Crystal Radio Engineering
Antenna and Ground System

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Introduction

This article explains the basics of the antenna and ground system for a crystal radio and the associated mathematical model. The mathematical model tells us how to design the antenna input section of the radio for optimum performance.

The passing RF wave induces an RF voltage across a length of wire referred to as an antenna. The induced voltage is the signal strength in volts/meter multiplied by the electrical (not the physical) height of the antenna in meters. For antennas that are shorter than one-quarter wavelength the electrical height is roughly the wire length (including lead-in wire) in meters. There are very little directivity effects for short antennas so orientation is not really a factor – i.e. the antenna is omnidirectional. The physical height of the antenna above the earth affects the signal amplitude as there is increased attenuation of the signal close to the ground.

The antenna should be as long as practical and as high as practical. A quarter wavelength for 540 kHz is (300,000/4)/540 = 139 meters. A quarter-wavelength at 1700 kHz is 44 meters. For a basic crystal radio there is little to be gained by an antenna longer than about 40 meters or higher than about 8 meters – that is a substantial antenna that few have the room to construct. A minimum antenna might be about 10 meters long and about 3 meters off the ground. Anything in-between can produce acceptable performance. Advanced crystal radio enthusiasts will construct bigger and more advanced antennas but that involves a degree of engineering beyond the scope of this article.

One advanced method that the author has not had the space to try is a true dipole antenna that is one-half wavelength long (in some cases longer). Such an antenna is balanced and so does not depend on a low-impedance ground for operation. The power received by the antenna would be significantly more than that of the simple long wire antennas described in this article. With such an antenna a local station could drive a speaker to significant volume. But, the antenna is only useful over a narrow band of frequencies and is also directive so it must be oriented properly relative to the transmitting antenna.

Figure 1 shows a typical antenna and ground setup for a crystal radio. The following sections discuss each attribute.

Crystal Radio Engineering
Antenna and Ground System

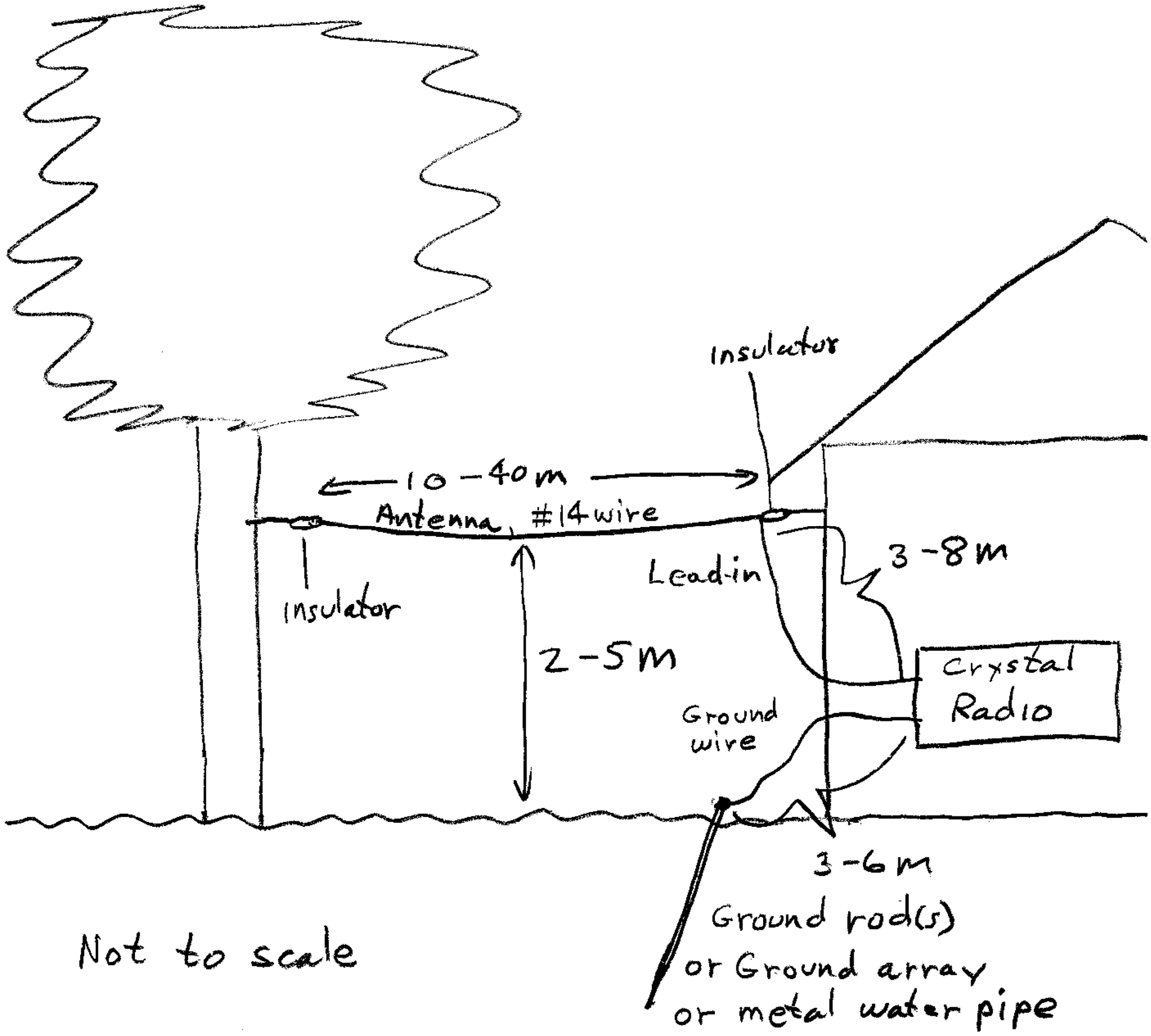

Figure 1: Basic Antenna System for a Crystal Radio

Distal support

If available, a tree makes a convenient support for the antenna wire. Otherwise some kind of post will have to be constructed. Never use a utility pole or any other support that is not your property – your potential liabilities could be astronomical if some accident (lightning for example) or failure causes damage to someone else's property or person.

An insulator typically made of ceramic or plastic is used to terminate the antenna wire and to connect to the antenna support usually via some kind of rope. These insulators are readily available from various hobby electronics sources. A large wood screw typically with a hook or eye end driven into a tree or other support is used as an attachment point for the rope. Do not wrap the rope around the tree as that will constrict growth in future years.

Crystal Radio Engineering
Antenna and Ground System

Antenna wire

The antenna wire is typically #14 AWG solid or stranded copper wire and may or may not be insulated. Insulation has no effect on reception but is an advantage to reduce corrosion effects. There is no advantage to using heavier wire such as #12 or #10 as the resistance of the wire is negligible compared to everything else and the added weight makes the end supports more challenging. Wire sizes of #16 and #18 also work well but are less strong – but are also lighter and will put less stress on the supports. Wire gauge sizes higher than 18 are not recommended because they are more fragile and are hard to see if they fall – you would like to not run over the wire with a lawn mower – could be very disastrous! Although low resistance is nice, it is a myth to go to great efforts for low resistance in the antenna wire as the resistance of the ground is going to be considerably higher.

The height of the antenna absolutely must be above head level for someone who might be standing on some vehicle (i.e. bicycle or motorcycle) that might possibly travel under the antenna to prevent what could be a horrible or even tragic accident – this means at least 3 meters. The antenna wire should not pass over anything such as a road or other wires such as electrical power such that if the antenna fell that a dangerous situation could result. Within practical limits the higher the antenna the more signal it will pick up. That does not extend indefinitely and there is a point of diminishing returns reached at roughly 5 meters. If it is easy for you to make the antenna higher then do so but there is little point in going to great effort to achieve that as you will only notice a difference in the extreme small signal case.

Proximal support

This support is similar to the distal support and may be attached to either the dwelling or a convenient tree that happens to be close. An insulator supports the antenna and rope. The lead-in wire attaches to the antenna at the insulator. It is important to make sure that the support can break away without damaging the structure should something fall on the antenna wire.

Lead-in wire

The lead-in wire can be whatever is convenient and is often #18 wire. Since the antenna system is much shorter than one-quarter wavelength the lead-in counts as part of the antenna length. Thus, if the antenna wire was 25 meters and the lead-in wire was 5 meters, the total antenna length would be 30 meters.

Crystal Radio Engineering
Antenna and Ground System

Lightning arrestor

A lightning arrestor is an important part of the antenna system that is located outside the building and usually close to where the antenna and ground wires penetrate. A lightning arrestor consists of a spark gap that will arc when more than a few hundred volts exists across the points. Contrary to the name, a lightning arrestor will not protect you or the dwelling from a direct lighting strike. A lightning arrestor will reduce the probability of damage to your crystal set and anything nearby should lightning strike in the vicinity. A nearby strike can induce many hundreds or even thousands of volts on the antenna that could cause damage or injury. The lightning arrestor will then arc to limit the voltage to typically several tens of volts. You should never operate a crystal radio if there is any possibility of a lightning strike. A number of people install shorting switches or connections to connect the antenna to ground when the radio is not being used. This provides some measure of safety but is not absolute. Nothing can protect you or your dwelling from a direct lightning strike.

Ground wire and ground system

The ground wire is typically #18 copper (because that is a convenient size) and should connect to either a nearby metal water pipe or some ground system – either buried pipe or ground rod(s). It is a myth to use wide braid or other large conductor for the ground wire as the resistance of a short length of #18 is negligibly small in comparison to the earth. It is nice for the wire to be no longer than necessary because inductive reactance in the wire can interfere with the operation of the radio – but that is a small point.

Most difficulties or frustrations with crystal radios can be traced to a poor ground system. Building a good ground system is the most labor intensive and even most expensive part of a crystal radio. If you are lucky then there is a long metal water pipe located just outside the window of your crystal radio. In that special case your ground system is easy and cheap.

If you are not so lucky then one alternative is to drive three or more 2.4 meter (8 foot) ground rods straight into the ground near the house. These should be spaced roughly 2 meters apart. The quality of this ground can vary a lot depending on soil conditions and it is not likely to be as good as that of a water pipe. At the easiest, this is a very labor intensive to even impossible job if the ground is very hard. A heavy duty hammer drill can make the job easier. Otherwise you will need a very heavy sledge hammer and strong and enduring muscles as well as significant patience.

An alternative is to dig a shallow trench at least 0.2 meters deep and bury a 10 meter or more length of copper pipe. It helps for the soil to be wet down to the level of the pipe when the radio is being used. This can make a decent ground for radio reception although it should in no way be considered a “safety” ground.

The following table provides a general idea of the quality of the ground system.

Ground Quality	Resistance
Excellent	< 10 ohms
Good	10 to 20 ohms
Fair	20 to 40 ohms
Poor	40 to 100 ohms
Bad	> 100 ohms

A good question is how to measure the ground resistance. This is kind of hard to do since you have access to only one wire. Where is the other end that we measure with respect to? The answer is that it is nebulous but there does exist an effective point that completes the circuit for the radio signal. The effective ground resistance can be inferred from measurements using a received signal. The method is discussed in another chapter.

Mathematical model of the antenna and ground system

A simple electrical model of a short wire antenna less than one-quarter wavelength is shown in Figure 2. It consists of a voltage source equal to the induced amplitude with a small series resistance and very large series capacitive reactance. A simple electrical model of the ground circuit is a series resistance that may range from single digit ohms (an excellent ground) to several tens of ohms. A poor ground may have a series resistance of over one hundred ohms.

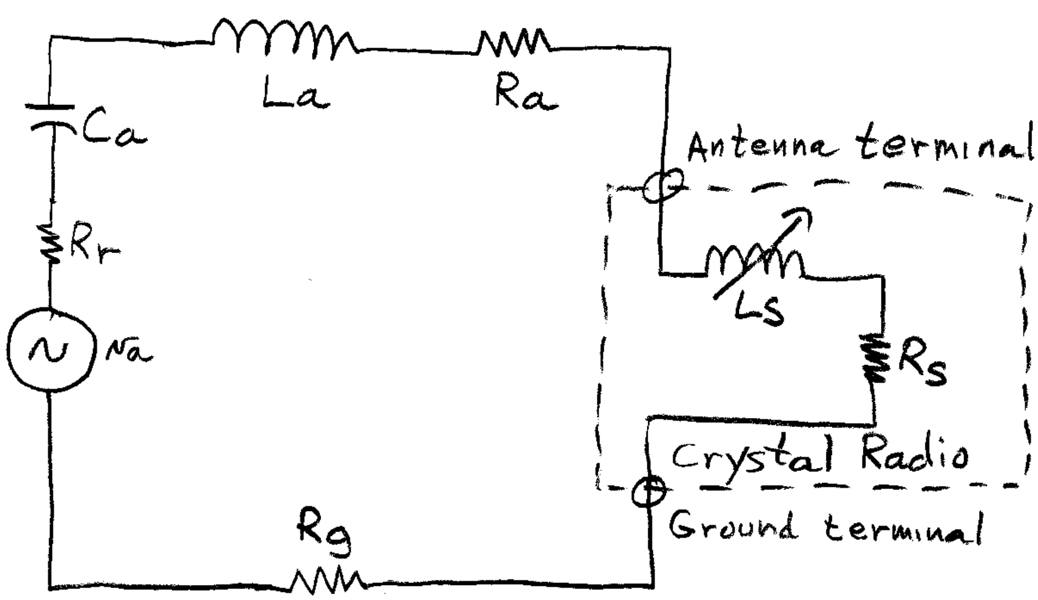

Figure 2: Simple Circuit Model for Antenna and Ground

Crystal Radio Engineering
Antenna and Ground System

Signal pickup

The radio frequency field strength is measured in volts/meter (or amperes/meter if you divide volts/meter by the free space impedance of 377 ohms). This is a cyclic voltage gradient. The voltage that will be induced in a conductor that is short in comparison to a quarter wavelength is roughly the RF signal multiplied by the length of the conductor. Proximity of the conductor to other conductive objects (such as trees and the earth) will reduce the induced voltage. This is one reason why it is desirable for the antenna to be as high as practical above the earth. There is no difference between the antenna proper and the lead-in so the total length is what counts. In Figure 2 this voltage is shown as va.

Radiation resistance

There is an effective radiation resistance associated with the total antenna length. For electrically short antennas this may only be a few ohms but can rise to several tens of ohms as the antenna length approaches one quarter wavelength. In Figure 2 this resistance is shown as rr.

Antenna reactance

An antenna has both a series capacitance and series inductance that makes up a net reactance that varies with wavelength. Capacitive reactance dominates if the antenna is shorter than one-quarter wavelength and inductive reactance dominates between one-quarter and one-half wavelength at which capacitive reactance dominates again for the next quarter wavelength, etc. Normal antennas for crystal radios are significantly shorter than one-quarter wavelength so there is a large capacitive reactance in series with the induced voltage. The inductive reactance reduces the net reactance somewhat for short antennas. At quarter-wave resonance the reactance terms cancel and the antenna is purely resistive. In Figure 2 these are shown as Ca and La.

Antenna resistance

The antenna wire has electrical resistance that is mainly due to the skin effect of the conductor since the frequency is high. This resistance is typically a few ohms and is often small in comparison with the ground resistance. In Figure 2 the antenna wire resistance is shown as Ra.

Antenna tuner inductance

The first element typically found in a crystal radio is an adjustable inductor to neutralize the capacitive reactance of the antenna thus maximizing the power transfer from the antenna to the receiver input resistance. This is known as conjugate matching where the sum of the positive inductive reactance of the inductor and negative capacitive reactance of the antenna is zero. In Figure 2 this inductance is shown as Ls for series inductance.

Crystal radio input resistance

The crystal radio generally appears as a pure resistance at resonance with a received signal. For optimum power transfer this resistance should be equal to the sum of the ground plus antenna plus radiation resistance. The ground resistance typically dominates this equation. The input resistance of the radio can be adjusted via taps on the tuning inductor or other matching network. For best performance it is important to match the radio to the antenna and ground system. Failure to do this results in an underperforming radio.

Ground resistance

The ground resistance completes the circuit back to the rather nebulous point that is the effective reference for the radio frequency signal. Ideally, this resistance is less than 10 ohms but typically is in the 10 to 100 ohm range.

A single short wire antenna is unbalanced and a low-impedance ground is required to complete the RF circuit. It is easy to set up a simple wire antenna that can work well but it is a challenge to construct a low-impedance ground. Without a low-impedance ground much of the signal picked up by the antenna will be wasted and the crystal radio will perform poorly if at all. Much frustration from poor performance of a crystal radio set is often caused by a high-impedance ground. An ideal situation is to connect the crystal radio set to a metal water pipe (either old-fashioned galvanized or preferably copper). The long exposure length to the earth produces a low-impedance ground in the low tens of ohms. The impedance is even lower if the soil is very organic and wet from a recent rain. Dry sandy soils are the worst. One common error is connecting to a metal water pipe assuming that there are no plastic pipe lengths involved.

If a metal water pipe is not available then it might be tempting to connect to the ground system of the electrical distribution in the house or building. For safety considerations I do not recommend this. In the vast majority of cases it may be alright but you never know what errors or faults may be in the system that could result in a nasty or lethal surprise. Even if safety were not an issue, because of inductance the impedance of the ground system at radio frequencies will be much higher than the impedance at 60 Hz. So, this practice is dangerous at worst or is not likely to work well at best.

There are basically only two choices for constructing your own ground. One is to purchase several standard eight foot ground rods and laboriously install them spaced six or more feet apart. This can make a decent ground but is very difficult (impossible is probably more accurate) without the right equipment for installation. An easier alternative that is fine for RF (although not recommended for 60 Hz systems) is to bury a length of bare copper wire or pipe perhaps six to twelve inches below the surface of the ground. Deeper is better but the incremental improvement is probably not worth the extra labor. The total length should be fifty feet or more and parallel runs spaced several feet apart can be used to accumulate effective length. AM broadcast stations use such a system with many buried radial wires from the tower. Each wire is typically a quarter wavelength and the total wire length of all the radials is often over a mile. Such extreme measures are necessary for a high power transmitter because otherwise many thousands of watts could be wasted. The much more modest system described is fine for home use and a point of diminishing returns is quickly reached.

Figure __ shows the theoretical radiation resistance for a single wire antenna that is shorter than one-half wavelength calculated under the assumption that there are no nearby objects that interfere with the impedance. For most situations the antenna is not very far above the ground and the actual resistance will likely be somewhat less than shown. But this is a reasonable model to use for analysis.

Figure __ shows the theoretical series capacitive reactance

How much signal can be received? With a variety of impedance transformations we can obtain most any voltage or current we want but what really matters is how much power we can receive. It is power that will make audible sounds in our earphones.

Assuming that there are no losses and that the load consists of an inductor with the same magnitude of reactance as the antenna capacitive reactance in series with a resistive load equal to the radiation resistance of the antenna, then the power delivered to the resistive load is:

P = (V/m/2 * L)^2 /(40*pi^2*L^2*FMHz^2 /300^2)

= (V/m)^2 *57 / FMHz^2