional to the power. So in summary cut off which is minus 3 dB is a reduction of power to 50% the original power but also it is a reduction of voltage to 70% the original value. Examine the Bode plot of Figure 516.5. Power reduction begins at approximately frequency 30k Hz, cut-off is at approximately 60k Hz, and at about 200k Hz signal power has decreased by almost 90% (100 to 12).

Single Capacitor as a Filter: Refer to Figure 516.3 and notice that a capacitor offers extremely high reactance (ohms) at frequencies below a particular frequency. That same capacitor offers very low reactance to frequencies at higher frequencies. This would then be considered a “high pass” filter. This is the case when the capacitor is connected in series with the circuit as illustrated in Figure 516.6.

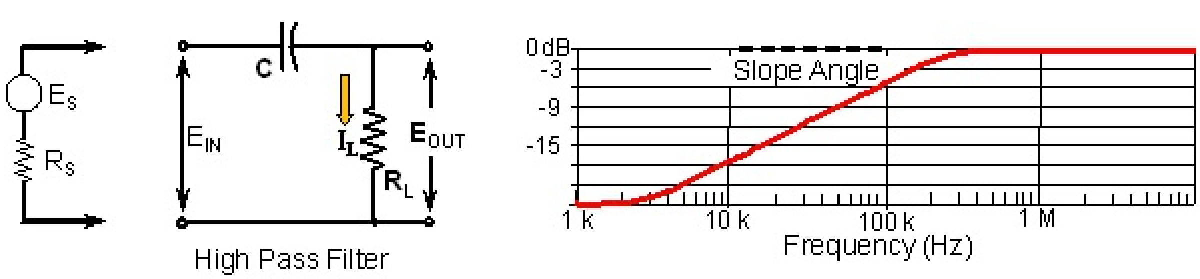

Figure 516.6 *A capacitor connected in series creates a high pass filter. Low frequency signals are blocked by high capacitive reactance (ohms). At high frequencies the capacitive reactance becomes negligible and a current flows (I_L) through the load resistor (R_L) resulting in an output voltage (E_{OUT}).*

A filter consisting of a single capacitor (Figure 516.6) usually results in a signal power reduction slope angle too small to block unwanted frequencies. The transition from total signal blocking to signal let-through is spread out over too wide a range of frequencies. The slope angle for an ideal filter is 90°. A high order filter can achieve a signal power reduction over a much shorter frequency range.

A filter can be constructed by placing a capacitor in parallel with the output load resistor (Figure 516.7). An output (E_{OUT}) using Ohm's law is the result of current (I_L) flowing through the output load resistor. If current flow is through the capacitor (I_C) instead then the load resistor current (I_L) will be zero and E_{OUT} will be zero. If the capacitor blocks all current flow (I_C = 0) then I_L will be maximum and E_{OUT} will be maximum. At zero Hz up to a higher frequency depending on the value of the capacitor, the capacitive reactance (ohms) will be maximum forcing all signal current through the load resistor R_L. There will be a range of frequencies where the capacitive reactance decreases and finally drops to a level at which nearly all of the signal current flows through the capacitor and very little flows through the load resistor resulting in E_{OUT} approaching zero . When placed in parallel with the load resistor (R_L) a capacitor creates a low pass filter as shown in Figure 516.7.

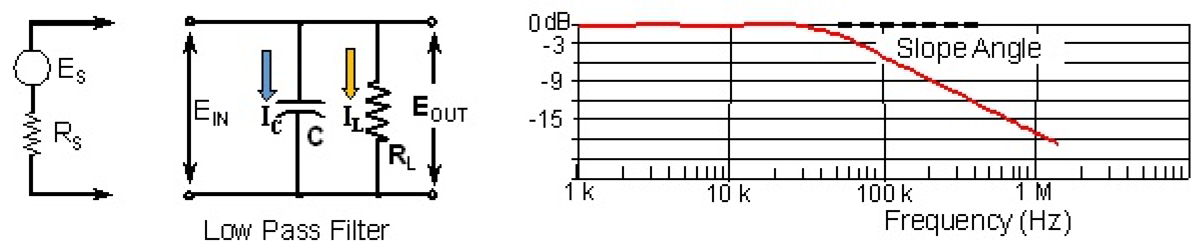

***Figure 516.7** Locating the capacitor parallel to the output load resistor creates a low pass filter. At low frequencies no current can flow through the capacitor resulting in all of the current flowing through the load resistor which results in an output voltage. At high frequencies all of the current flows through the capacitor resulting in very little current flowing through the load resistor and all high frequency signals are blocked from the output.*

Inductor Used to make a Frequency Filter: Instead of using a capacitor, an inductor can be used to make either a low pass filter or a high pass filter. As shown in Figure 516.4 the inductive reactance (ohms) of an inductor increases as the frequency increases and decreases as the frequency decreases. At a frequency of zero Hz (direct current) the inductive reactance of an inductor is zero. This is just the opposite of the capacitive reactance (ohms) as a capacitor. The diagram of Figure 516.8 is the same as the diagram of Figure 516.6 except the capacitor in series with the load resistor has been replaced by an inductor. This changes the high pass filter to a low pass filter as shown in Figure 516.8.

Compare the diagram of Figure 516.9 with the diagram of Figure 516.7. In one case a capacitor is connected in parallel with the load resistor to create a low pass filter. In Figure 516.9 an inductor is connected in parallel with the load resistor to create a high pass filter. When a signal frequency is very low the inductive reactance (ohms) of an inductor is very low and most of the current passes through the inductor. With little or no current passing through the load resistor the output voltage of the filter will be zero. Current bypasses the output resistor by flowing through the inductor. In the case of a high frequency signal the inductor blocks current flow forcing the current to flow through the output resistor thus creating an output voltage and a high pass filter.

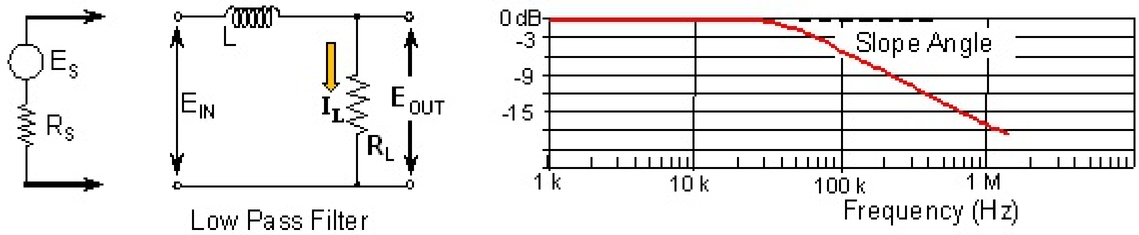

Figure 516.8 *With an inductor in series with the output resistor a low pass filter is created. This is just the opposite the output of a filter with a capacitor in series with the output resistor.*

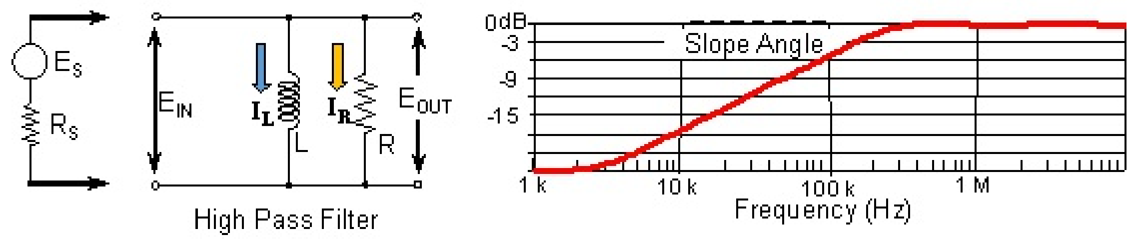

Figure 516.9 *With an inductor connected in parallel with the output resistor a high pass filter is created. This is just the opposite the output of a filter with a capacitor connected in parallel with the output resistor.*

Capacitor and Inductor in Series with the Output Resistor: When both a capacitor and an inductor are connected in series with the output resistor as shown in Figure 516.10 a resonant circuit is created. When capacitive reactance (X_C) and inductive reactance (X_L) are connected in series the resultant reactance is the difference. One reactance subtracts from the other. Low frequencies experience a high impedance caused by the capacitive reactance. High frequencies signals also experience high impedance primarily caused by inductive reactance. There will be one frequency where the capacitive reactance and the inductive reactance are equal resulting theoretically zero impedance. The result does not drop completely to zero because the inductor is a coil of wire where the wire has some resistance. This point is called resonance and a narrow band of frequencies will result in a current to flow through the output resistor. This type of filter shown in Figure 516.10 is known as a band pass filter.

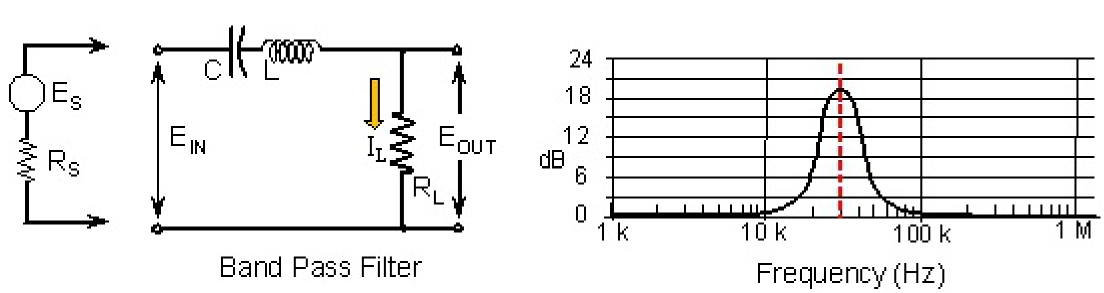

Figure 516.10 *A band pass filter can be created when a capacitor and an inductor are connected in series with this combination then connected in series with the output resistor.*

Band Reject Filter: A band reject filter can be created by locating the series capacitor and inductor in parallel with the load resistor as shown in Figure 516.11. At low frequency and at high frequency the series capacitor and inductor have very high impedance (ohms) which forces the current through the output load resistor. But at a narrow band of frequencies near the resonant frequence of the series capacitor and inductor the impedance is very low allowing the circuit current to bypass the load resistor and flow through the series capacitor and inductor. With very small current flow through the output load resistor the output voltage E_{OUT} decreases to nearly zero. The value of capacitor and inductor are chosen so that their resonant frequency corresponds with a specific frequency that needs to be eliminated from the output. Sometimes this type of filter is known as a "notch" filter.

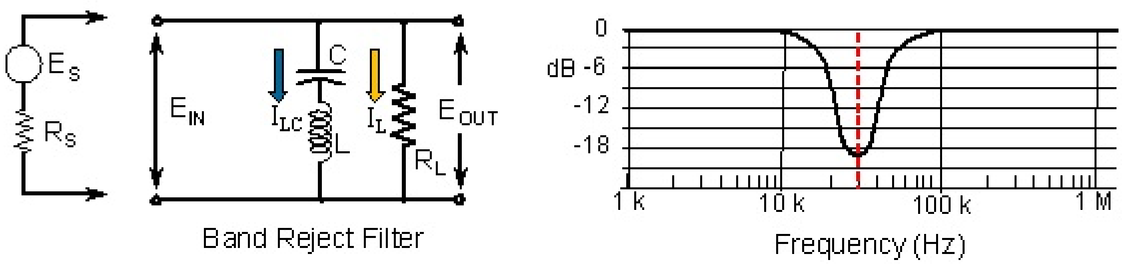

Figure 516.11 *With the series capacitor and inductor located parallel to the output load resistor a band reject filter is created. A small band of frequencies near the resonant frequency of the series capacitor and inductor circuit can be blocked from the output.*

Parallel Capacitor and Inductor "Tank" Circuit: Rather than arranging the capacitor and inductor in series with each other, they can be arranged in parallel which instead of having theoretically zero resistance at the resonant frequency they create infinite resistance with respect to the external circuit. Current oscillates back and forth from the capacitor and inductor. Such a circuit is shown in Figure 516.12. Notice the resistor in series with the inductor. This is the resistance of the wire making up the inductor, it does have a noticeable effect. Low frequency signals will pass through the inductor but not the capacitor. High frequencies will pass through the capacitor but not the inductor. At the resonant frequency when the capacitive reactance and the inductive reactance are equal these two components are in resonance and to the overall circuit they act as a very high resistance blocking current flow. Refer to Figure 516.12. When the components are at or near resonance current (I_{LC}) through the "tank" is nearly zero thus the current through the output load resistor (I_L) will also be zero. At resonance output E_{OUT} is minimum and current through the "tank" is also minimum. Frequencies above resonant frequency and below resonant frequency are not blocked and will appear at the output.

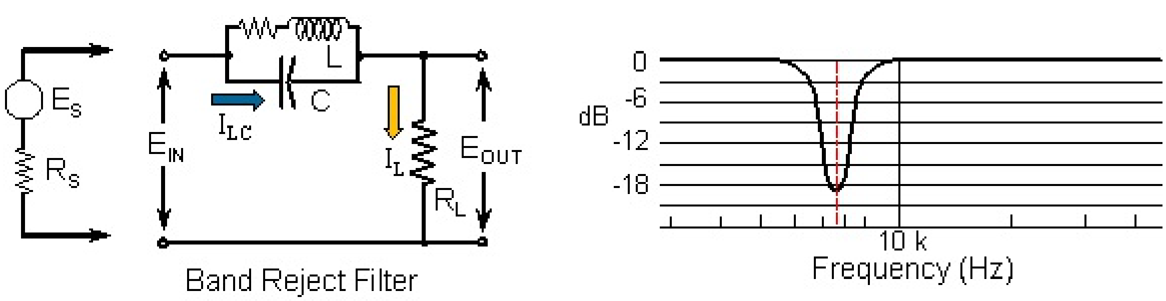

Figure 516.12 *The parallel capacitor and inductor pass current except near the resonant frequency thus blocking a selected narrow band of frequencies.*

The parallel capacitor inductor circuit (tank) can be connected in parallel with the output load resistor as shown in Figure 516.13. Remember that when the current is flowing through the parallel tank circuit there is little of no current flowing through the output load resistor and the output voltage will be at or near zero. The only time current will be flowing through the output load resistor is when the tank circuit is at or near the resonant frequency. When the components are at or near resonance, current (I_{LC}) through the “tank” is nearly zero forcing all of the circuit current through the output load resistor. At resonance output E_{OUT} is maximum and current through the “tank” is minimum or zero. This is another way of creating a band pass filter.

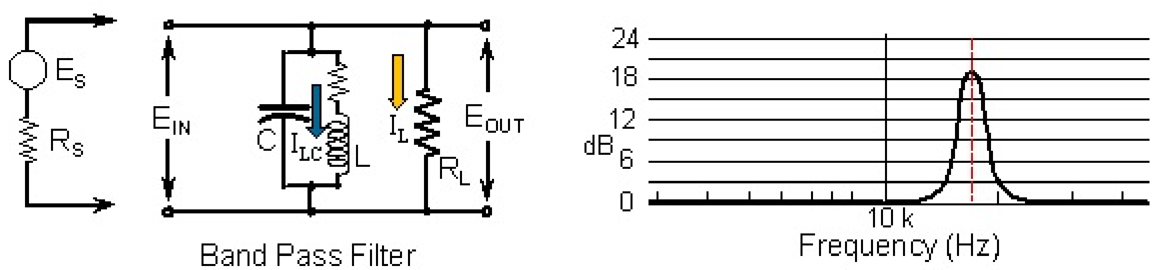

Figure 516.13 *A parallel capacitor and inductor circuit is connected in parallel with the output load resistor. At the resonant frequency of the parallel capacitor and inductor that portion of the circuit reaches a high impedance and forces all circuit current through the output load resistor to create a band pass filter.*

Conclusion: When transporting signals wireless or through wires the signal received at the destination may have been obscured by extraneous signals at other frequencies to the point where it is difficult or impossible to distinguish the desired frequency. Sometimes the desired frequency is distorted resulting in inaccurate results. The signal received can be passed through a filter that can decrease the effect of these extraneous signals. The purpose of this Tech Note is to provide a basic understanding of the techniques for creating a band pass, band reject, high pass, and low pass filter. Building a filter is much more complex than these simple circuits discussed. The goal is to attempt to approach the ideal filter results shown in Figure 516.1, but in reality that process is complex, but in most cases can be achieved. Figure 516.14 is a multi-stage filter that attempts to eliminate the effects of an undesired frequency that is close to the desired frequency. Recall that an inductor in series with the output load resistor acts as a low pass filter. A capacitor connected in parallel also acts as a low pass filter. The filter in Figure 516.14 has several stages with different values of inductors and capacitors.

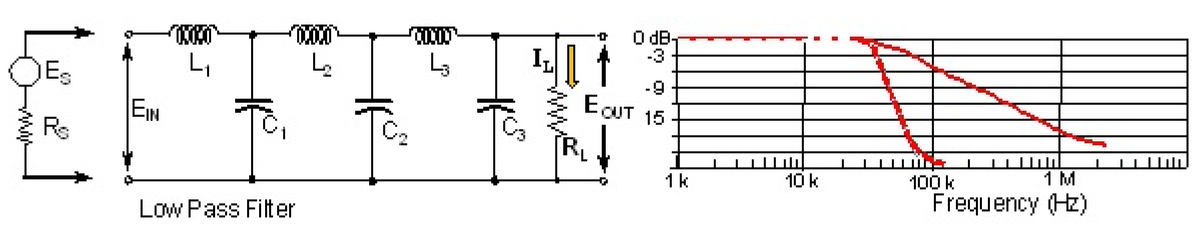

Figure 516.14 *By adding additional components the slope of the frequency cut-off curve of the Bode diagram can be increased. However other undesirable effects can occur.*