Antenna Design for FM-02

I recently received my FM-02 FM transmitter which I purchased from WLC. I researched the forum on what antennas where being used by the DIY community and found a nice write-up on building a dipole. I also found many people were having issues with their antenna transmitting to the road in front of their house when using this dipole.

I offer this white paper as some technical information on antenna design and where this information might explain and help those with issues resolve their problems. At the end of the paper, I will present a ¼ wave vertical antenna I built which alleviates many of the issues that can be associated with a dipole antenna.

I will support my statements by referencing information published by ARRL (American Radio Relay League) and several Ham sites on the Internet.

As a note up front – when you start researching information about your FM Broadcast Band antenna – you will find a ton of Ham information on the topics you are looking for. Be for-warned, most all of the Ham information is based on transmitting in the HF (High Frequency) spectrum – 10 meters being the top of the band – around 30 mhz. Our FM system is part of the VHF (Very High Frequency) spectrum – where small issues in the HF band can become very big in the VHF realm.

The FM-02 is rated as transmitting 30mw (that's milliwatts --- .030 watts) into a 50 ohm load. Compare that to a CB radio rated at 4.0 watts AM.

Transmitters are designed to be paired with a coax transmission line whose line impedance is expected to match its load. The FM-02 was designed for 50 ohms so this means we should use a 50 ohm coax.

I purchased some 25ft of RG8 already terminated with BCN connectors from Amazon for under $10. At the end of this paper, I will present a list of various cables and the important characteristic associated with each.

Most on the forum have elected to use a dipole.

The following shows the radiation pattern associated from a dipole (taken from AARL Handbook – page 21.6)

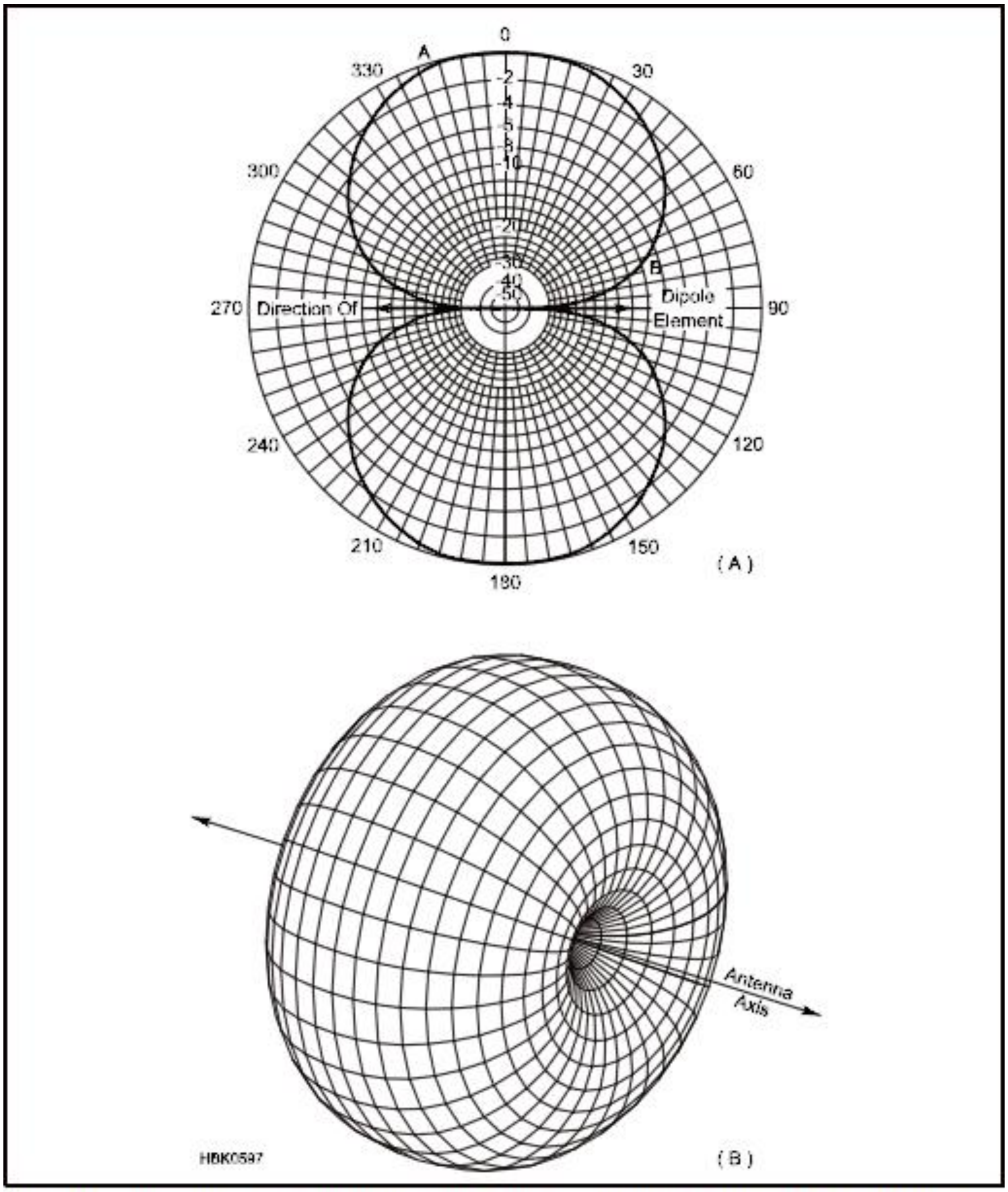


Fig 21.9 — Response of a dipole antenna in free space in the plane of the antenna with the antenna oriented along the 90° to 270° axis (A). The full three-dimensional pattern of the dipole is shown at (B). The pattern at A is a cross-section of the three-dimensional pattern taken perpendicularly to the axis of the antenna.

The important point to this illustration is that the energy is radiated perpendicular to the axis of the dipole.

If you use a dipole antenna and orient it horizontally and one of the ends points towards the street – you have the antenna positioned incorrectly – the smallest amount of energy is being transmitted towards the street – you need to place it on a wall that is parallel to the street.

What is the feed-point impedance of your dipole antenna?

The following graph (ARRL page 21.3) shows radiation resistance for a dipole mounted both in a horizontal and vertical position. Notice how the horizontally positioned dipole's resistance changes with respect to height above ground. The dipole mounted vertically sees much less variation as long as it's positioned greater than .3 wave lengths above the ground (at least 3 to 5 feet).

Those of you using your dipole antenna, and it's positioned horizontally, should make sure it is at least 12 feet above ground. If the antenna is any closer to ground, the characteristic impedance of 70 ohms will not hold true; (as you can see – it will be about 45 ohms is 1 foot off the ground, 98 ohms if 4 feet off the ground, 58 ohms if 6 feet off the ground, and 84 ohms if 9 feet off the ground).

In summary, If you are using a dipole antenna – you should position it vertically at least 5 feet above the ground or horizontally – at least 12 feet above the ground.

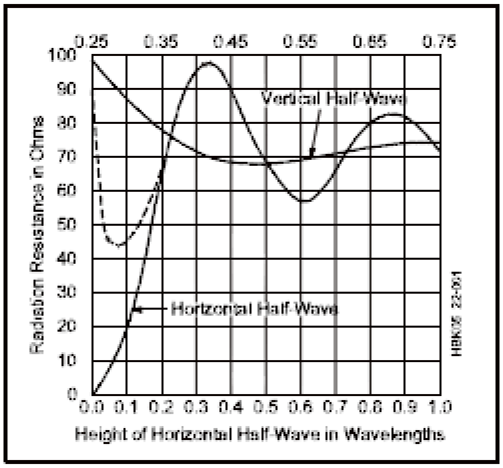


Fig 21.2 — Curves showing the radiation resistance of vertical and horizontal half-wavelength dipoles at various heights above ground. The broken-line portion of the curve for a horizontal dipole shows the resistance over *average* real earth, the solid line for perfectly conducting ground.

Let's assume the dipole is position so that the characteristic impedance of 70 ohms is presented to the RG8 coax cable. Since the antenna's 70 ohm impedance does not match the 50 ohms being presented by the coax – we have an impedance mismatch which will result in some of the power being reflected back down the coax creating standing waves. You would have a SWR (Standing Wave Ratio) of 1.4 to 1.

Note – this is an acceptable SWR.

SWR meters are usually used to measure this mismatch. Note – there are very few SWR meters that can be used in the system we are creating (those that can are expensive or custom made). The SWR meters normally available and within the DIY budget are designed for the CB community. They are designed to measure transmitters greater than 1 watt – remember – we are .03 watts max. These meters are just not sensitive enough to be useful.

Your dipole antenna is created by cutting two lengths of wire and connecting them to the coax cable. How long of a wire do you cut?

In free space (vacuum), wave length (in feet) is equal to 983.6 / frequency (in mhz).

The wave length is smaller (only 95% of free space) when the rf wave runs through copper – speed is slower (AARL Handbook page 19.1) If you elect to use wire that is enclosed with insulation (not bare copper) it is slowed another 3 to 5% because of the capacitance associate with the insulation (AARL Handbook page 21.8)

As an example – let's say we want to transmit on 100.1 mhz – how long of wire do I cut if I'm uses bare wire and how long if I'm using insulated wire?

Bare wire:

Each segment is ¼ wave length in size – so L = (983.6 * .95) / (100.1 * 4) = 2.3337 ft or 28.0 inches. The .95 is due to the RF being conducted down copper and the divide by 4 is because we want ¼ of a wave length.

Insulated copper wire:

L (@ 3%) = 28.0 * .97 = 27.2 inches
L (@ 5%) = 28.0 * .95 = 26.6 inches

So … if we are using bare wire – cut it to 28 inches – if using insulated wire – cut it at 27 inches.

This is the point where most of the forum information stops ---- but there is a very critical aspect of our dipole design that has not been addressed.

The dipole antenna is a "balanced" load where equal, but opposite, currents are traveling down each segment of the antenna. Coax is not balanced – hence it is "unbalanced".

DC current run through the complete cross section of the wire. When we are dealing with AC current, it no longer runs through the complete cross section – it migrates (based on frequency) so it is only being conducted on the out rim of the copper wire. This is known as skin effect. At 100 mhz, most of the current is being conducted very close to the surface of the copper conductor.

The following diagram illustrates current flow associated with a coax joined to a dipole antenna (AARL Handbook page 21.6)

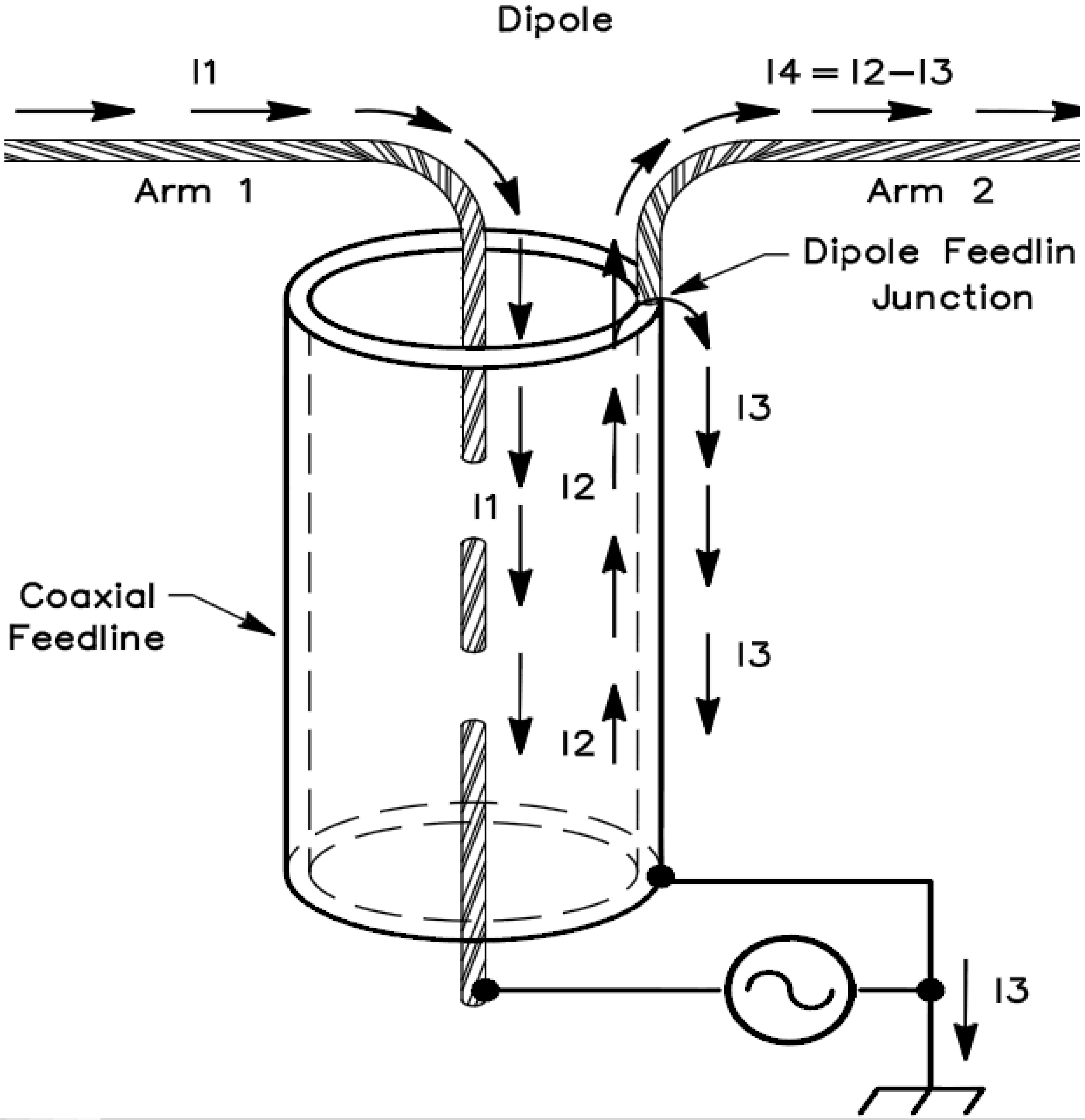


Fig 24—Drawing showing various current paths at feed point of a balanced dipole fed with unbalanced coaxial cable. The diameter of the coax is exaggerated to show currents clearly.

Remember skin effect. Current I2 is flowing on the "inside" surface of the coax braid and current I3 is flowing of the "outside" surface of the coax braid. Current flowing on the "outer" surface of the coax is called "Common Mode" current.

The impedance seen by the “common mode” current is called “common mode impedance”. The common mode impedance is directly related to the length of wire from dipole segment connection all the way to rf ground --- this means the length of your coax, plus the length of wire associated with your transmitter and power supply, and also length of wire in your house to get to the rf ground. (ARRL Antenna Book page 26.17)

Common mode currents cause your antenna’s radiation pattern to distort because your coax and house wire now also become part of the radiator.

Worst case occurs when the length associated with this common mode current is a multiple of ½ wave length. This causes the common mode impedance it appear as a short and I3 (common mode current) to be at its maximum.

This is not wanted and needs to be addressed.

I believe this is one of the main reasons some people are having transmission issues. This common mode current can wipe out the output stage in your FM transmitter and dramatically reduce transmitter power.

On the other side of the coin, as the rf length approaches multiples of ¼ wave length – the common mode impedance is very large – and I3 is minimal. That is why it just hooking the coax directly to the dipole works for some and won’t for others. Note – we are talking about a wire length (includes house wiring) difference being a multiple of 2 to 3 feet in length --- making your dipole’s perform go from from “OK” to “Terrible”. (ARRL Antenna Book page 26.17)

Consider this worst case scenario – Can’t transmit to the street because we have our dipole position horizontally, directly fed by coax (with none of the solutions below in place), the segment closest to the street is the segment conducting common mode currents and the rf cable length is a multiple of ½ wave length (shorted segment)!

So – how do we stop I3 (common mode current) from occurring. Three (3) ways:

Solution #1.

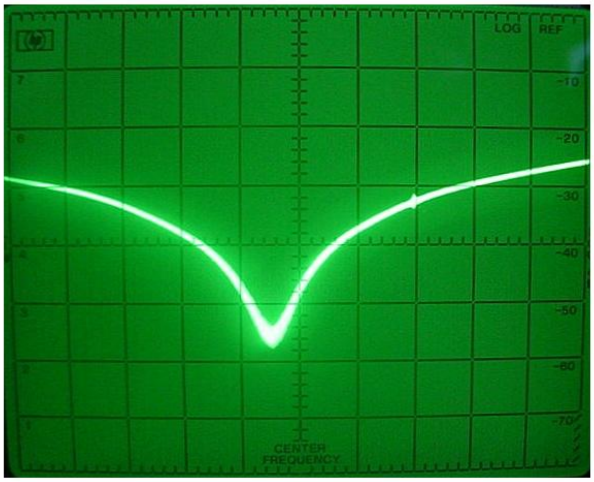
The easiest way is to place an rf choke in the path of I3. Hams have been doing this for years. Simply make a coil from your coax feed line near the dipole. The coax braid is then the conductor which forms an inductor – hence a choke. You will see this coil referred to as a "choke balun" or "ugly balun". I have stayed from calling it a balun – because it is not.

The key is to create a coil of X inches in diameter and Y number of turns. X and Y are unknown. There are tools that can show the frequency of resonance for your coil – but very few of us will have access to those tools. You must do this by trial and error. Try different sizes and turns until you find one that improves your situation.

The only problem with this solution is not knowing at what frequency the coil resonates at (fo). The impedance for frequencies less than fo are inductive (which we want) and the impedance for frequencies above fo are capacitive (don't want). So as a guide line in your trail and error process – keep coil diameter as large as possible (not over 4 inches) and keep the number of turns to a minimum – not over 6.

The following site discusses this type of rf choke:

http://www.ham-radio.com/k6sti/balun.htm

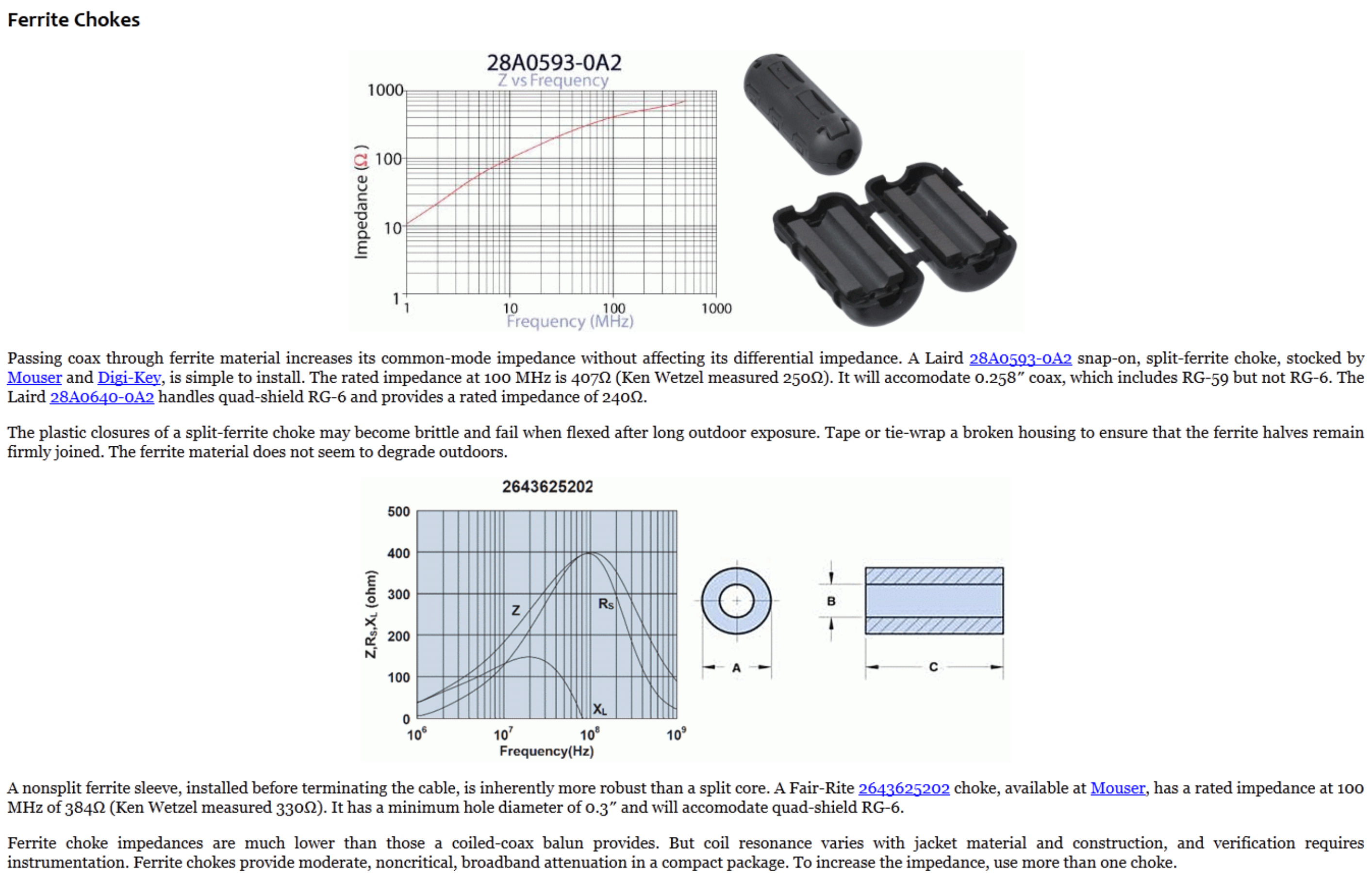


This shows shield attenuation from 88 to 108 MHz in a 50Ω system. This particular balun resonated at 97 MHz. The attenuation range corresponds to a common-mode impedance of 1.9kΩ to 63kΩ.

Solution #2:

We can also create a choke by adding ferrite material to the coax.

Taken from site: http://www.ham-radio.com/k6sti/balun.htm



Ferrite Chokes

Passing coax through ferrite material increases its common-mode impedance without affecting its differential impedance. A Laird 28A0593-0A2 snap-on, split-ferrite choke, stocked by Mouser and Digi-Key, is simple to install. The rated impedance at 100 MHz is 407Ω (Ken Wetzel measured 250Ω). It will accomodate 0.258″ coax, which includes RG-59 but not RG-6. The Laird 28A0640-0A2 handles quad-shield RG-6 and provides a rated impedance of 240Ω.

The plastic closures of a split-ferrite choke may become brittle and fail when flexed after long outdoor exposure. Tape or tie-wrap a broken housing to ensure that the ferrite halves remain firmly joined. The ferrite material does not seem to degrade outdoors.

A nonsplit ferrite sleeve, installed before terminating the cable, is inherently more robust than a split core. A Fair-Rite 2643625202 choke, available at Mouser, has a rated impedance at 100 MHz of 384Ω (Ken Wetzel measured 330Ω). It has a minimum hole diameter of 0.3″ and will accomodate quad-shield RG-6.

Ferrite choke impedances are much lower than those a coiled-coax balun provides. But coil resonance varies with jacket material and construction, and verification requires instrumentation. Ferrite chokes provide moderate, noncritical, broadband attenuation in a compact package. To increase the impedance, use more than one choke.

Please note – one of these is not enough. A typical application requires from 8 to 24 of these devices.

Solution #3:

Use a balun. Balun is an acronym for “Balance” to “Unbalanced” transformation.

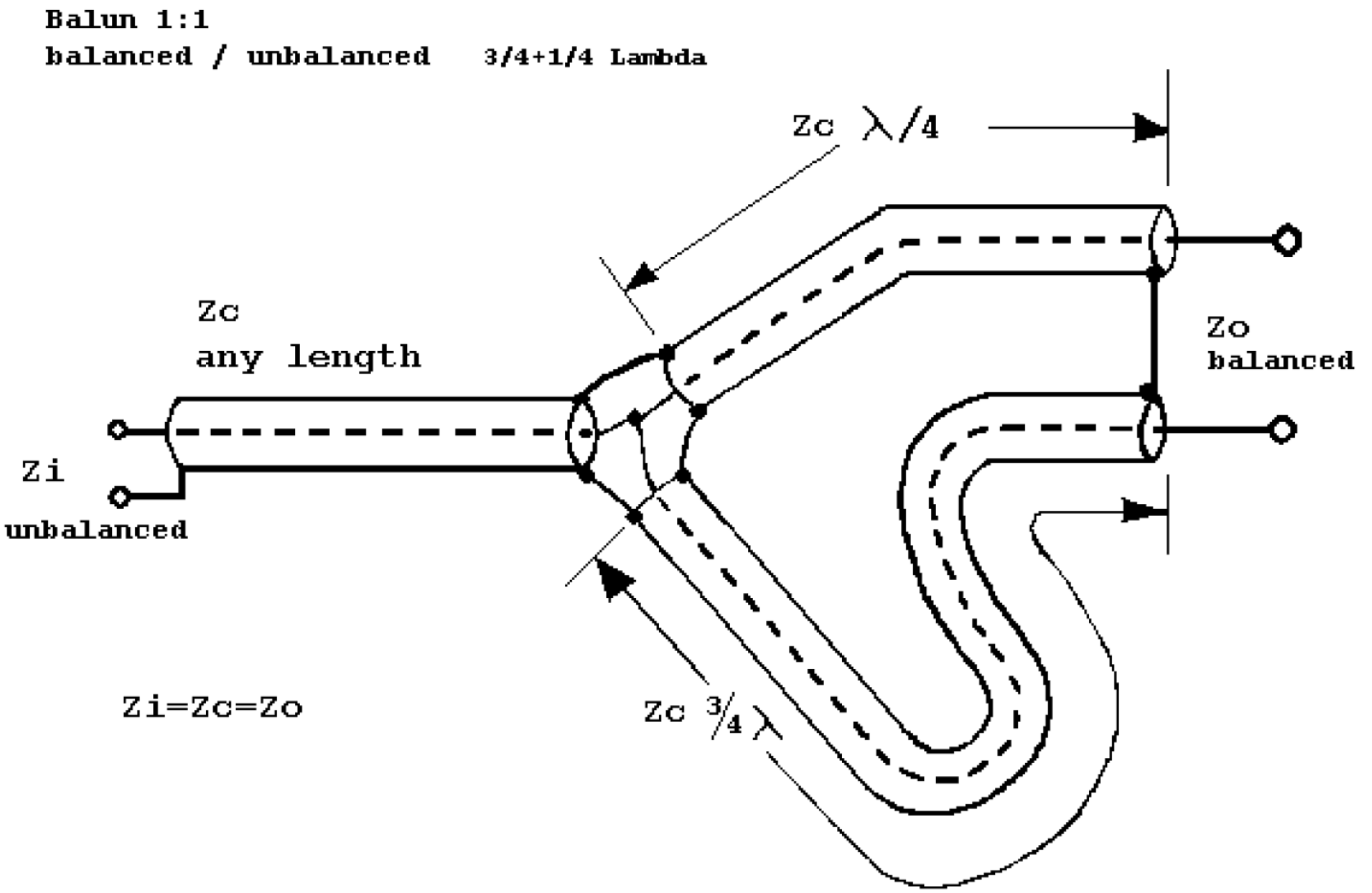
A balun is used to transform the system from unbalanced feed to a balanced feed – and transform impedance at the same time (if required)

Most of you will recognize the TV balun used on old televisions – 300 ohm twin lead to coax. This device also performed a 4 to 1 impedance transformation – 300 ohms to 75.

Coax can be used to manipulate impedances at specific frequencies. Do a google for “Stub Tuning” if you are interested or pick up the ARRL Handbook.

The following balun can be found at http://www.iw5edi.com/ham-radio/files/I0QM_BALUN.PDF

This is the only method where you design the system so you don’t have to take other measures to block common mode current because they are NOT present. Your unbalanced coax is transformed into a balanced line by placing the two segments, of proper length, in parallel.



The two additional lengths of coax are added to you feed and placed within your PVC pipe.

If you choose to build the above balun – how long are the lengths of coax required?

Let’s go back to our example of transmitting on 100.1 mhz.

I stated earlier that L (wave length in ft In free space (vacuum)) =   983.6 / frequency (in mhz).

I also stated that current runs on the surface of the copper conductor and it is slowed by the capacitance associated with the material directly in contact with the copper conductor.

There is a term called “Velocity Factor” that defines the amount the rf wave is slowed by when not conducting in free space.

From ARRL Antenna Book – page 24.4 the following equation for the length of coax associated with a ¼ wave:

$$\lambda/4 = \frac{245.9}{f} \times \mathrm{VF} \qquad \text{(Eq 2A)}$$

The following table is from ARRL Antenna Book – page 24.18:

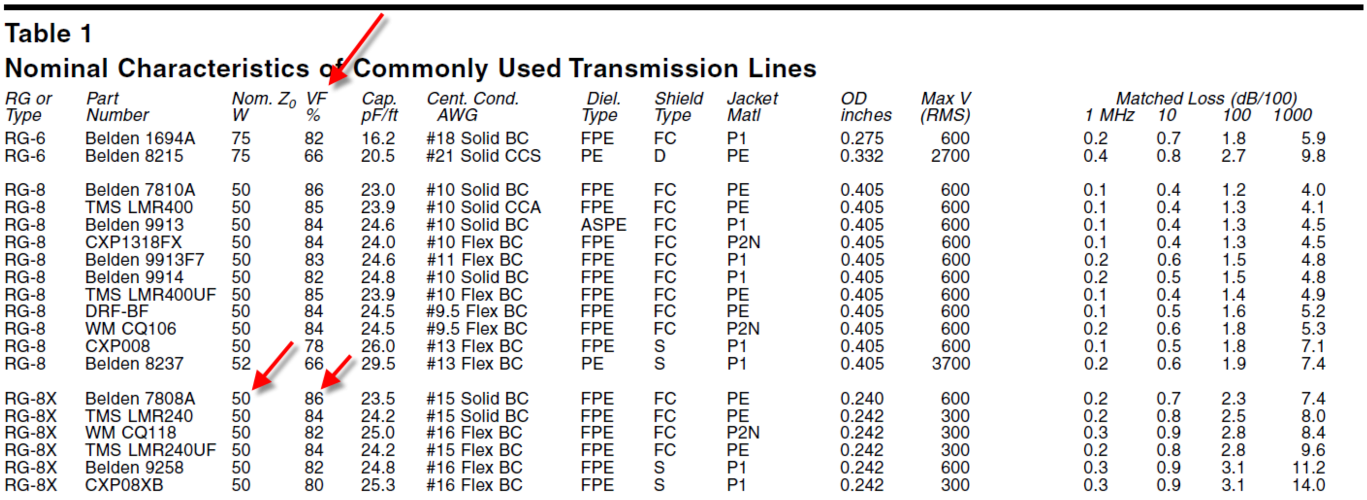


Table 1

Nominal Characteristics of Commonly Used Transmission Lines

RG or Type	*Part Number*	*Nom. Z_0 W*	*VF %*	*Cap. pF/ft*	*Cent. Cond. AWG*	*Diel. Type*	*Shield Type*	*Jacket Matl*	*OD inches*	*Max V (RMS)*	*Matched Loss (dB/100) 1 MHz*	*10*	*100*	*1000*
RG-6	Belden 1694A	75	82	16.2	#18 Solid BC	FPE	FC	P1	0.275	600	0.2	0.7	1.8	5.9
RG-6	Belden 8215	75	66	20.5	#21 Solid CCS	PE	D	PE	0.332	2700	0.4	0.8	2.7	9.8
RG-8	Belden 7810A	50	86	23.0	#10 Solid BC	FPE	FC	PE	0.405	600	0.1	0.4	1.2	4.0
RG-8	TMS LMR400	50	85	23.9	#10 Solid CCA	FPE	FC	PE	0.405	600	0.1	0.4	1.3	4.1
RG-8	Belden 9913	50	84	24.6	#10 Solid BC	ASPE	FC	P1	0.405	600	0.1	0.4	1.3	4.5
RG-8	CXP1318FX	50	84	24.0	#10 Flex BC	FPE	FC	P2N	0.405	600	0.1	0.4	1.3	4.5
RG-8	Belden 9913F7	50	83	24.6	#11 Flex BC	FPE	FC	P1	0.405	600	0.2	0.6	1.5	4.8
RG-8	Belden 9914	50	82	24.8	#10 Solid BC	FPE	FC	P1	0.405	600	0.2	0.5	1.5	4.8
RG-8	TMS LMR400UF	50	85	23.9	#10 Flex BC	FPE	FC	PE	0.405	600	0.1	0.4	1.4	4.9
RG-8	DRF-BF	50	84	24.5	#9.5 Flex BC	FPE	FC	PE	0.405	600	0.1	0.5	1.6	5.2
RG-8	WM CQ106	50	84	24.5	#9.5 Flex BC	FPE	FC	P2N	0.405	600	0.2	0.6	1.8	5.3
RG-8	CXP008	50	78	26.0	#13 Flex BC	FPE	S	P1	0.405	600	0.1	0.5	1.8	7.1
RG-8	Belden 8237	52	66	29.5	#13 Flex BC	PE	S	P1	0.405	3700	0.2	0.6	1.9	7.4
RG-8X	Belden 7808A	50	86	23.5	#15 Solid BC	FPE	FC	PE	0.240	600	0.2	0.7	2.3	7.4
RG-8X	TMS LMR240	50	84	24.2	#15 Solid BC	FPE	FC	PE	0.242	300	0.2	0.8	2.5	8.0
RG-8X	WM CQ118	50	82	25.0	#16 Flex BC	FPE	FC	P2N	0.242	300	0.3	0.9	2.8	8.4
RG-8X	TMS LMR240UF	50	84	24.2	#15 Flex BC	FPE	FC	PE	0.242	300	0.2	0.8	2.8	9.6
RG-8X	Belden 9258	50	82	24.8	#16 Flex BC	FPE	S	P1	0.242	600	0.3	0.9	3.1	11.2
RG-8X	CXP08XB	50	80	25.3	#16 Flex BC	FPE	S	P1	0.242	300	0.3	0.9	3.1	14.0

VF is the “Velocity Factor”.

RG-8 is the BIG ½ inch cable used by most Hams.

RG-8X is what I purchased with BCN connectors already attached. If you look at the table – this coax is only ¼ inches in diameter. This was commonly used for Ethernet wiring before CAT5 cable became popular.

So --- the ¼ wave length segment is (245.9 * .86) / 101.1 = 2.11 ft or 25.35 inches.

The ¾ wave length segment = 3 * 25.35 = 76 inches or 6.3 ft.

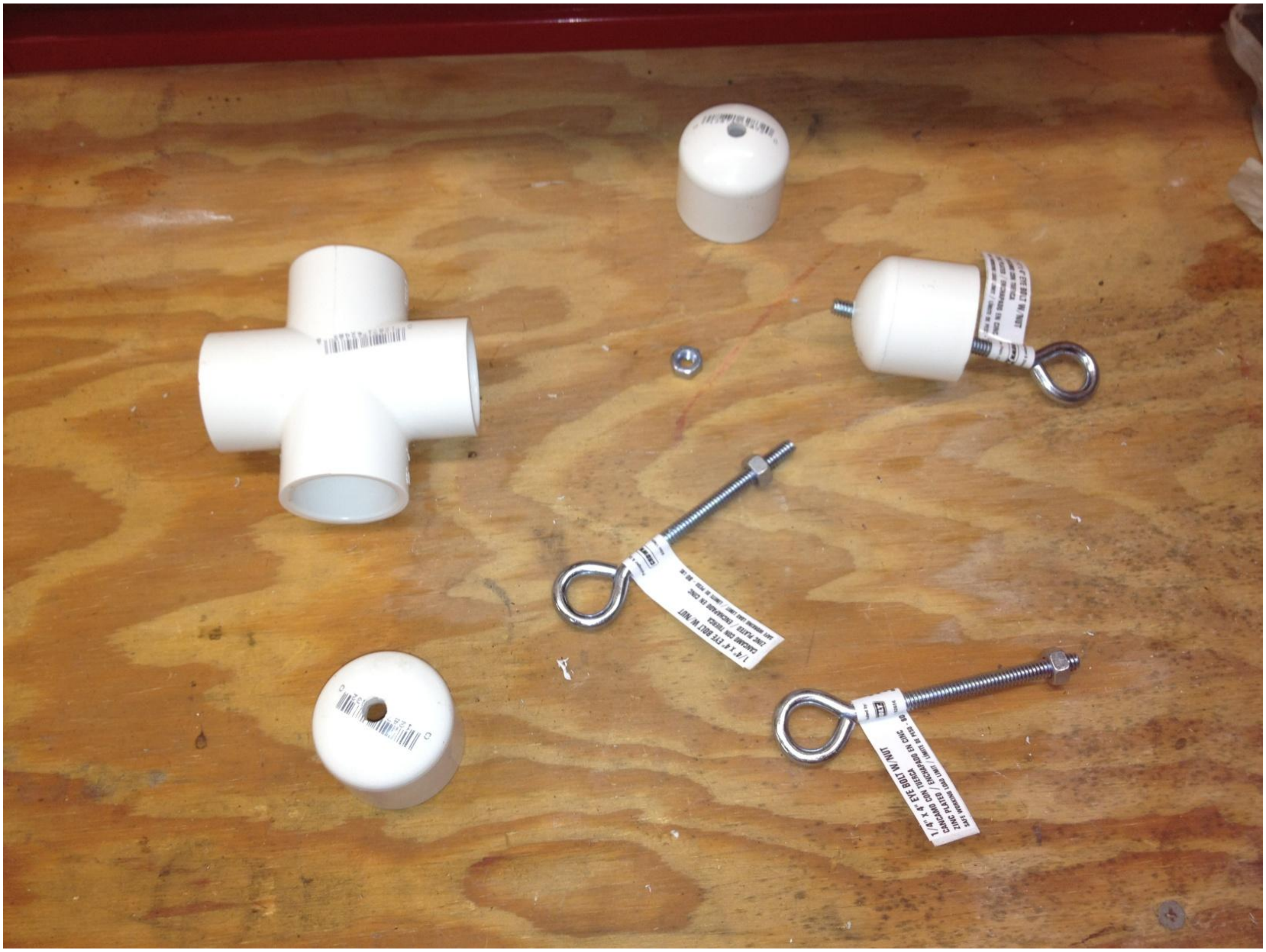
Quarter wave Vertical antenna:

I present the following antenna to the DIY community to be used with your FM transmitter instead of the classic dipole antenna.

The active element is ¼ wave length (1/2 of your dipole) mounted vertically on top of a ground plane. The feed-point impedance is 50 ohms and “unbalanced” so we can directly connect our coax line without fear of common mode currents and the issues associated with them. I use a modified ground plane – I only use two (2) ¼ wave radials.

Many of the build techniques used in the dipole antenna are used here – so I will not repeat them.

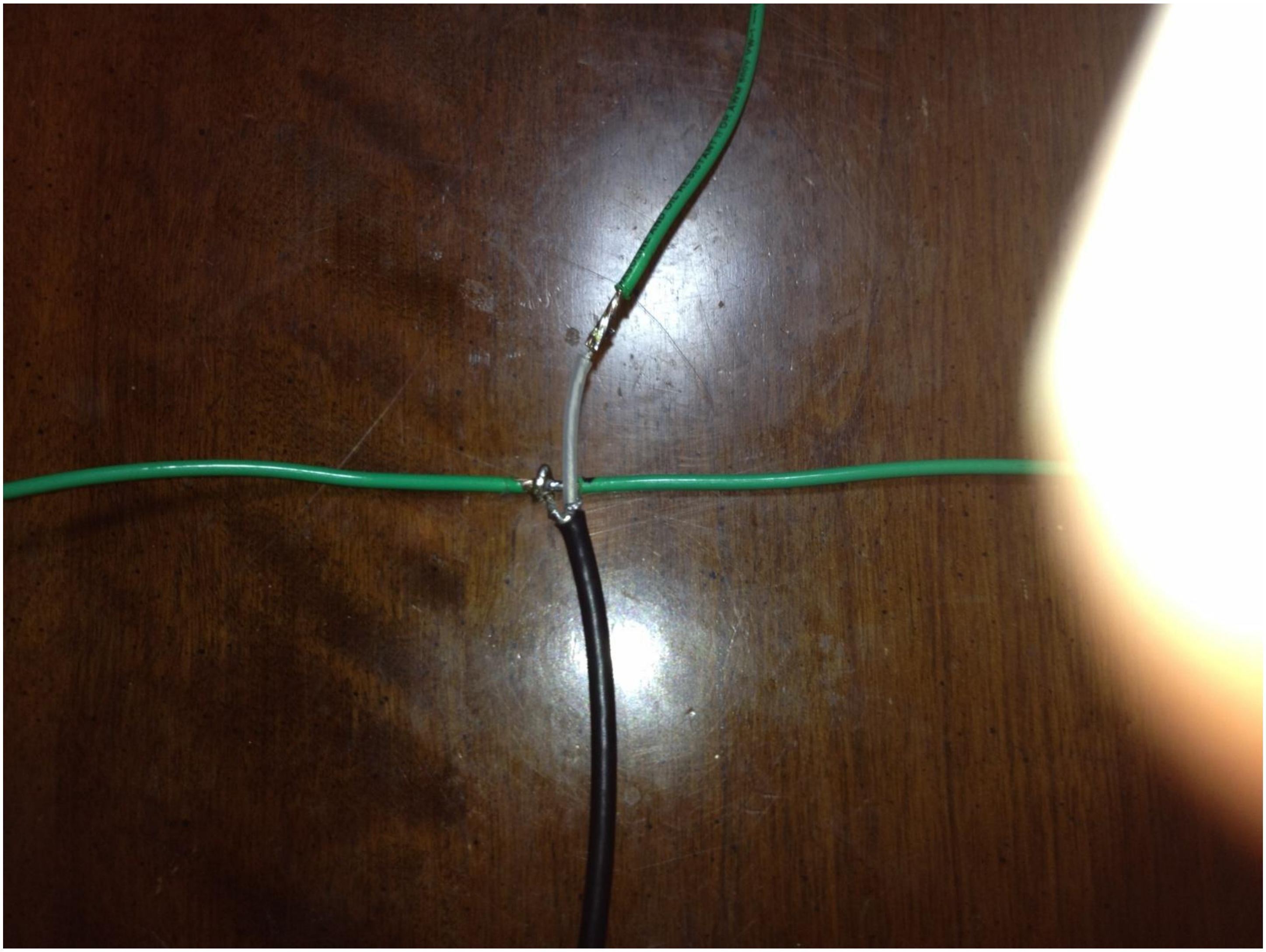
I purchased ¼ inch eye bolts at HD. I had to use 1 inch PVC so that the eye bolts would fit inside the PVC pipe.



The dipole constructions calls for the use of a “T”. I use a “CROSS” connection instead.

The dipole construction suggests connecting the antenna elements (wire) to the coax by using a piece of perf board.

I directly soldered the coax to the ¼ wave length pieces of wire as shown below.



I used insulated 12 ga wire I had left over from wiring my garage – so I used that as the antenna elements. I used the 4% length adjustment because of the capacitance associated with the insulation.

The two ground radials are really a single length of wire ½ wave length in length (after I created loops in the ends per the dipole construction technique. Simply remove a 1/2 inch of insulation in the middle of the ½ wave length piece of wire and directly solder the coax braid to it. I left about a ½ inch of free braid from the coax to the solder connection so that heat (during soldering) would not melt the coax insulation (see picture below). I cut the 12 gage wire used for the active antenna element 1 inch less than calculated because of the exposed inch of coax inner conductor.

I used the eye bolts to apply tension to the antenna elements thereby achieving the correct length without kinks or bends.

This is the finished antenna. I plan on installing a short length of PVC pipe out the bottom to serve as a strain relief for the coax. The BCN connector is also shown.

When I purchased the FM-02 from WLC, I also purchased the “dummy” antenna used for testing.

Max length on the vertical element is 12 inches.

Antenna performance:

I am powering my FM-02 from a well regulated 13.4v power supply capable of delivering 3.5 amps.

I originally tested the transmitter using the “dummy” antenna positioned on my desk. Audio was provided via an IPOD.

Transmitting frequency was 107.5 mhz. My office is located on the second floor – so I’m not at ground level.

The dummy antenna provided excellent audio to a range of about 500 yards. My truck radio was used as the receiver. Reception was not line of site as multiple houses and trees were in the transmission path. At 500 yards, I started losing the hi frequencies in the audio – the “s” sounds in speech became very poor.

I replaced the dummy antenna with the ¼ wave vertical antenna presented in this paper.

The antenna was placed on a bed positioned vertically (in reality – I will hang it on a wall).

I was able to drive more than twice as far before I noticed the “s” distortion.

The antenna is simple to build and does not have the common mode current concerns associated when driving a dipole antenna.

Enjoy.

Joe Hinkle