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TECHNICAL NOTE #2 – CARRIER CURRENT SYSTEM DESIGN

1.0 PRACTICAL SYSTEM DESIGN

We turn to the nuts and bolts of carrier current system design. The following sections will consider the practical application of a carrier current system to your requirement, be it a dormitory, an office building, a retirement community, or otherwise. We present this discussion in the college context only because it is the most frequent application of carrier current broadcasting. The reader can readily interpret to his specific requirements.

1.1 Distribution of RF Power

We will consider a hypothetical campus with eight residence halls as an example of how to approach to the design of a system. Our fundamental requirement is to inject RF (Radio Frequency) power into the low voltage AC power wiring of all buildings in which reception is desired. We are often asked which approach we prefer, that of one central transmitter with cable distribution of RF power to each building, or of separate transmitters in each building. What we prefer is what does the job best, easiest and most economically. This is a complex question, which requires analysis of the details of each different application.

In our hypothetical campus the residence layout includes a quadrangle of four close-spaced residences. There are also two residences about 200 feet apart in another area of the campus, and the remaining two are mutually isolated from each other and all others.

- **Interference Possibilities**

When two buildings are within about 300 feet, the possibility of beat note interference between the separate transmitters (see further discussion in § 1.5) is high. It is also true that, for spacings of less than about 300 feet, it may be practical to run coaxial cable for RF power distribution, whereas for a building a quarter mile away the long cable run would be expensive, difficult to install, and would display excessive attenuation of the input power. Buildings in a group, such as a quadrangle, are likely to have all been built at the same time, be about the same size and of similar design.

A number of buildings grouped within a few hundred feet at their closest points should first be considered as candidate for single transmitter coverage. If this can be done the reduction in the number of transmitters will save initial equipment costs and will ease ongoing maintenance. Broadcasting to such a group of buildings is achieved by locating the transmitter in the most convenient building, logically central to the group, feeding some of the transmitter output to that building, and using a coaxial cable RF distribution system to convey fractions of the transmitter output power to each other building.

RF power splitters are standard and inexpensive devices to use at the transmitter output to provide power division to multiple loads. They may be designed to divide up to six outputs efficiently, and with any desired fraction of input power delivered to each of the outputs.

- **Determining Needed Power**

There are advantages to the use of one transmitter and coaxial cable distribution to serve close-spaced buildings, but how do we specify the amount of power needed in each building, hence design the system? This is easily done by temporarily connecting a transmitter into the building power system and, with a listener at the farthest point in the building from the transmitter, begin reducing the transmitter output power until the listener reports that further power reduction would result in inadequate reception. LPB's solid state transmitters provide continuously adjustable power output. In addition, the current model TCU-30 transmitter coupling units include a meter which directly reads the amount of power being provided from the transmitter. This provides the ability to determine how many watts are needed for good broadcast coverage in each building. From these tests the system can be designed.

Such tests also provide a realistic demonstration of carrier current broadcasting in the building. This may be helpful in establishing the credibility of carrier current to anyone who has reservations.

- **Coaxial Cable Interconnection**

Coaxial cable is required to convey the transmitter power to adjacent buildings. Telephone or other types of wire lines are not suitable. This prompts questions in three areas:

A) How and where to install the cable,
B) What type of coaxial cable should be used, and,
C) What coaxial cable lengths are practical.

How feasible is the use of coaxial cable to interconnect two or more buildings? One must know the buildings and grounds and the local restrictions to answer that question. Cable can be buried or run overhead, depending upon local restrictions. If the distance is short, a hand-dug trench may be practical. If the distance is long, consider renting a Ditch Witch or similar machine which digs a narrow trench with a cutter resembling a giant chain saw. Another type of Ditch Witch will plow the cable directly into the ground in a single vibrating plow slit which requires no fill operation after cable burial. Getting the cable through the outer walls of the buildings can be difficult. This also comes back to obtaining permission to install cable in this manner.

- **Coaxial Cable Selection**

There are only a few practical choices of coaxial cable. The standard of the broadcast industry is cable of 50 ohms characteristic impedance, to match industry-standard 50 ohm transmitter outputs. The AM broadcast band is relatively low in the frequency spectrum, allowing the use of less expensive coaxial cable. This narrows the standard types to RG-8/U and RG-58/U. Some properties of these coaxial cables which are of interest include:

type	est. cost	O.D.	typical transmission loss
RG-8/U	57¢/foot	0.405"	3 dB per 3,000' @ 640 kHz
RG-58/U	22¢/foot	0.195"	3 dB per 1,500' @ 640 kHz

Our cost information may quickly become out of date, but the relative ratio of the two costs should remain about constant.

The smaller RG-58/U is inexpensive, but lacks mechanical strength. It is practical only for shorter runs and/or indoors. In the Òtypical transmission loss column above, 3 dB is the loss of half of the input power for the stated length. This power is lost in the cable as heat, due to imperfect electrical properties. (Don’t worry about temperature rise of the cable; at our power levels you will never detect it.) At the low end of the broadcast band a 3,000 foot length of RG-8/U will waste half the input power in losses. These losses are twice as great for RG-58/U. For building spaced only a few hundred feet, the transmission line loss will be quite low and of no consequence. What usually fools you when estimating required cable length is how much it takes to wind around within the buildings to get from the point of building entry to the coupling unit.

- **75 ohm Coaxial Cable**

Comparable 75 ohm cables are, respectively, RG-11/U and RG-59/U. These are the standard of video systems, hence are often available at attractive prices. It is possible to design a power distribution system around 75 ohm cable if necessary, but modifications are needed to the transmitter output and the coupling units. Since 75 ohm cable is not common in radio broadcasting, we suggest you avoid the confusion and stick with 50 ohm cable. Above all, don’t mix 50 ohm and 75 ohm cables in your system.

- **Cable Installation**

Installing cable between buildings may not be something you or your physical plant department cares to undertake. The local CATV installer may be your answer. These people are knowledgeable and are fully equipped to install cable. Your administration may also be more comfortable having a professional team do the job. CATV people are video types, so make sure they use 50 ohm cable in your system.

Economics and cable burial effort inhibit long runs. There are actually two economic factors; the cost of the cable and of the installation, and the power loss in long lengths. The loss of a significant fraction of the input power amounts to throwing away part of the transmitter price.

- **Fiber Optic Alternative**

At many colleges we find fiber optics replacing telephone cables to provide a needed increase in on-campus communications capability. Fiber optics can be used to convey carrier current in place of coaxial cable. The system design approach will be different because fiber will handle only a low-level signal, not power. The incredible wide spectrum of frequencies which fiber optics can handle makes it possible to put on a fiber a low-level signal from a master carrier current transmitter (the modulated 540 kHz carrier, for example) which can then be picked off in any other building to which the fiber goes. This signal is then amplified and connected into the low voltage power system for carrier current AM coverage of the building.

The routing of a fiber system might either be similar to a star centered at the master transmitter location, or it might be a daisy-chain or series circuit, hopping progressively from one building to another. In the star arrangement the carrier current signal must be fed into multiple fibers and then utilized at the end of each fiber. In the series circuit the signal feeds a single fiber. In the next building it is used both to drive a second outgoing fiber and is also amplified for carrier current broadcasting in this building, and so on to other buildings.

Special equipment is required to interface the carrier current signal with the fiber optics. As suggested above, the interface equipment may differ with the arrangement of the fiber available to the campus station. LPB has designed modifications of LPB 30 watt transmitters and linear RF amplifiers which include this interface equipment. Maximum economy and ease of installation results from building the fiber optics interface into the carrier current equipment. The added cost, though considerable, may be less than the cost of buying and installing coaxial cable.

1.2 RF Power Splitters

The tests described above will determine the amount of power needed for each building, from which one can work backwards to include estimates of cable loss (if significant) so as to arrive at a specification of the transmitter power output needed and of the definition of power splitters. Power splitters with 2, 3, 4, 5 or 6 equal outputs are standard items. I.e., a three-way power splitter with three equal outputs, each 33% of the input power, is a stock item. Power splitters can also be designed and manufactured to special order for about any requirement. An example might be a three-way splitter with outputs of 50%, 25% and 25% for a group of three buildings in which one requires more power than the other two.

- **Transformer Ratings**

Experience in carrier current system design often makes it possible to test one building and estimate accurately for others that are similar. One basis for estimating is the kVA rating of the AC power distribution transformer serving the building. Given the kVA rating (usually found on the transformer case) and the background of having been down this road many times before, one can come up with a good system estimate. Consider the following experience factors:

A) AC power distribution transformers of 300 kVA and larger indicate a turning point from a 5 watt transmitter to a larger power requirement. Below 300 kVA, 5 watts may be sufficient.

B) Expect additional problems with high-rise (6 floors or more) buildings.

- **High-Rise Buildings**

It is often more difficult to provide good broadcast signal uniformity throughout a high-rise than a low-rise building. Analysis of the main power distribution trunk in the high-rise is necessary. To your facilities people, the layout drawing of the main power distribution trunk is known as a one-line electrical diagram or a power riser diagram. For a high-rise, it will either show a single power riser running up the center core of the building with power tap points on each floor, or several power risers going up from the main power distribution panel to serve groups of floors or areas of the building.

If there is a single riser, injecting RF at a mid-floor level to feed this central point will result in most uniform signal distribution throughout the building. If there are multiple risers, it is generally necessary to take the brute force approach of supplying enough power at the main power distribution panel to get adequate signal to the upper floors. If a building using multiple power risers is really big it may be necessary to use a master transmitter driving power into coaxial distribution cables which connect to linear RF amplifiers located at the mid-point of each power riser. The carrier current system in the Massachusetts State Capitol building in Boston required this approach with a transmitter and four linear RF amplifiers.

Combinations of power splitters can be arranged to suit complex building situations, especially where underground tunnels exist making it easy to install coaxial cable. Be aware that complex distribution systems are less flexible in the future and tend to produce eventual maintenance problems. By nature, carrier current has growth flexibility. This is stifled when complex distribution systems are installed.

1.3 RF Power Choices

We are using an example of an eight residence hall campus. We discussed some aspects of distribution system design for the quadrangle. From that discussion it is clear that power distribution for the other two closely spaced dorms would be approached in a similar manner. A second transmitter would result in the coverage of six of the total of eight residences. The remaining two isolated residences will require a separate transmitter in each. Recognize that if you have only one size of transmitter for all applications, maintenance is simplified. Those remaining two isolated residences might be adequately served using the less expensive 5 watt transmitter in each building. However, the small savings for the 5 watt transmitter will limit interchangability.

Consider differences in transmitter power. To make a point, we will use a situation with which you are familiar. Picture your audio console showing peaks of 0 VU from a music input source. While listening to the program on the monitor speaker, and without changing any other controls, back down the input fader to show VU meter peaks at -3 VU. What apparent volume level difference do your ears perceive? Very little, isn't it? Changing from 0 to -3 VU reduced the power output of the monitor amplifier to half, yet your auditory system perceived only a minute decrease in volume. With a receiver we have an even more striking situation when changing transmitter power output (TPO) by a factor of two up or down because of the additional power-leveling effect of the receiver automatic volume control (AVC) system, and because a receiver antenna senses voltage, not power. What makes a receiver respond is the field strength (voltage) it receives. Note that:

1/4 TPO decreases the field strength by 50%,
1/2 TPO decreases the field strength only 29%,
2 X TPO increases the field strength by 41%, and,
4 X TPO is necessary to double the field strength.

- **AVC Systems**

The AVC (Automatic Volume Control) system in every receiver seeks to maintain a constant audio output regardless of changes of received signal strength, such as when you drive your car through an underpass. This is accomplished by sampling a relatively long time-averaged portion of the audio output (to avoid reaction to short term speech and music volume level changes) and using this to control the gain of the receiver. An AVC system will only work over a certain range of input signal strength. When the signal becomes very weak, there is simply no more gain available in the receiver. This explains why the signal will remain rather good as you walk away from a building with a carrier current system, until a point at which the noise level suddenly comes up. Conversely, if the received signal is too strong, the AVC system can't handle it and saturates. This explains why the receiver may sound bad in the room with the transmitter.

- **Spares**

Using all the same type and style of transmitter in your system makes one universal spare affordable. Always have a spare transmitter. Can't afford one? More likely, you can't afford not to have one. Not many licensed broadcasters risk being without a back-up, even if they have a full-time engineer to keep maintenance at a high level. We design and build our equipment for a high level of reliability, and we express our confidence in these products with a one year no questions asked guarantee, however, this is not the same as a guarantee that our equipment will not break down. It is impossible to make a zero-failure guarantee. Spares are the only answer!

- **Two Buildings from One Coupling Point**

Possibly those two close residences, or even the quad, are supplied from a single AC power distribution transformer. If the low voltage AC lines from this transformer are common to the several buildings we might expect to feed RF power into one building and obtain coverage in all. This generally doesn't work, for although low voltage AC lines are efficient at the 60 Hz power line frequency, they are quite inefficient at broadcast frequencies. Try a test transmission, however you may be a winner.

Our experience is that separate buildings, even very close together and on the same power transformer, usually require splitting the transmitter output for coupling separately into each building to obtain good uniformity of signal strength throughout all buildings.

- **Linear RF Amplifiers**

We must also introduce the use of Linear RF Amplifiers in carrier current systems. A linear RF amplifier may be thought of as a power booster. Given a small fraction of a watt of RF power from a distant transmitter via coaxial cable or fiber optics, the linear RF amplifier functions just as its name implies, producing a larger power level for local use. Special power splitters with a 5% output are often used in systems with linear RF amplifiers. With a 30 watt main transmitter, a power splitter with 95% and 5% outputs will put over a watt into a cable to drive a linear RF amplifier in another building at the end of the cable. The 95%

transmitter power output is available for the building in which it is located. LPB linear RF amplifiers are also 30 watt Transmitter Power Output (TPO) devices.

A good example of the use of linear RF amplifiers is campus station WUDC on the Van Ness Campus of the University of the District of Columbia. A huge main building of six floors employs two large AC power distribution transformers, one on each side, supplying sets of vertical main power risers. The WUDC system employs a main transmitter followed by a four-way power splitter with outputs of 85%, 5%, 5% and 5%. The 85% output is coupled into the AC system at the lower level on one side of the building. Three coaxial cables carry the three 5% outputs to three linear RF amplifiers. One is located on the other side of the building at the lower level, the other two are at the top of each power riser. It is very unusual for a building to require this much power into the low voltage AC system for good coverage, but the ability to provide good carrier current broadcasting to this building was made possible by the flexibility of design offered by the availability of linear RF amplifiers.

Another example is WRUB at SUNY/Buffalo. The Amherst campus residence halls are one huge pile of bricks exceeded only by the Pentagon in Washington DC (we have a carrier current system there, too). Without linear RF amplifiers, carrier current coverage of these large inter-connected residence halls would have been impossible. A 30 watt main transmitter and six linear RF amplifiers did the job.

1.4 Coupling to the AC Power System

The low voltage AC power wiring in a building is an inescapably convenient limited area broadcast antenna. No other form of wiring could provide an antenna so close to the listener's receiver. It is also likely that the listener's receiver will actually be wire-connected to this antenna via the power cord. This is not necessary, for battery-operated receivers will function well within the building. At distant points in a large building, however, it may be observed that signal strength is greater when the receiver is operating on AC power.

♦ Feeding the Power Wiring

The building power wiring was designed for a very specific function. Doubling as a carrier current antenna was never considered in the original design, hence you may expect the AC wiring to be something less than ideal for carrier current. It presents a number of problems, but with experience and understanding they can be overcome. The typical building of significant size will have its own power distribution transformer in the basement or just outside on a pole or a cement pad. This transformer steps down the incoming high voltage, often as high as 13,800 volts, to low voltage for use within the building. Three phase power (3ϕ) will be found in a building of any significant size.

On the low voltage side of the distribution transformer will be found a three phase four-wire system composed of three 117 V lines and a common neutral (a white wire). Each 117 V line is 120 degrees out of phase with the prior line, but phase rotation is of no significance in carrier current systems which are feed in RF parallel without respect for which phase is which. Hence we feed RF energy into the AC system in a neutral to line manner. The transmitter coupling unit connection point to the AC system has four adjacent screw terminals which are marked L - L - L - N (meaning Line-Line-Line-Neutral).

LPB Tech Note #4, ELECTRICAL CONNECTIONS OF A CARRIER CURRENT SYSTEM, discusses the details of connection to three phase and other simpler systems in specific detail.

♦ Neutral Loading

Another technique for connecting RF energy into the AC power system is called Òneutral loading. This is sometimes resorted to where particularly elusive noise sources (see § 1.8) ruin clear carrier current reception.

In neutral loading only one of the Line outputs and the Neutral of the transmitter coupling unit is used. The Line output is connected to the power system Neutral (sounds backwards, but this is correct in neutral loading) at a central point. The Neutral output of the coupling unit is then connected to a good earth ground nearby. In this manner, use of the 117 V lines containing the noise sources is actually avoided. We have a drawing of Neutral Loading which will be furnished upon request.

The writer has found neutral loading helpful in a few particularly difficult installations, but not always. Neutral loading is not without it's problems. At Elizabethtown College we found the field strength produced with neutral loading within a residence lower than with conventional three-phase coupling, while outside the building it was higher. This is counter to the requirements of carrier current systems. Perhaps the message here is that when deviating from the proven approach one must always be on the outlook for other possible resulting problems.

♦ Efficient Coupling

Getting the available RF power efficiently from the transmitter into the AC power wiring has always been a big challenge in carrier current technology. Failure to accomplish this leads to the assumption that good coverage requires more transmitter power. We have documented many cases of improved signal coverage with less transmitter power as a result of more efficient coupling of the transmitter power into the AC power system. Our understanding of power system matching is undoubtedly not yet complete, but major strides have been made in recent years.

- **The Problem of Power Line Coupling**

Carrier current transmitters employ the broadcast industry standard of 50 ohm unbalanced output impedance. The Maximum Power Transfer Theorem of electrical engineering states that the transmitter output must be connected to a matched 50 ohm (resistive, that is, 50 + j0 ohms) load for maximum power transfer into this load. This requires a coupling unit between the transmitter and the AC power system, which makes the power system look like 50 ohms to the transmitter. Maximum power transfer from the output of the coupling unit into the AC power system similarly requires that the coupling unit output match that of the AC line. This is a problem area, for the AC power system impedance is dynamic. It is different from one building to another, and changes with time of day as loads are turned ON and OFF. The load impedance will be lower during evening hours when more lights and appliances are in use.

Measuring the AC power system impedance might be a nice idea, but it is highly impractical for the following reasons:

A) The necessary instrumentation is expensive, highly specialized, and inconvenient to carry into the field.
B) Since the measured value is expected to change substantially with time, all we could expect is a range of values for averaging. Obtaining these values would require tedious measurements over many hours in each building.

Further, only an indirect measurement is possible because the AC line voltage on our antenna presents another requirement to the coupling unit; that of isolating the AC power line voltage from the transmitter. The coupling unit must be designed to provide efficient transfer of RF power from the transmitter into the varying impedance AC power system, yet in the other direction it must present a roadblock to the flow of 117 V 60 Hz energy from the AC system back into the transmitter. Stated another way, the coupling unit must be a low-Q high-pass filter capable of variable impedance matching on the AC line side.

A product of space-age technology which has come to the rescue of carrier current coupling is ferrite, an efficient high frequency transformer core material. Present-day transmitter coupling units utilize this material. Previously the only means of providing the needed impedance matching in the coupling unit was to use tuned circuits. These simply could not be maintained tuned due to the changing characteristic of the AC line. They were also ineffective as stop filters to the flow of AC back into the transmitter output. The result was enough 60 Hz voltage in the transmitter output circuit to produce hum modulation. This is the basis of an old story about unavoidable carrier current hum. Today's LPB coupling units display in excess of 3,000-to-1 attenuation to the flow of 60 Hz AC back into the transmitter. The ferrite materials are also broadband (low-Q) devices, which do not detune as the AC line impedance changes.

Additional attenuation is provided by any power splitter which may be in the path between the transmitter and the coupling unit, for they also employ ferrite cores. Further, the ferrite core harmonic filters in modern transmitters provide further low frequency attenuation. As a final blow to 60 Hz modulation, solid state transmitters which employ low level modulation cannot be plate modulated in the power amplifier output stage anyway; we purposely designed them that way.

If it were possible to go to each building coupling point at an optimum listenership hour and make at least one typical measurement of the AC power line impedance, the coupling unit could be tailored to match this. Practicality, however, requires the design of a coupling unit with a maximum of matching flexibility within the limits of what is economically feasible. The resulting LPB coupling units satisfy all matching situations. The occasional flexibility limit of the coupling unit is overcome by having a qualified consultant come in with the equipment needed to make AC power line impedance measurements which define the solution to the matching problem. This is very seldom necessary. Interestingly, most cases where it has been necessary have been on the West Coast.

- **Central Installation**

Having developed the logic behind the transmitter coupling unit, consider where to install it. Simply view the AC power wiring in the building as a spoked wheel with a central hub. In such an AC system the various branch circuits all originate from the central main power distribution panel, our hub. It is clear that optimum uniformity of broadcast signal distribution within the building will be achieved if the RF power is coupled into the AC system at the central point. Other coupling points may be more convenient, but they will not produce as good results.

The best way to determine the proper coupling point into the AC system for uniform signal distribution is the same way we measure the RF power requirement of a building; by a test transmission. Experiment with coupling points near the main power distribution panel, avoiding sub-panels which serve mostly machinery loads. The main power distribution panel itself is seldom a practical coupling point.

1.5 Avoiding Interference Between Transmitters

We found a suitable frequency and presumed to use it for all four satellite transmitters that appear to be the design choice of our hypothetical campus example.

- **Staggered Frequencies**

Suppose we are unable to install cable between buildings in the quad. We must turn to the alternate of separate transmitters in each building. Another possible technical problem now surfaces. Consider the listener in a location in one building immediately adjacent to the other. He will receive a strong signal from the transmitter serving his building and also a weaker signal from the transmitter in the adjacent building. Unless the ratio of the two received signals is quite large the listener is likely to hear a beat note which is the small frequency difference between the two transmitters. This beat note may change with time, temperature, crystal aging, etc. If the frequency difference is in the audible range we have a system problem which would have been avoided with a coaxial cable distribution system. Note that a system using linear RF amplifiers also avoids the potential beat note problem.

There is another simple solution to the beat note problem, should you experience it. It is to operate the two adjacent transmitters on adjacent broadcast channels. The beat note will now be in the 10 kHz range, and this is not likely to come roaring through an AM receiver. If the 10 kHz difference bothers you as possibly being audible on better receivers now coming onto the market, consider operating 20 kHz apart in adjacent buildings. The use of adjacent channels makes the frequency selection problem a bit more difficult, 20 kHz spacing makes it even more so. On the other hand, changing the frequency of a carrier current transmitter by only a channel or two after the system is installed is only a matter of changing crystals.

The listener of an older radio with a slide-rule dial would not be able to distinguish between two frequencies, such as 640 and 650 kHz, so no confusion would result to him as a result of the campus station using staggered frequencies. A listener with a radio providing digital readout of frequency will be confused to find 640 on one dorm and 650 in the next.

With what typical building separation will we expect to have a beat note problem? Referring to Tech Note #1, CARRIER CURRENT BROADCASTING, § 3.0 and the discussion of signal strength vs. distance within the Induction Field provides guidance. The signal strength limitation of 15 µV/m at 157,000/f suggests that at 300 feet no beat note interference problems would be anticipated in the buildings. Our practical experience confirms this. A contributing factor is considered next.

1.6 Building Shielding

At colleges in large cities we are often questioned as to how we expect to provide a good carrier current signal in the buildings where it is difficult to receive local AM stations. Consider the amount of steel used in the construction of a downtown high-rise dorm. It is in the structure, the window and door frames, etc. Then consider the wavelength at the lower AM broadcast frequencies and it becomes clear that the metal in the building results in a semi-shield effect to shield out the local broadcaster. Walking out the front door of one of these buildings while watching a field intensity meter clearly demonstrates this effect.

The reason for the success of carrier current where local AM station reception is unsatisfactory lies in the fact that the carrier current signal is injected into the inside of the building. What shields out the local stations shields in the carrier current signal. This gives us an advantage in meeting Part 15 of the Rules. Referring back to the previous discussion, it also makes life with separate transmitters in adjacent buildings easier than might have been expected.

1.7 Measuring Field Strength

Tech Note #1, CARRIER CURRENT BROADCASTING, introduced the Part 15 field strength limit of 15 µV/m at a distance of 157,000/f from the electric power line, and we have seen the significance of how this field strength varies as a function of distance from the antenna within the Induction Field. We will now consider measuring this field strength.

The standard instrument for measuring field strength is properly called a Field Intensity Meter (FIM), of which the Potomac Instruments model FIM-21 is the standard of the industry. It is the instrument with which the FCC Field Engineering Bureau engineers are equipped. To simplify, a FIM may be thought of as a precision AM receiver without an AVC system (see § 1.3), and with a calibrated meter on the output. At the time of this writing, a Potomac FIM-21 sells for over $6,000., and is not calibrated below 540 kHz or above 1600 kHz (unless ordered special). Other models cover lower and higher frequencies, as well as the original 540-1600 broadcast band.

- **Making the Measurement**

For a 540 kHz carrier current system, one would presume to move to a position 290 feet from the extremity of the AC power system and make a measurement. This is easier said than done:

A) FIM meters are calibrated logarithmically; the scale reads from 1.0 at the left (the normal 0 position) to 10 at the right. The minimum an FIM-21 will indicate is 10 µV/m, and this is at the left end (the 0) of the scale. The Commission requires any reading be in the upper third of the meter scale for meaningful accuracy.

B) Background noise on the frequency is an even more important problem in most locations. Turn OFF your transmitter and chances are excellent that the FIM will still read well in excess of 15 µV/m at 290 feet. The source of this is electrical noise on the frequency, weak signals from afar, etc.

The measurement is better made by moving inwards to perhaps half the 290 foot maximum, so the signal strength reading from the carrier current transmitter has a chance of being above the noise background and within the accurate range of the FIM. At 145 feet look for a maximum of 8 X 15 = 120 µV/m. This is still not a good position on the meter scale, but it's at least likely to be well above the background noise on the frequency.

An FCC Field Engineer once made measurements at the University of West Virginia's carrier current station the day after LPB had checked the station. Being accustomed to working in the Radiation Field, he looked for 2 X 15 = 30 µV/m at 145 feet, but found something close to 120 µV/m. He closed the station down for excessive radiation. The manager was irate with LPB, but after a talk with the FCC man about the Induction Field, the close-down order was rescinded. This actual experience reinforces the uniqueness of the Induction Field to carrier current broadcasting.

Thorough measurements of compliance with the Rules for carrier current station operation requires several measurements at intervals around the perimeter of the system. Enough measurements should be made to show that the system is consistent. Note that measurement anomalies may be found under or in the vicinity of overhead power lines. These appear to absorb and re-radiate broadcast energy, thus confusing any attempt at meaningful measurements. It is our experience that FCC Field Engineers understand and excuse these localized problems.

The high cost of a FIM makes it difficult for a carrier current station to justify buying it for occasional use. The same is true for smaller licensed stations, hence a FIM is difficult to find. It requires frequent and costly factory recalibration to make valid measurements. The initial investment plus the recalibration costs make all but the larger commercial stations unwilling to loan their FIM to a carrier current broadcaster unless considerable mutual trust exists. Should actual measurements become necessary, the station may wish to hire a consulting engineer with proper equipment in current calibration.

1.8 Carrier Current Noise

An old problem is hum modulation on the carrier current system as a result of 60 Hz power line energy getting back into the output of the transmitter and modulating it. If this is suspected, simply disconnect the transmitter from the power line coupler and reconnect it to a 50 ohm dummy load (this is an integral part of LPB couplers). Listen on a nearby receiver. If the hum persists it certainly isn't the result of 60 Hz getting back through the coupler. Next, disconnect the audio feed to the transmitter. This will isolate any hum that may be present in the audio feed. The writer once flew from Philadelphia to Dallas to spend 5 minutes proving to the management of a large college station that the hum on all the transmitters resulted from an open filter capacitor in the audio console power supply back in the control room. It is necessary to develop logical trouble-shooting procedures which can isolate problems of this nature.

- **Nonlinear Loads**

If the hum was not found to be on the audio input or within the transmitter but does come back when you reconnect the transmitter to the coupler, odds are very high that you have a case of the classic nonlinear load problem. This is invariably described as 60 Hz hum but really is a composite of all kinds of garbage. The usual reaction to overcome this problem is to go for higher transmitter power. The logic of this comes from consideration of signal-to-noise ratio (S/N) where, given a noise level, the S/N can be improved by increasing the signal level. The logic is good, but the assumption of a fixed noise level may be wrong. If the problem is a nonlinear load on the power system, more transmitter power makes the hum worse. To understand what is happening, consider the following.

In the mathematical analysis of nonlinear devices, specifically the mixer circuits used in superhetrodyne receivers, the electrical engineering student learns that it is a characteristic of real-world nonlinear devices that the magnitude and mix of output components, which we will regard here as noise, increases sharply as the input signal to the mixer is increased. Nonlinear devices of similar nature sometimes appear to exist on AC power systems. They often are a worn and dirty set of commutator brushes on a motor. The motor appears to work fine, but when turned OFF the carrier current broadcast signal cleans up instantly; this instant cure occurs often.

- **A Cyclic Problem**

This problem, once cured by replacing the brushes in the motor and cleaning the slots between the armature segments, may be expected to recur on cyclic basis. A few years later the same problem, with the same cure, is back again. By then the station staff will have changed and the new staff won't know of the past experience. They just sit there and curse carrier current, until finally they get fed up enough to call in a experienced carrier current engineer to come in and solve the problem. We experienced this several years ago at Clarion State University when the manager called with a hum problem in a high rise residence hall. We had solved the problem in this residence a few years past for the prior manager, hence only needed to tell him which motor brushes to renew. He was quite surprised!

- **Location is Important**

The nonlinear load hum problem is also related to where the transmitter is coupled into the AC wiring system. Sometimes moving the coupling point from one electrical sub-panel to another, both possibly in the same utility room as the main power panel, can make a world of difference. Experience suggests avoiding panels dominated by machinery loads, as mentioned earlier. The problem is also related to the efficiency of coupling into the AC wiring system. Accurate coupling substantially reduces system noise, reduces signal strength measured outside the building, and increases the signal received inside the building. Few things in nature produce the best of three worlds all at the same time, but good coupling is one of them.

Finding the offending nonlinear device on the AC power system requires pulling switches while listening to the signal. Don't do this without an electrician present, lest you trip an alarm system. The first two classes of device everyone suspects are fluorescent lights and elevator machinery. Defective fluorescent lamp ballasts have been found as carrier current noise sources, but seldom compared to the motor brush problem. Elevator machinery is on a regular maintenance schedule for public safety considerations. We have never found the problem in elevator machinery. Sometimes disconnecting the RF coupled to only one or two phases of the three phases of the power system is a simple way of avoiding the nonlinear device. Neutral loading (see § 1.4) is the best approach to try first.

Finding the offender can be tedious and sometimes impossible. With today's dorms loaded with personal computers it is not possible to pull switches unless this can be done over a vacation time when the dorm is empty.

- **Localized Noise Problems**

How about a bad hum problem in the receiver, even with the transmitter OFF? We have found problems where unacceptable noise background was highly localized within a building, but have noted that these were only found in a narrow part of the AM band. The simple solution here is to move the station frequency to a quiet part of the band. Carrier current is often said to be 99% art and 1% technology. If you have read this far, you will agree!

1.9 Transmitter Audio Feed

Preceding sections have mentioned audio feed to the transmitter(s). This is one step removed from the RF transmission system, but is a requirement of the use in satellite transmitters.

- **Audio Line Characteristics**

The standard of audio transmission in the broadcast industry is 600 ohm impedance balanced audio lines. This two-wire system is balanced with respect to ground to reduce hum and noise pickup. Audio consoles have 600 ohm transformer balanced program line outputs, and transmitter audio inputs are the same. Higher power transmitters for licensed stations usually require an audio input line level of +10 dBm, which corresponds to about 2.5 volts RMS. The industry standard audio console output is 0 VU = +8 dBm, which is 1.95 volts RMS on a 600 ohm line.

Typically the console output is followed by audio processing equipment and then goes to the transmitter either via leased telephone lines or a radio link. At the transmitter location the audio feeds a limiting amplifier before going to the transmitter. The limiting amplifier is at the transmitter location to remove any transient spikes of noise that may find their way into the audio in route (the relatively long distance) from the studio. Audio wire lines are particularly susceptible to induced transients from lightning, etc. Since the limiting amplifier is at the transmitter it is simple to design it to provide the additional audio gain to drive the transmitter at the required input level of +10 dBm.

In a carrier current system the audio path length from the control room to the satellite transmitters is much less than usually found in a commercial station. This reduces the probability of transients being induced into the audio line. Although available on LPB transmitters, a good limiter at all of the several transmitters found in most carrier current systems gets expensive. The transmitters are, therefore, designed for a lower audio input level, usually as low as -10 dBm. This allows the transmitter to be fed directly from the audio line, even allowing for considerable loss in that line. For more information about audio lines, refer to LPB Tech Note 8, AUDIO PROGRAM LINES, which considers the characteristics of audio lines and basic line equalization.

- **Audio Distribution Amplifiers**

Note the unique need to often feed audio from a single source in the control room to several satellite transmitters in carrier current systems. To drive these several lines from a single source, an audio Distribution Amplifier (DA) is needed. It fills the need for:

A) Additional gain to drive multiple audio lines at the same, typically +8 dBm, input power level,

B) Isolation between audio lines so that a fault on one will not affect the signal level or quality on any others, and,

C) Correct impedance matching between audio source and audio lines to maintain good frequency response.

The Audio Line Itself

We recommend completely separate audio lines from the audio distribution amplifier in the control room to each transmitter location. Separate lines facilitate good frequency response and are convenient to diagnose in the event of a malfunction.

An audio line problem often arises at college stations when they are not used, as during summer vacation. A telephone company technician, in searching around for unused lines during the summer months to install new telephones, listen to one or more of the stations lines and hear nothing. The immediate assumption is that this line is unused, hence available for some other service. As the fall semester begins the station suddenly finds it has no audio feed to certain satellite transmitters. To avoid this, put some audio on your lines at all times. Anything will do, a tone from a cheap audio oscillator or the audio output of a receiver tuned to a local station.

1.10 Modulation Levels

In Amplitude Modulation (AM) the information is conveyed by changes (modulation) of the power level (amplitude) of the transmitter output. Less than 100% modulation on audio peaks simply results in less perceived signal strength by the listener. It is no different than throwing away transmitter power. Operating a transmitter at 100% modulation on program peaks is to use it to maximum available capability and to present the maximum signal strength to the listener.

After a system is installed there still remains the task of setting modulation levels. This is described in your transmitter instruction manual. An excellent additional text on this and other information is THE RADIO AMATEUR'S HANDBOOK, published by the American Radio Relay League of Newington, CT.

- **Audio Processing**

Once modulation is set correctly, additional steps may be taken to keep the average modulation level high for maximum loudness to the listener. From the growing family of audio processing equipment comes audio compressors and limiters for this purpose. Artistically incorrect as it may be, it is technically advantageous to:

A) Compress the dynamic range of the audio information, to keep the average modulation level high, and,

B) Limit the maximum volume level of audio presented to the transmitter, to prevent overmodulation and attendant signal distortion.

In applying compression and limiting to the audio output from the console, it is often possible to achieve an average 3 to 6 dB increase in the apparent loudness to the listener. The desirability of this is clear when considering that it is the direct equivalent of increasing the transmitter power by a factor of 2 to 4. State-of-the-art audio processors offer considerable ability and sophistication at prices from about $600 to over $4,000 for a mono AM system. The choice is highly subjective and, obviously, budget-limited.

1.11 AM Stereo Carrier Current

As stereo AM gains momentum with licensed broadcasters, the logical question arises of stereo AM carrier current. It is quite possible.

An AM stereo system employs, in addition to everything else common to an AM station, an AM Stereo Exciter and a Stereo Modulation Monitor. For carrier current applications it is practical to delete the stereo modulation monitor. Considerably less expensive AM stereo exciters have recently been introduced, and at this writing, can be bought under $5,000.

A carrier current station probably cannot afford more than one stereo exciter. The solution, for those interested, is the design of the transmission system around a single transmitter/stereo exciter and a coaxial cable RF power distribution system and linear RF amplifiers. LPB has designed and redesigned several campus systems for AM stereo, although interest is expected to remain low until home-type AM stereo receivers become more readily available. The initial emphasis in AM stereo has been directed to car receivers (most recent ones have AM stereo capability) because of the importance of the drive-time audience to commercial broadcasters.

The Motorola C-QUAM AM stereo system has, since its introduction, always been demonstrated at conventions by both Motorola and Delta Electronics using LPB transmitters. The formerly competing systems by Kahn-Hazeltine and Magnavox also chose to use LPB transmitters for demonstrations. Would any of these firms have chosen anything but the best to demonstrate their equipment?

2.0 CONCLUSION

This LPB Tech Note is a summary of what LPB personnel have learned about the design of carrier current limited area AM broadcasting systems since we started building transmitters for college stations in 1960. At that time design options were severely limited, coupling into the AC power system was a nightmare, and station engineers were always running around changing transmitter tubes. We have seen and, we believe, helped carrier current grow into the reliable and effective means of broadcasting that it is today. Dozens of other interesting applications of this technology have grown from carrier current. We hope this information will assist you in understanding and implementing it. Call us at at LPB if we can be of help with your specific needs.