TMCC Signal Basics

Posted on August 2, 2011 by Dale

The following discussion will cover the actual transmission of train control information over wireless links for the Lionel TMCC and Legacy control systems. There are four types of communication:

Wireless CAB-1 to TMCC Command Base and Powermaster (and Bridge to Powermaster) at 27 MHz

Wireless CAB-2 to and from Legacy Command Base at 2.4 GHz (covered lightly)

"Wireless" TMCC Command Base to locomotives, operating accessories, ZW, SC1 and SC2 at 455 KHz via the "Track" signal

Wired serial data in RS-232 format for power controllers and accessory controllers (not covered here)

Antennas 101

Before we delve into the various links, we should build up a bit of background in how an antenna works. Radio waves propagate through space (including an empty vacuum) by continually exchanging energy between electric and magnetic fields. The electromagnetic wave can be of any frequency higher than DC, including radio, microwave, infrared heat, light, ultraviolet, X-Ray and gamma rays.

All of these waves travel at the same speed in a vacuum – about 186,000 miles per second. A radio wave takes about 3 seconds to bounce off the Moon and return to Earth. We can easily calculate the distance between crests of the wave by dividing the distance traveled per second by the number of full cycles of the wave per second.

Wavelength = Speed/Frequency

For our three wireless links, the wavelengths are

TMCC handheld 11 meters or 36 feet

Legacy handheld 12.5 centimeters or 5 inches

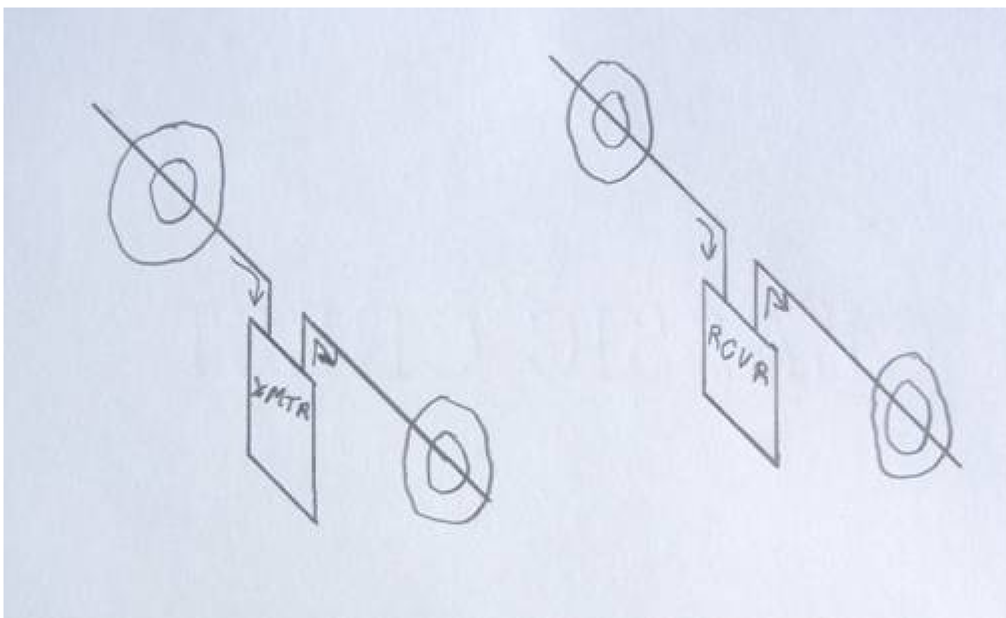
TMCC/Legacy Track 660 meters or 2160 feet

We are going to transmit and receive these wireless signals through various antenna configurations. Fortunately for our discussion here, anything that makes an antenna good for transmitting also makes it good for receiving. This is known as "reciprocity". The only difference is that some transmitting antennas must carry more current and voltage because of the higher transmitting power.

Our electromagnetic wave is generated around a flowing current. Currents are generated by differences in electric potential (voltage), and the resulting flow of current produces a magnetic field. If we set up a way to pump current into our antenna at a rapidly reversing rate (our operating frequency), we will generate electric and magnetic fields around the antenna that will carry power away from the transmitting antenna as a wave.

Thanks to reciprocity, if our transmitted wave strikes a receiving antenna, the wave's electric and magnetic fields will generate a (small) current in the receiving antenna. We can selectively amplify and detect that signal to recover our transmitted information.

To illustrate these principles, we will use a simple dipole antenna as our example. We all used dipole "Rabbit Ears" in the early days of television. We soon learned that varying the length, angle and orientation of the two rods could help or hinder the quality of TV reception. The dipole antenna is simply two conductors stretched in opposite directions, with a transmitter or receiver feeding or receiving signals at the midpoint of the array. The dipole is a "balanced floating" antenna, meaning that the two halves mirror each other and there is no antenna connection to earth ground.



Simple dipole transmitter and receiver systems

The transmitter establishes equal and opposite currents in the two radiating conductors. Usually the antenna length and characteristics are chosen to tune the antenna to resonance so that maximum power can be coupled from the transmitter to the antenna. Note that the driving current is passing through the transmitter. Whatever current comes in one side is also going out the other side.

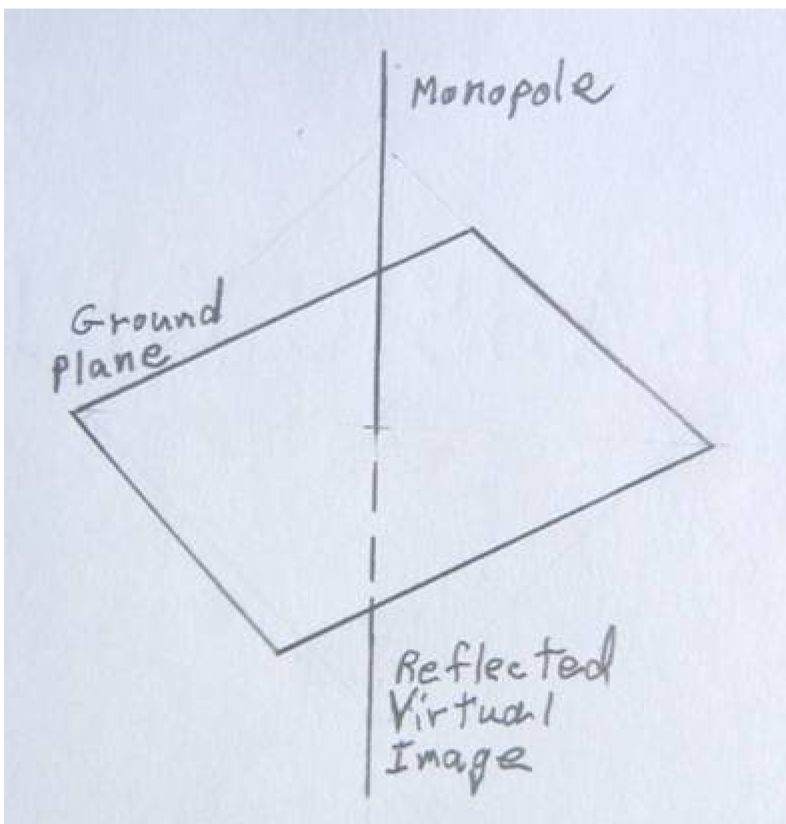
If we were to scan along the length of the antenna conductors, we would find there is a voltage wave and a current wave. In essence, the current wave charges up the voltage on the antenna, with the limitation that the current is always zero at the far ends of the conductors. Electrons don't jump off the ends of the conductors into nearby space. All of the radiating of power is accomplished by the varying electric and magnetic fields.

Our receiving system operates exactly in reverse. The incoming electromagnetic waves generate a voltage difference along the receiving antenna's elements, and that voltage difference causes a current to flow through the receiver at the middle of the antenna.

Unfortunately, nobody operating a TMCC system wants to have a pair of Rabbit Ears sticking out of their CAB-1. The usual choice is to replace the dipole antenna with a monopole or single-rod antenna. This category includes collapsing whips, rubber ducks and even the large transmitter towers used by AM radio stations (yes, size matters!)

In reality, the rod is only half of the antenna system. We still need a second component so that we can have current flow through the transmitter and receiver. If we only had the rod, there would be no way to force current to flow into a dead-end circuit. The answer is to add a ground system on the other side of the transmitter or receiver connection so that current can flow back and forth between the ground and the rod, passing through the transmitter or receiver. The term "ground" should not be taken literally. For an AM radio tower, ground may consist of a radial star of copper conductors centered at the base of the tower, buried in the dirt. For the rod antenna on an automobile, ground is the metal body of the car.

An ideal monopole antenna would be a rod one quarter wavelength long, mounted on a ground surface (ground plane) that is highly conductive. The ground plane acts as a mirror for the antenna rod, creating a second



Monopole antenna with phantom mirror image

"phantom" rod that would extend into the earth from the base of the rod. This creates the equivalent of a vertical dipole. The current flow between the ground and the rod is equivalent to the current flow at the center of a two-rod antenna. (Ham operators – For simplicity I am ignoring things like characteristic impedance.)

Handheld-to-Base Link

For maximum efficiency our CAB-1 antenna should be a quarter-wavelength rod nine feet long, surrounded at the base by a metal disk 18 feet in diameter. Not too portable and convenient? We bow to practicality and do the best we can in the available space. The collapsible antenna is far less than a quarter wavelength (minimum length = 5”) and we use the ground traces of the printed circuit board as our ground plane. As a result, we have a very inefficient antenna system, but it is good enough to cover the area of a normal train layout comfortably. (The capacitance of the operators body may help somewhat, but there isn’t a good connection between the RF ground inside the case and the operator’s body. The electrical gap through the plastic is approximately ¼”, and using the area of a hand palm as 30 square inches, the capacitance would be about 60pF, yielding a coupling impedance of about 200 ohms at 27 MHz.)

The receiving antennas in the Command Base and Powermaster are planar coils of wire that are 28” long. This configuration may be dictated by the space available and the resonant frequency of the coil.

The bottom line is that the CAB-1 communications is much less than optimal. The transmitter’s output power and the receiver’s sensitivity make up for the inefficiencies of the antenna configurations.

We can make some useful observations about the antennas. The CAB-1 antenna radiates sideways from the rod with an annular wave similar to sliding a donut or bagel (choose your favorite) over the rod. The antenna does not radiate much power off the end of the rod. Pointing the rod at the Base is the worst case orientation. At the receiving end the coil of wire picks up best when a wave encounters the loop of wire edge on. Pointing the CAB-1 rod at the top of the Base would be the worst relative orientation.

The Legacy system has a wavelength of only 5”, allowing the use of more ideal transmitting and receiving antennas with higher efficiencies. Since Legacy uses bidirectional communication, the antennas in the Base and handheld are used for both transmitting and receiving.

Base-to-Locomotive Link

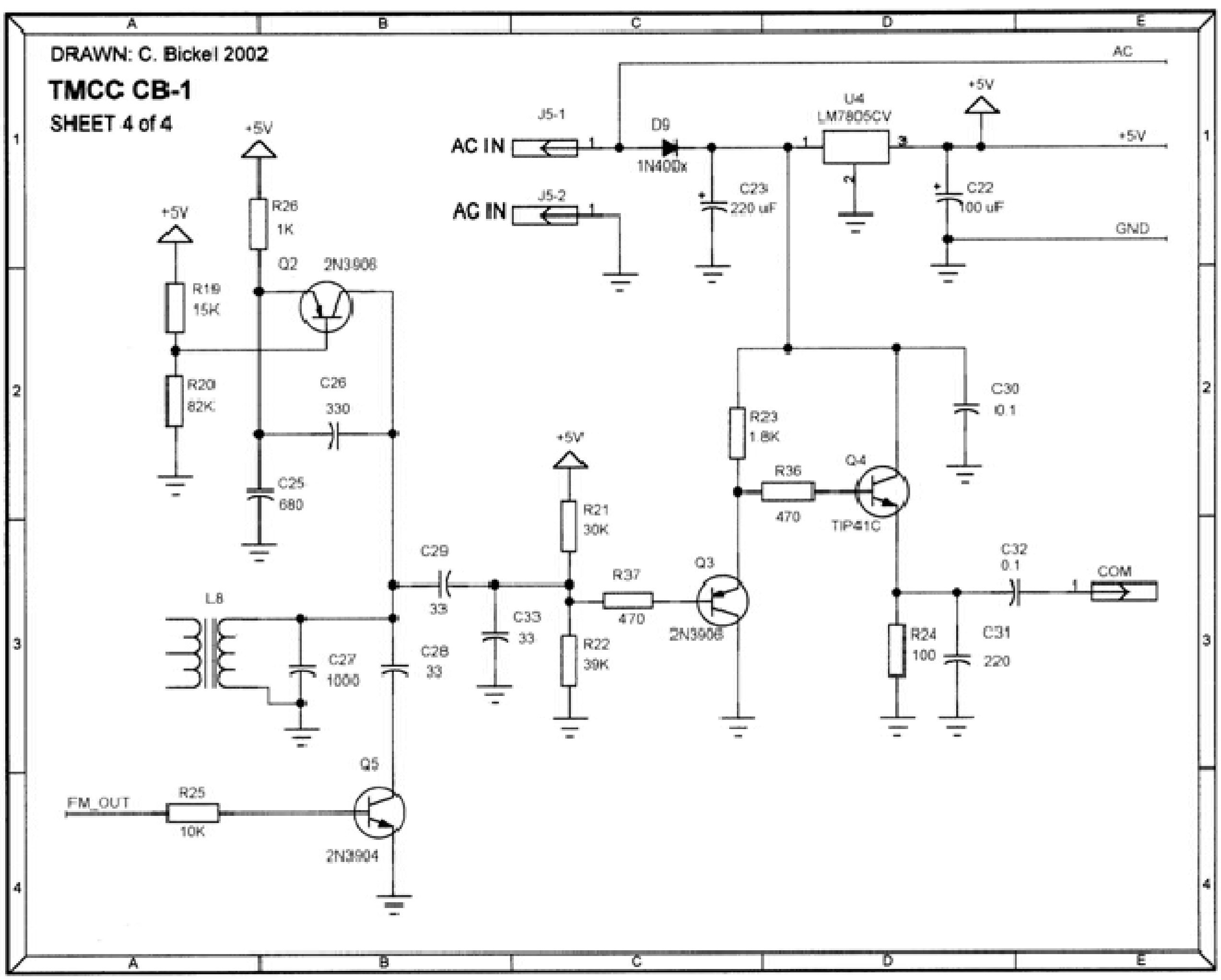
Everything was fairly obvious in the previous discussion, but things become much fuzzier when we tackle the Track signal. The best way to approach this problem is to work backward from the locomotive to the Base.

The locomotive contains a receiver that is tuned to the 455 KHz track signal. The front end of the receiver couples the transmitted airborne signal to the receiving circuitry. As in our antenna theory discussion above, we need to have two parts to the receiving antenna, and the receiver connected between the two halves. What are the two parts of the antenna? The locomotive has an antenna in the form of an insulated handrail or wire or foil strip. For locomotives with cast metal shells, the antenna is on the outside of the shell. For plastic shelled diesels, the antenna can be mounted under the roof of the shell.

The antenna connects through a wire to the input stage of the radio receiver. As we saw earlier, we also need a second half to the antenna system so that we can get current to flow through the receiver. For this application we use the frame of the locomotive as our ground reference. The received radio signal will flow between the antenna and the frame of the locomotive. Note that the frame is also connected to the wheels and hence the track outer rails. That means that our receiver is sensing the current flow between the antenna and the outer rails.

We must stop here to dispel Myth Number 1 – "*The antenna on a TMCC locomotive picks up the Track signal*." As we just concluded, one side of the receiver's input connects directly to the outer rail, and hence the Track signal. If the antenna also picked up the same signal, there would be no voltage difference and no resulting current flow. The antenna IS NOT PICKING UP THE TRACK SIGNAL. If not the Track signal, then what is the antenna receiving?

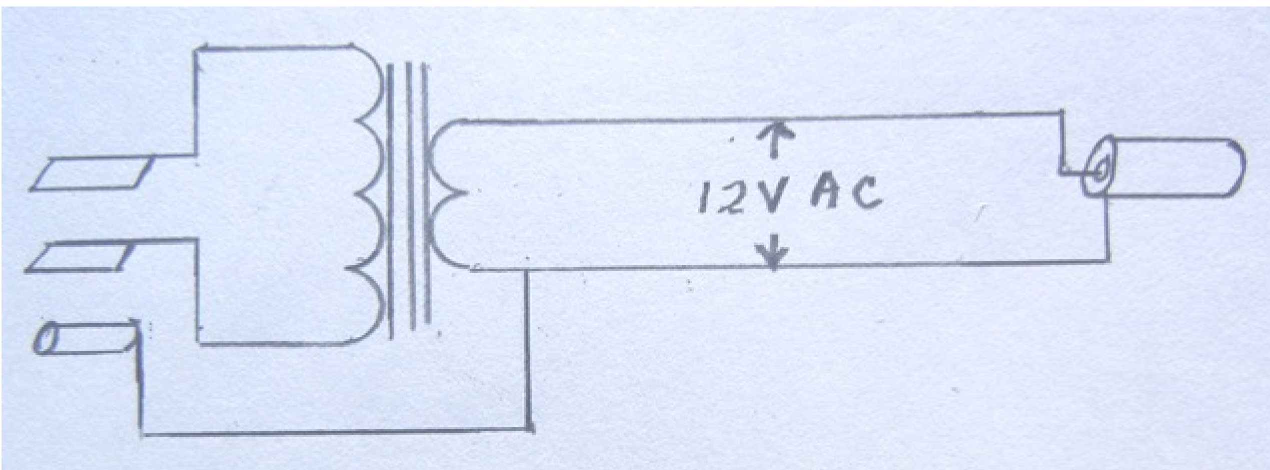
To answer that question we must jump over to the other half of the system – the Command Base. The circuit that transmits the Track signal is shown in the following drawing. Transistor Q4 is the final stage that drives



the "U" thumbscrew terminal on the back of the Command Base. This signal is conducted down the outer rails, through the wheels of the locomotive, into the frame and then to the "ground" side of the radio receiver's input circuit. This "ground" isn't sitting still at zero volts, but rather it has part of the 455 KHz signal moving it around electrically.

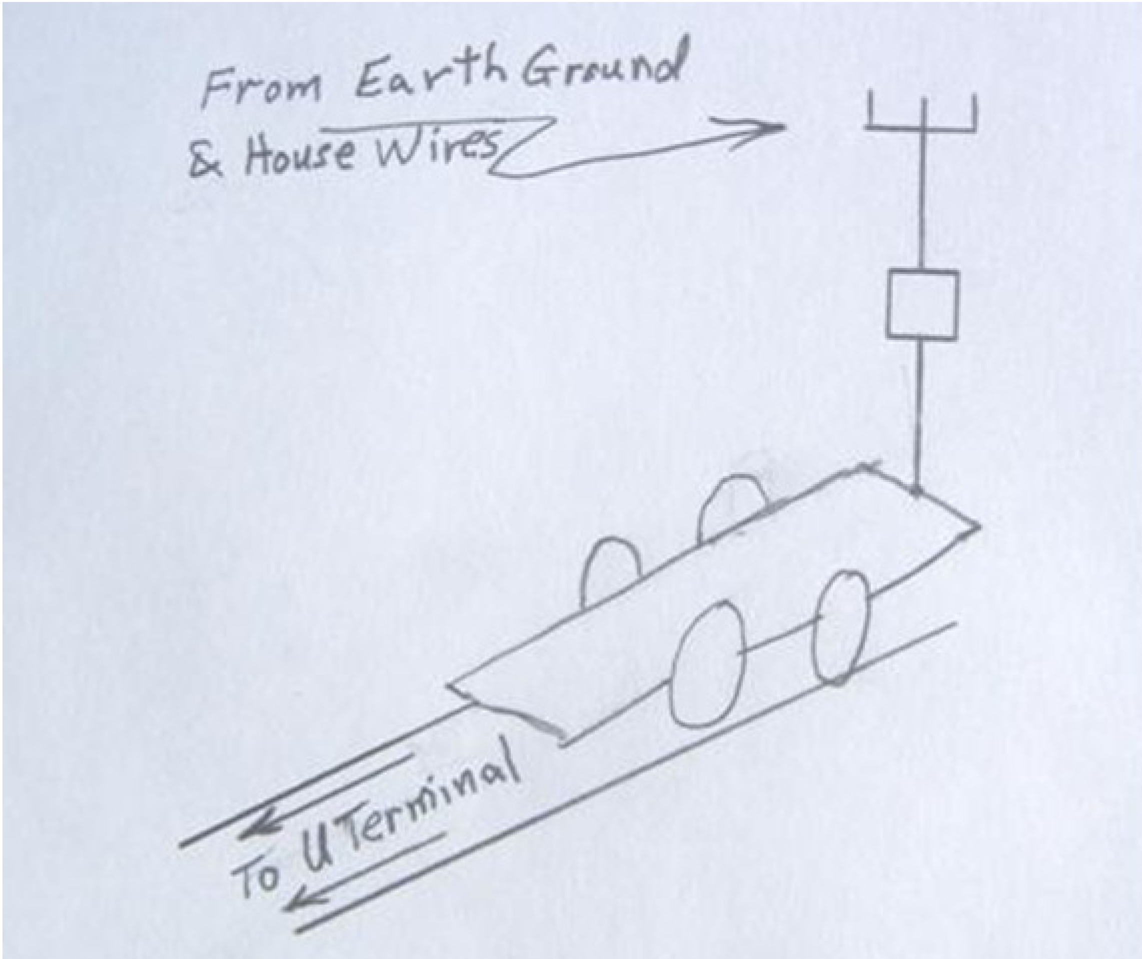
We can consider this path from the thumbscrew through the track and into the locomotive frame as one half of the transmitting antenna for the Command Base's output signal. We know that an antenna must have two parts so that current can flow back and forth. Where is the second part of our transmitting antenna?

The output signal on the emitter terminal of Q4 feeds positive current out from the collector of Q4, and sinks negative current through R24. Both of these points tie back to the local signal ground in the Base. R24 is directly tied to ground, and the collect of Q4 is tied to ground by the big bypass capacitor C30. That means that the other side of our transmitter signal is the local signal ground in the Base. We need to connect the other half of our antenna to this ground. Now note that one side of the incoming AC, J5-2, is directly tied to this signal ground. This AC lead comes from the wallwart that is plugged into the AC wall receptacle, and in the wallwart the wire to J5-2 is jumpered to the U-ground safety ground pin.



Wallwart schematic

The other half of our antenna is the house wiring! The track signal generated by Q4 flows back and forth between the house wiring and the outer rail. The house wiring radiates the signal through the air to the antenna



on the locomotive, and thus feeds the other side of the receiver's input circuit. The current in the receiver is an image of the current that flows between the house wiring and the outer rails.

The house safety ground green wire eventually makes its way back to power panel and there it is tied to the neutral and the earth ground rod or clamp on a water pipe. We now have the other half of the TMCC signal radiating from all of the house wiring – safety ground, neutral and even the hot wire thanks to cable capacitance and any electrical loads that connect the hot to neutral through a resistance, and from the earth. We will refer to this connection as "earth ground" to distinguish it from layout common, which is sometimes called "ground". Earth ground and layout common SHOULD NEVER BE TIED TOGETHER!!!!

Although the TMCC system is intended to have a conduction path through the wallwart via a wire jumper, I suspect that some TMCC signal will be fed into the house wiring just through the winding capacitances of the wallwart's transformer. I have not measured the effectiveness of this coupling path.

Problems and Solutions

Now that we know how the TMCC Track signal is transmitted and received, we can look at some common problems and their solutions.

1. We must establish a good connection between the Command Base and the AC wiring in the house.

    1. Our house wiring must have proper safety ground wiring with U-ground receptacles. Do not use a 3-pin to 2-pin adapter plug on the Base wallwart.
    2. We must use the Lionel wallwart so that we have the jumper between the Base ground and the house safety ground. Check for continuity between the outer barrel of the coaxial power connector and the U-ground pin on the wallwart.
    3. If you use an outlet strip, verify that the U-ground receptacles are connected to the U-ground pin on the plug.
    4. Do not connect the Base wallwart to a coiled up extension cord. The coiling of the cord can create an inductor that hinders the flow of the Track signal to the house wiring.
    5. Use only proper 3-wire extension cords with safety ground pins.
    6. I don't think surge suppressors in an outlet strip should degrade the signal. At worst, the suppressors will capacitively couple the safety ground TMCC signal to the hot and neutral, but the wiring capacitance throughout the house wiring also does that without ill effect.
2. Eliminate any electrical noise sources.
    1. Use a portable AM radio to "sniff" for noise sources. Tune the radio to an unused frequency. Common problems are faulty fluorescent lamps, arcing capacitors in the AC line filter for most electronic devices, faulty aquarium thermostats, failing power supplies, arcing power supplies in TVs or computer monitors and DC motors.
    2. Add capacitors to the brushes of Pullmor motors in older locomotives and motorized accessories.
    3. Keep your track and pickup rollers clean.
3. Check the integrity of the locomotive's antenna
    1. If the antenna is metal handrails, there must be no resistive path between the handrails and the boiler casting.
    2. Verify that the antenna is securely connected to the TMCC receiver board.
    3. Some diesels will benefit from extending the antenna by adding foil tape or just wires.
    4. An antenna inside a closed metal box is blind. If the receiver and antenna are inside a tender shell:

1) Insulate the top part of the tender shell from the frame with tape and connect the antenna to the insulated portion.

2) Poke a hole in the shell and route a section of antenna wire outside the shell.

We must avoid configurations that block out the airborne Track signal by having too much outer rail Track signal. Imagine what would happen if you put your locomotive inside a metal box that was connected to the outer rail. You would have lots of Track signal conducted through the wheels, but there would be not airborne signal on the antenna to cause current to flow back and forth through the input stage of the receiver. This is the situation you create if you have overhead bridges and/or trackside metal structures connected to the outer rails of the track, or many parallel tracks.

Now imagine that we drill a hole in the metal box containing our locomotive, and we insert a wire connected to the earth ground signal. Now the locomotive's antenna can pick up some of the earth ground signal and create a voltage differential across the receiver's input. We can pick up the earth ground signal from the center screw on a grounded wall receptacle, a metal water pipe or electrical conduit, or Pin 5 of the 9-pin connector on the back of the Command Base.

1. Avoid overwhelming the airborne signal with too much conducted Track signal
    1. Do not connect tubular track ties directly to metal bridges with metal mounting screws. Alternatives are nylon screws or using insulating shims and plastic shoulder washers.
    2. Beware of trackside accessories with metal parts that are tied to the layout's common bus. This will put the conducted Track signal onto the metalwork. One solution is to use a separate transformer and wiring for accessories that are not tied to the track common.
    3. If necessary, add some earth ground antennas in the region where there is too much conducted Track signal. Run a wire connected to earth ground on the underside of the bridge or between the parallel tracks, or string some fine wire as power lines on power poles.
    4. We can temporarily augment the airborne signal by using our body as a secondary antenna, and placing our hand near the locomotive. This brings more earth ground signal to the locomotive. If this helps the locomotive, the permanent fix is to add an earth ground antenna to that area.

Note that this overwhelming is not what we would normally consider to be interference or cancellation. The multiple Track signals are not interfering and reducing anything. They are all adding up quite nicely, too nicely in fact. (There is no "interference" because a wavelength .4 mile long is much too long to create cancellations in a space the size of a layout. We are dealing with a simple imbalance.)

Many folks talk about a "halo of track signal". Indeed there is a signal radiated by the track, but this is really an unwanted signal. Our antenna doesn't want to pick up this signal, and we are already getting all the Track signal we need by conduction through the wheels.

Years ago a "TMCC Signal Enhancer" was sold to overcome signal weak spots. The Enhancer merely added some of the TMCC signal from the outside rails to the center rail. As we have seen, this is quite unnecessary, and any signal problems are probably due to too much Track signal rather than too little.

I have heard from people who run TMCC outdoors and in other environments that aren't surrounded by house wiring. There still must be a second half of the antenna system, possibly though an extension cord into the house wiring and then to earth ground at the power panel. The layout outdoors is still over good old earth.

Conclusion

Many of the ideas presented here run contrary to the folklore, but I believe that this is a cohesive argument that will hold up against testing. I don't claim to be a certified expert, but I do hold a MS in Electrical Engineering, and I have been a ham radio operator for over 20 years. You are welcome to disagree with me and my ideas, but please present factual evidence for any competing theories.