Seminar Subjects

Repeater Amplifier Systems: Principles and Applications

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INTRODUCTION

Definition

Repeater amplifiers, also known as *signal boosters,* are specialized RF systems that extend radio coverage into enclosed or shadowed areas where abrupt propagation losses impair communication. Materials such as soil or rock, brick, cement, reinforced concrete, metals, and metal-coated thermal glass panes are notorious for their ability to block electromagnetic radiation in the radio frequency range. In the interior of structures made of those materials, and in areas where natural or man-made structures block radio propagation, radio frequency levels may be 30 to 100 dB or more below unobstructed levels (nothing but cosmic ray particles and neutrinos penetrates into deep mines, for example). Repeater amplifiers boost radio signals to levels sufficiently high to provide reliable communication in those enclosed or blocked areas.

Historical Background

Repeater amplifiers have acquired great prominence in the radio communication industry in the last few years, due to a rapidly growing demand for extended communications services inside all types of urban structures. However, they made their first appearances several decades ago, as a part of "leaky feeder" or "leaky coax" radio communication systems in underground mines, vehicular and railroad tunnels. One-way repeater amplifiers were used in various configurations for simplex and semiduplex radio communication in underground tunnels. Two-way repeater amplifiers appeared more recently, and TX RX Systems Inc. has played a significant role in their development.

TX RX Systems Inc. was the first manufacturer of fully integrated, two-way repeater amplifier systems in the U.S. The first UHF two-way repeater amplifiers were manufactured in 1978, in response to a requirement by Motorola Communications. They were subsequently installed in an Inland Steel Corporation coal mine in Illinois, where they continue to provide reliable underground radio communication to this day. Since then, thousands of TX RX Systems' repeater amplifiers have been sold for private, commercial, government and military applications that include paging, radiotelephone, trunking and two-way radio systems in the frequency range from 66 to beyond 960 MHz.

TX RX Systems' repeater amplifiers have been used in such places as:

- The construction phase of the English Channel Tunnel or "Chunnel" (few people know that 140 VHF two-way repeater amplifiers manufactured by TX RX Systems Inc. were used in the system described in references 5 and 20)
- O'Hare International Airport in Chicago
- New York Port Authority facilities
- The San Francisco Bay Area Rapid Transit System (BART)
- The King Fahd International Airport in Saudi Arabia
- Subway stations in Lyon, France
- Many commercial high-rise buildings, shopping centers, manufacturing plants and hospitals in the U.S.
- Vehicular tunnels in Taiwan
- Nuclear and hydroelectric power plants in the U.S.
- The Cook County Jail in Illinois
- The largest copper mine in the world in Chile
- The subway system in Caracas, Venezuela

Key to TX RX Systems' long-term success has been its proven ability to solve tough application problems and provide substantive system engineering support to its customers. The quality and breadth of its engineering support is, in fact, a key element that has consistently differentiated TX RX Systems from its competitors.

About This Booklet

This booklet, a part of TX RX Systems' long-standing **Seminar Subjects** series, presents a broad but concise overview of repeater amplifier systems and design methods. Our motives for writing this material are twofold.

First, the best published technical articles on the subject have either provided exquisite technical detail on specific system implementations, or have provided highly theoretical discussions of narrowly specialized subjects. Lesser published articles fall in the category of marketing narratives which describe the great success of specific products in their peculiar applications, without providing much technical insight ("We put three of our Model XYZ amplifiers in a vehicular tunnel and reduced dropped cellular calls by 90%", etc.) To acquire a basic familiarity with the broad subject of repeater amplifier systems, the interested system engineer must locate and read many articles, textbooks and technical papers published over the last four decades or so. It is very difficult to put together a coherent mental picture of a multidisciplinary field, based on brief glimpses into unfamiliar subjects. The list of references at the end of this booklet includes only a small fraction of the many books, technical papers and articles that contain relevant information. Busy professionals in our sector of the industry may not have the time and motivation to engage in literature research of the kind required.

Second, prospective repeater amplifier customers frequently spend many hours in conversation with our engineering and sales personnel, in a process that eventually leads to our understanding of the application and the customer's understanding of the technology required to solve the communication problem. We take great pride in our ability to provide technical support, but we have long felt that we would rather spend long hours either analyzing our customer's application in ways that leave nothing to the imagination, or fine-tuning the system design to maximize the probability of mutual satisfaction.

Prospective repeater amplifier customers often wonder why we ask so many questions when they inquire about our products. After all, they just want a quick quotation on a specific repeater amplifier model number, right?. It turns out that every application parameter, from the frequency plan to the location of radios and antennas within the system, has a profound effect on how the hardware should be configured. We will have achieved a worthwhile objective if the material below succeeds in explaining why we need so much information to quote one bit of equipment.

We have divided the material into four self-contained but closely related parts:

- **Repeater Amplifier Basics** provides an introduction to repeater amplifiers and their basic components, without engaging in too much technical discussion, for the benefit of those who wish to quickly familiarize themselves with the subject.
- **Repeater Amplifier Applications** provides a brief overview of how repeater amplifiers are used to provide radio communication coverage in blocked or enclosed areas.
- **Amplifier Noise, Intermodulation and Dynamic Range** provides a practical compendium of technical facts about linear amplifiers, including formulas, tabulations and graphs that we use in our daily work for purposes of repeater amplifier system design.
- **Repeater Amplifier System Architecture** puts it all together: it discusses a repeater amplifier system design example, emphasizing how the system configuration has been calculated to satisfy application requirements.

PART I - REPEATER AMPLIFIER BASICS

Definition of Non-Heterodyne (Broadband) Repeater Amplifier

Non-heterodyne (broadband) repeater amplifiers utilize linear amplifiers with input and output filters that restrict pass bandwidth to a specified frequency range. No frequency conversion processes are involved in their operation. Filter pass bandwidth may range from 25 KHz at VHF to 25 MHz at GSM cellular frequencies. Non-heterodyne amplifiers are generally less complex and expensive than heterodyne (channelized) repeater amplifiers. They therefore provide a cost-effective solution to a wide variety of communication problems.

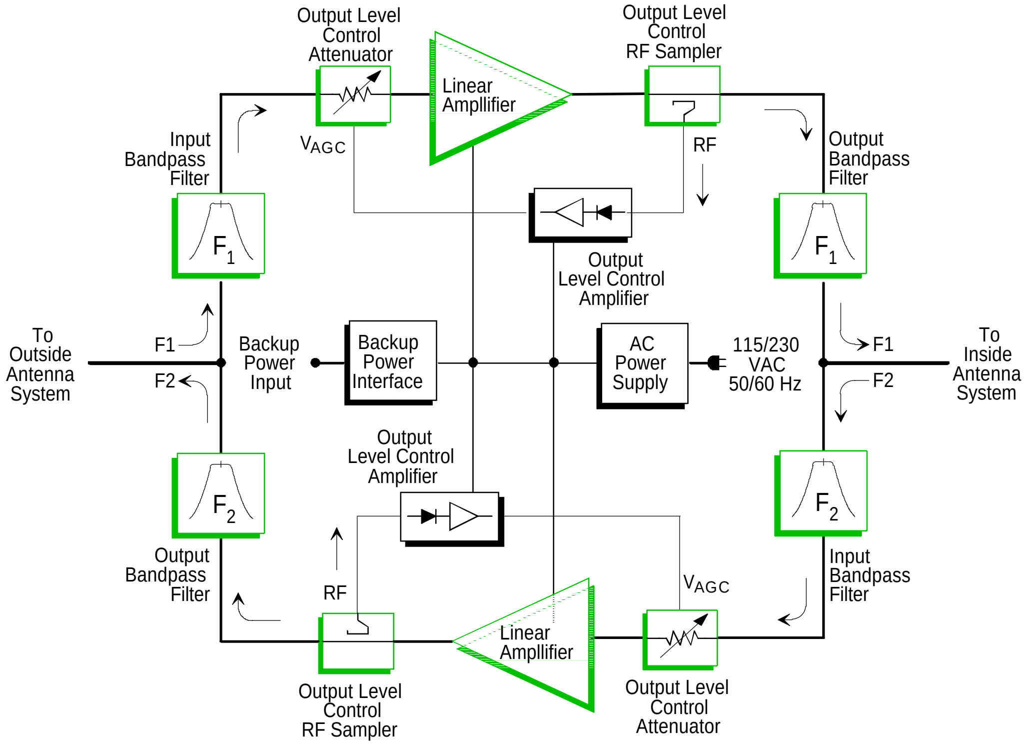


Figure 1 - Generalized Non-Heterodyne, Two-Way Repeater Amplifier System

Non-heterodyne repeater amplifiers typically consist of the following basic elements:

- *Linear amplifiers* that provide the required RF gain and output power
- Input and output *filters*
- *Gain control* circuitry
- *Power supply* or power conditioning facilities
- Optional *power backup*, *RF backup* and *supervisory* facilities
- A *cabinet* or *enclosure*

Figure 1 is a block diagram of a generalized non-heterodyne two-way repeater amplifier system. It features most of the components found in non-heterodyne repeater amplifiers for frequencies from 66 to 1000 MHz. Their nature and purpose will be described in detail below.

Linear Amplifiers

Amplifier linearity, i.e. the ability to amplify signals without creating output distortion products, is a primary consideration in non-heterodyne repeater amplifier systems, especially because of the frequent need to amplify multiple signals on different frequencies. Class-A linear amplifiers are a natural choice for this kind of service, because of their excellent linearity and predictable behavior.

TX RX Systems' linear amplifier stages have typical gains from +12 to more than +20 dB and 1-dB output compression points of a few hundred milliwatts to six watts. Output intercept points are in the range of +23 to +49 dBm, depending on the type and frequency range of the amplifier. Noise figure ranges from less than 2 dB in low-noise, low-level stages, to 10 dB in high-power stages. Broadband amplifiers are not required, as operating bandwidths rarely exceed 1% to 3% of center frequency.

Repeater amplifier systems may have one, two or more amplifier *branches*, one for each direction of signal transmission and/or frequency range. The gain, pass bandwidth, center frequency and output power of each branch may be completely different from each other. Low-noise, medium- and high-power stages can be combined in various ways to obtain optimum RF output power, noise figure and intermodulation characteristics.

Because the integrity of an entire communication system depends on reliable amplifier performance, careful attention must be paid to the choice of active devices. TX RX Systems utilizes linear bipolar devices of the highest quality and reliability. They are operated well within the manufacturer's recommended limits. High-level amplifiers are outfitted with heatsinks of ample dimensions to keep semiconductor junction temperatures well below maximum ratings.

Filters

Filters perform important functions in repeater amplifier systems. In one-way systems, input filters reject undesired signals to minimize the potential for interference, and output filters attenuate out-of-band amplifier noise and spuria. In two-way systems, the input and output filters on adjacent amplifier branches also provide selectivity well in excess of total amplifier gain at all frequencies, in order to assure unconditional amplifier stability. In repeater amplifiers with more than two amplifier branches, stable operation can only be achieved with filter designs that provide sufficient isolation between all possible branch pairs.

Pairs of filters that join adjacent two-way amplifier branches are sometimes described as "duplexers". Ordinary notch or pseudo-bandpass (pass/notch) duplexers are <u>not</u> suitable for repeater amplifier applications, as they provide high isolation at only two frequencies or narrow frequency ranges. Because repeater amplifier filter response must be predominantly of the bandpass type, the term "bandpass duplexer" would be more appropriate to the great majority of repeater amplifiers.

Real-world system applications impose requirements for many different filter types and designs, depending on the frequency range, frequency separation, bandwidth, and gain of the required amplifier branches. "Generic" helical, ceramic and surface acoustic wave filters have recently become commercially available, but they are generally aimed at mass markets and supplied in limited frequency ranges, pass bandwidths and responses. TX RX Systems' proven expertise in custom filter design is an advantage in a field that requires much more than generic amplifiers and filters.

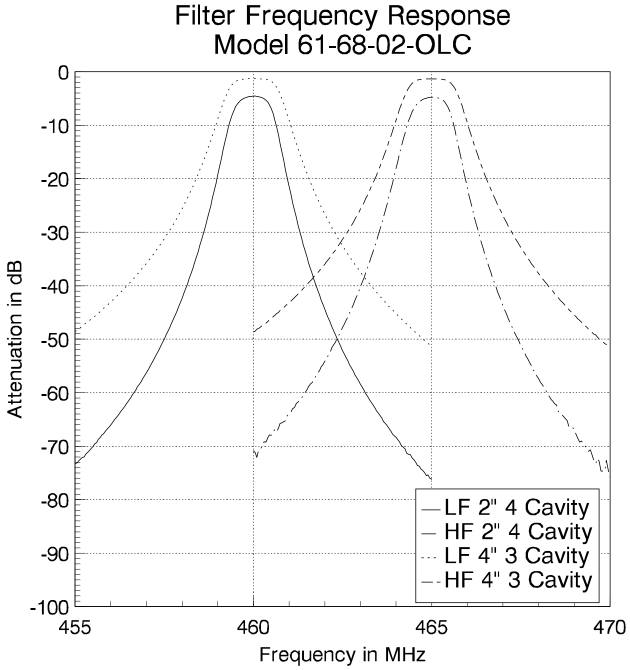


Figure 2

Figure 2 shows the frequency response of the bandpass filters used in repeater amplifier Model 61-68-02-OLC. A block diagram of the system is shown in ***Figure 3***. The two curves centered on 460.0 MHz are the response of the low-frequency passband input (lower curve) and output (upper curve) filters. The two curves centered on 465.0 MHz are the response of the high-frequency passband input and output filters. The input filter assemblies are 4-section, aperture-coupled designs utilizing 2" square 1/4-wave resonators. They provide excellent selectivity at moderate insertion loss, in a relatively compact package. Typical insertion loss is in the order of -4.7 dB at the center frequency. Typical pass bandwidth is ±0.4 MHz at -5.7 dB insertion loss. It is important to minimize output filter insertion loss, in order to minimize the degradation of amplifier output power and third-order intercept point. Because of this, the branch output filters consist of three loop-coupled, 4" quarterwave cavities which provide satisfactory selectivity at an insertion loss of only -1.3 dB at the filter center frequency. Pass bandwidth is ±0.4 MHz at -1.6 dB insertion loss.

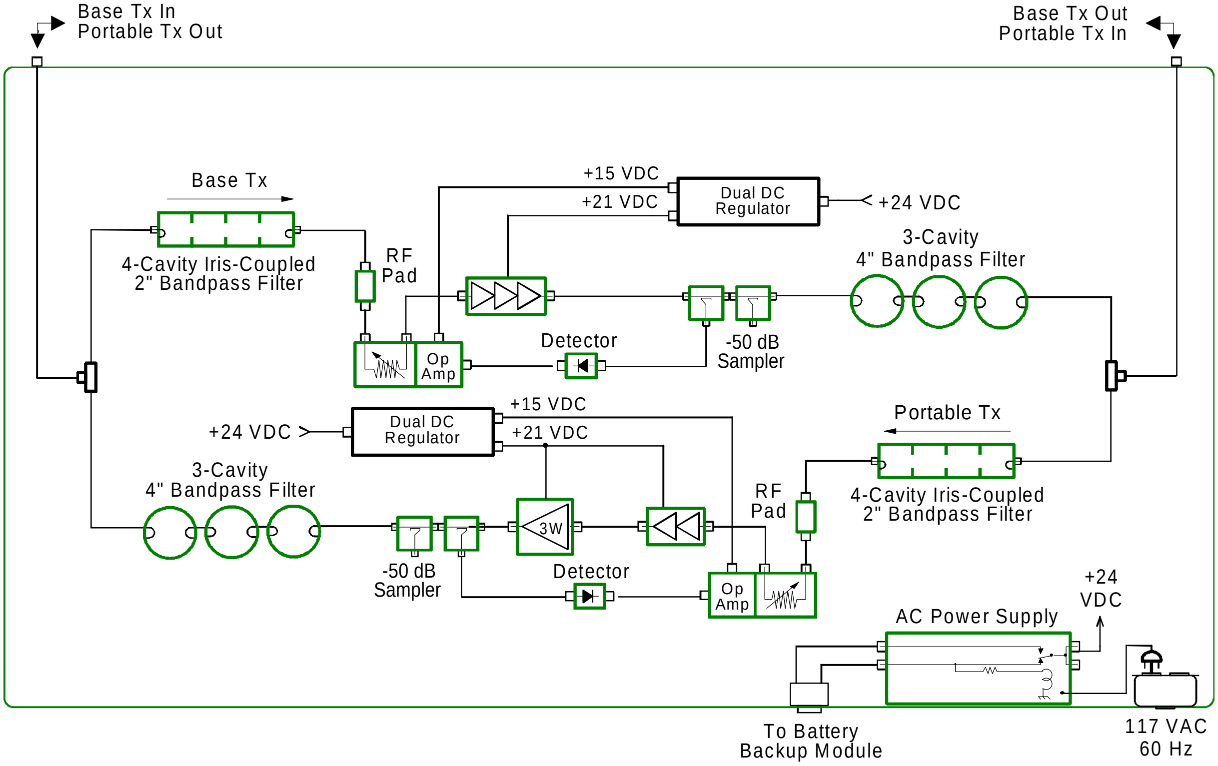


Figure 3 - Model 61-68-02-OLC Repeater Amplifier System

Isolation between the high- and low-frequency passbands at a specified frequency is the sum of filter selectivity at that frequency. Minimum isolation occurs at the upper edge of the lower passband and at the lower edge of the upper passband. In this case in particular, minimum isolation is -122.3 dB at 460.4 MHz (-5.7-68.4-1.5-46.7 dB). If a conservative isolation margin of 12 dB is allowed for amplifier stability at all frequencies, the sum of high- and low-frequency amplifier gain should not be higher than +110.3 dB. This particular filter configuration is therefore suitable for UHF repeater amplifier systems operating at minimum T-R separations of 5 MHz, at a gain of not more than 55 dB per branch. Amplifier gain in Model 61-68-02-OLC is approximately 48 dB per branch.

Bandpass filters made with TX RX Systems' 4-inch diameter quarterwave cavities, such as the three-cavity filter described above, are an excellent choice for VHF and UHF repeater amplifier work. Two to four cavities may be used to accommodate different bandwidth and selectivity requirements. Adjustable loops make it easy to set the selectivity of individual cavities as required to obtain a specified frequency response.

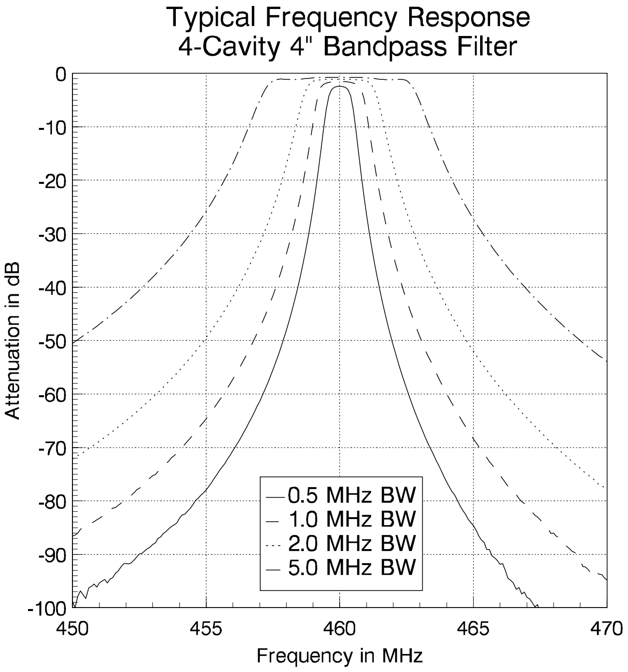


Figure 4

Figure 4 shows the frequency response of a 4-cavity, 4" quarterwave bandpass filter that is frequently used in TX RX Systems' UHF repeater amplifiers. There is a tradeoff between insertion loss, bandwidth and selectivity: greater bandwidth can be achieved at lower insertion loss, but at the expense of reduced selectivity.

Repeater amplifier Model 61-68-03-OLC, shown in ***Figure 5***, utilizes 4-cavity, 4-inch output filters and 4-cavity, 2" quarterwave input filters. ***Figure 6*** shows a set of possible amplifier frequency response curves. The greater filter selectivity provided by this configuration allows operation at a maximum amplifier gain of 63 dB per branch.

When the application requires operating at close frequency spacings and high gain, it is possible to increase isolation at the frequency of minimum isolation by introducing a notch at that point in the filter frequency response. This can be achieved either by adding notch or *Series-Notch* cavity filters in series with the bandpass cavities, or by substituting one or more bandpass cavities with a pseudo-bandpass, *Vari-Notch* or *Phase-Notch* filter that incorporates an adjustable notch in its response. The latter approach has the advantage of substantially increasing isolation without increasing the number of cavities in the system. This is desirable to minimize system size and cost.

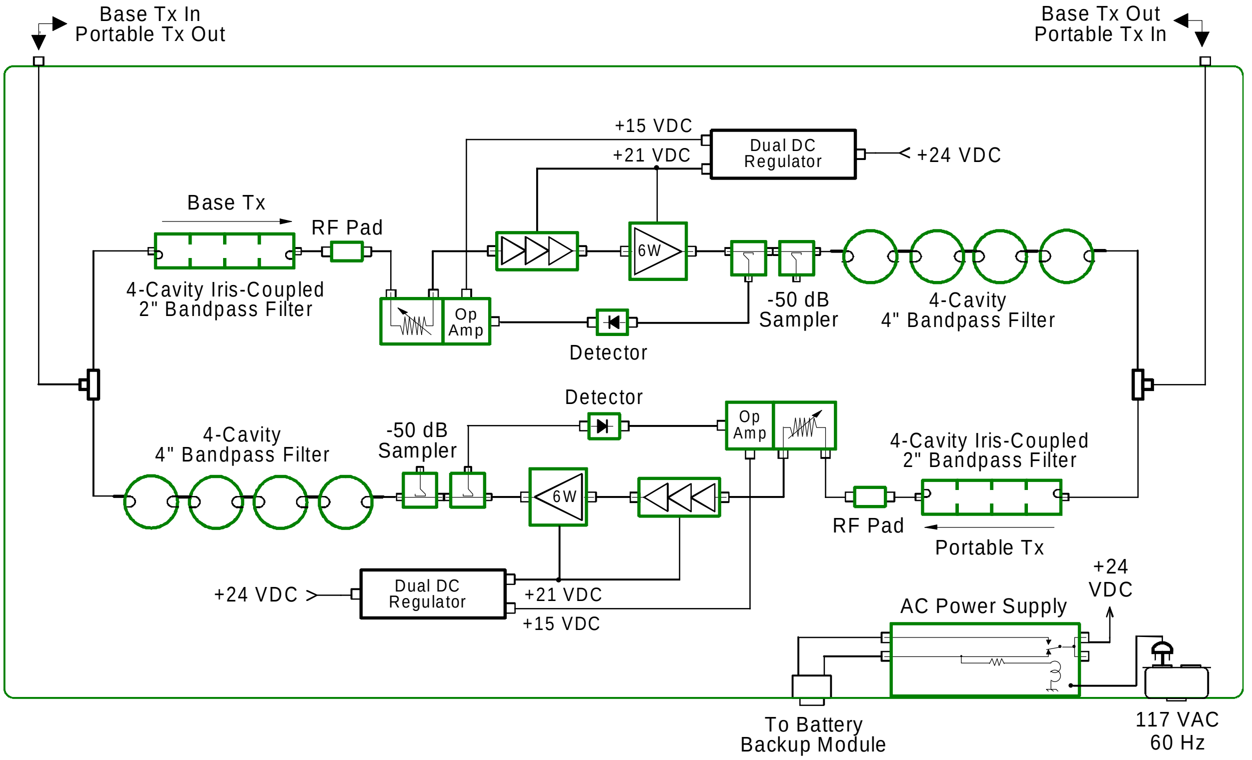


Figure 5 - Model 61-68-03-OLC Repeater Amplifier System

Figure 7 shows repeater amplifier Model 61-68-91361-0.35BW. The input and output filters are three-cavity designs in which the outer cavities are bandpass filters and the center cavity is a *Phase-Notch* filter. The curves in ***Figure 8*** are the sum of the measured response of the two filters in each passband. Minimum isolation is 164 dB at 508.3 MHz, 42 dB more than the isolation provided by the filters in ***Figure 2***. With a conservative isolation margin of 20 dB, this allows operation at a maximum amplifier gain of 72 dB, at a separation of only 3 MHz between passbands. Insertion loss at the passband center frequencies is -5.4 and -5.9 dB. 1-dB pass bandwidth is approximately 350 KHz.

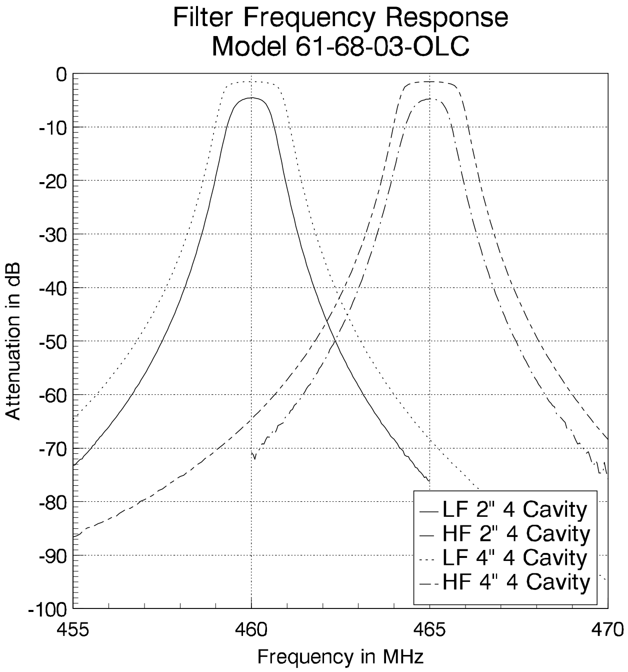


Figure 6

The top curve in ***Figure 4*** shows that it is possible to achieve a broad bandwidth with only four 4-inch UHF bandpass cavity filters. However, at pass bandwidths greater than about 2 MHz, passband flatness deteriorates, selectivity becomes poor, and it may not be possible to achieve a satisfactory return loss (or VSWR) over the entire passband. For these reasons, when a repeater amplifier application requires operation at high gain and/or broad pass bandwidths, multiple-section *combline filters* become an attractive alternative to discrete cavity filters. Combline bandpass filters are used in the majority of repeater amplifiers for the 800-1000 MHz frequency range.

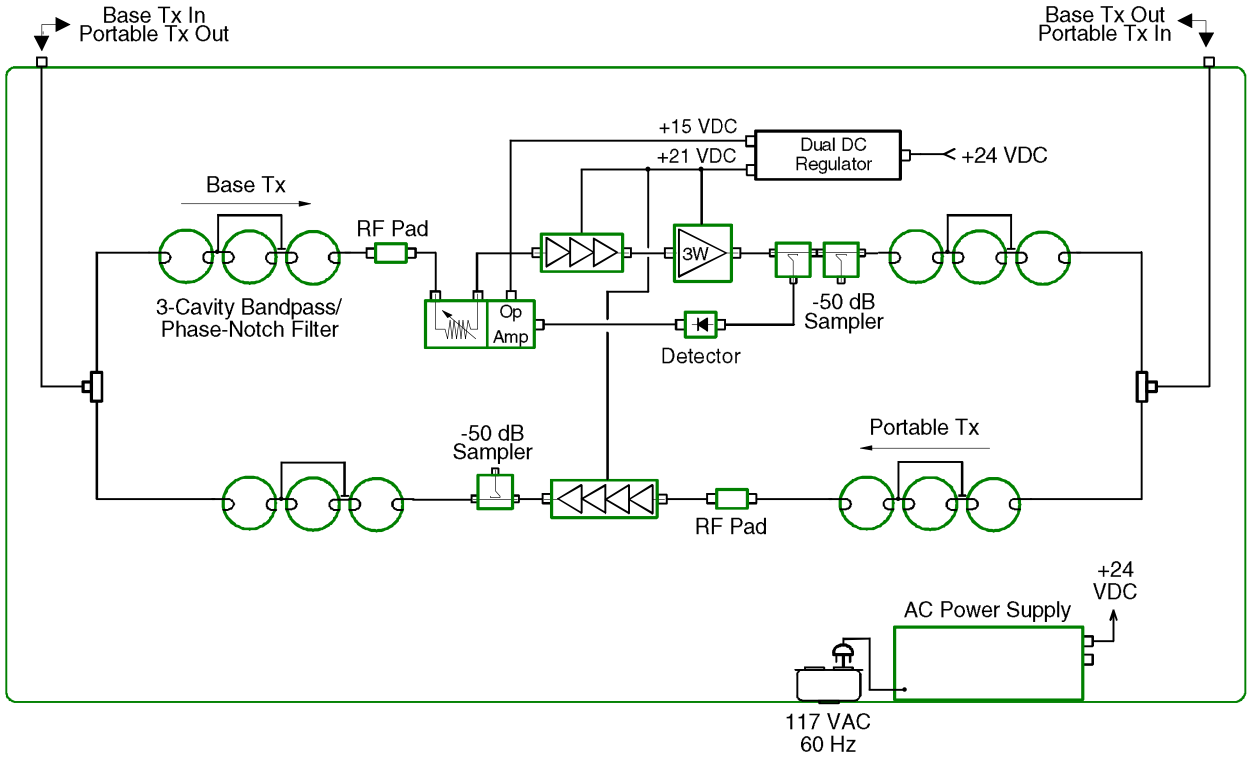


Figure 7 - Model 61-68-91361-0.35BW Repeater Amplifier System

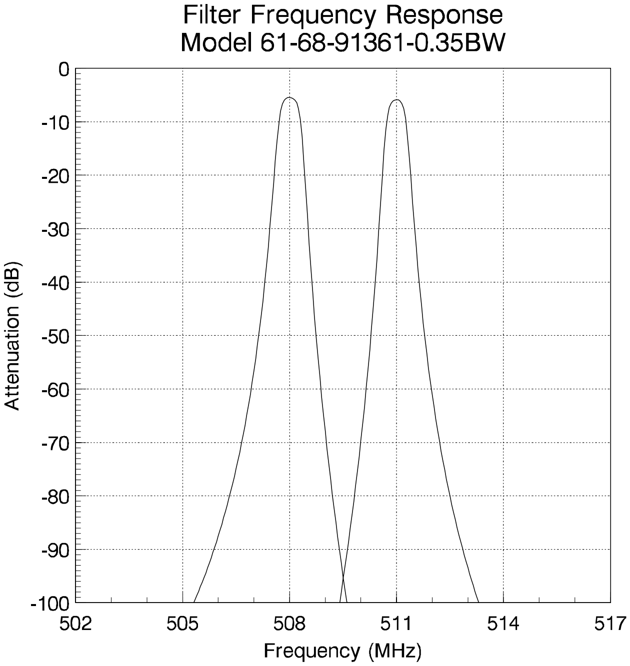


Figure 8

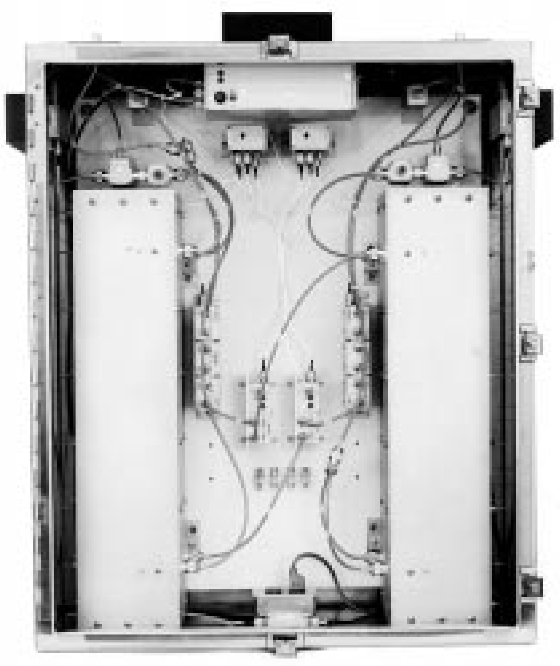


Figure 9 - UHF Repeater Amplifier

Combline filters consist of a number of tunable resonators, all installed inside a common rectangular cavity. Filter bandwidth and selectivity are determined by the number and type of resonators, and by the coupling between resonators. It is therefore possible to derive a very large number of different filter responses from a basic combline filter design. TX RX Systems' UHF and 800-1000 MHz combline filters have been optimized to provide flat passbands and high selectivity over frequency ranges of interest to two-way radio, trunking, paging and cellular operations.

Two types of combline filters are available for the 406-512 MHz frequency range: six-section bandpass filters, and eight-section designs with six bandpass and two notch sections to sharpen skirt selectivity or improve selectivity at specified frequencies. ***Figure 9*** shows UHF repeater amplifier that utilizes 8-section combline filters with built-in notch filters for operation at high gain over 4- to 5-MHz pass bandwidths. The combline filters are the two large rectangular devices on either side of the picture. A family of combline filters for the 800-1000 MHz frequency range includes six-, eight- and ten-section bandpass models in 5- to 18-MHz bandwidths, and eight-, ten- and twelve-section filters with two built-in notch filters, in bandwidths from 5 to 25 MHz.

Figure 10 shows a six-section combline filter of the type used in TX RX Systems' 800-1000 MHz two-way repeater amplifiers, such as Model 61-88-03-OLC in ***Figure 11***. The frequency response curves in ***Figure 12*** show the excellent selectivity and flat passband provided by a single filter in each amplifier passband. Typical insertion loss is -1.0 dB at the passband center and -1.1 dB at the passband edges. Two filters provide ample isolation for stable repeater amplifier operation at gains in excess of those required by practical applications. Model 61-88-03-OLC is typically configured for approximately 80 dB maximum gain.

Figure 10 - Six Section Combline Filter for the 800-100 MHz Range

Figure 13 depicts a 10-section combline filter with a pass bandwidth of 25 MHz. Filters of this type are used in Model 61-95-93131, a repeater amplifier that spans the entire GSM cellular frequency range. ***Figure 14*** shows the frequency response of one filter.

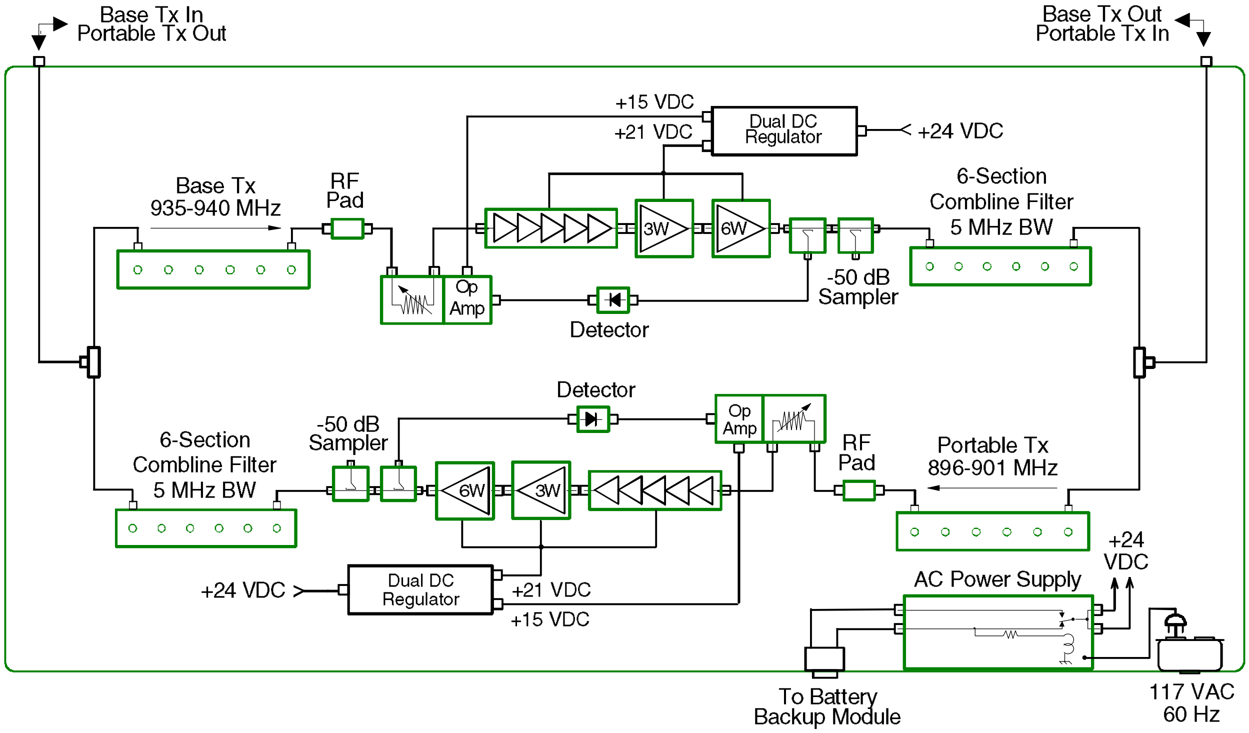


Figure 11 - Model 61-88-03-OLC Repeater Amplifier System (896-901/935-940 MHz)

Gain Control

Amplifier gain requirements vary widely from one application to another, or even from one location to another within the same system. Maximum repeater amplifier gain is set at the factory, in accordance with system design requirements. The maximum gain listed in the repeater amplifier system specification is the sum of individual stage gains in each branch, minus filter and other losses. Depending on the model, the gain can be reduced by means of fixed RF attenuators (pads) variable attenuators, or both. High-quality, 5%-precision fixed and rotary attenuators are used in TX RX Systems' repeater amplifiers. The gain can be further reduced, if necessary, by bypassing low-level stages.

Automatic gain control is required in applications where input levels vary over a wide range but output power per carrier must be kept below a specified maximum. This is the case, for example, in a tunnel communication system where 5-watt handheld transceivers and 25-watt mobiles transmit in the immediate vicinity of an amplifier, or at the end of long cable runs. Input power variations of 30 to 40 dB are typical under those conditions. Automatic gain control is also recommended in high-gain amplifier branches that utilize 3- or 6-watt output stages, to protect the output stages from destructive overloads.

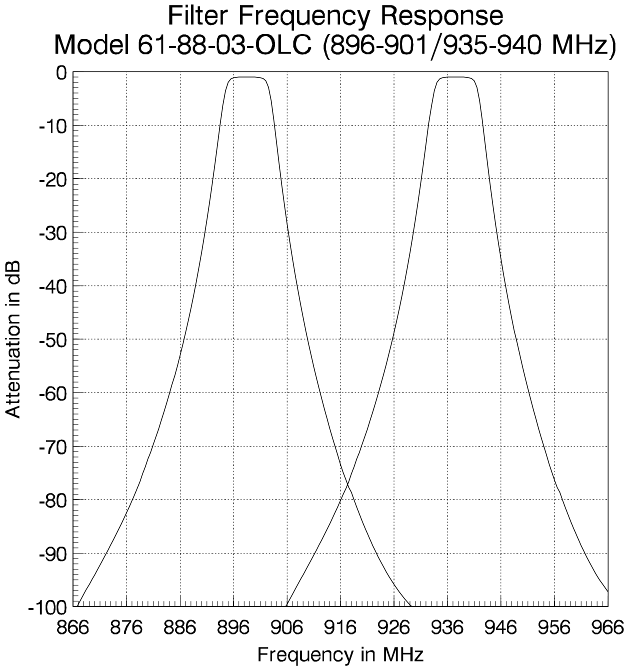


Figure 12

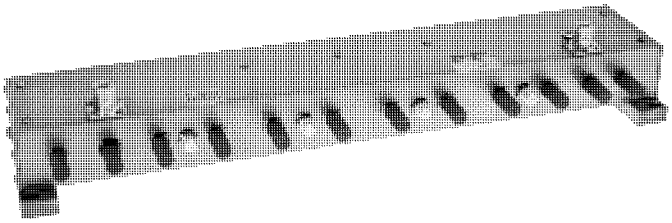


Figure 13 **-** 12-Section GSM Combline Filter
890-915 MHz or 935-960 MHz

TX RX Systems utilizes a high-performance Output Level Control system (OLC) consisting of an output RF sampler, an RF detector and a DC amplifier that controls a PIN-diode attenuator at the amplifier input. OLC examples can be seen in all of the repeater amplifier diagrams shown in previous pages. The system maintains output level within 1 dB over a minimum input level range of 35 dB. Amplifier intermodulation performance is not degraded as the OLC system reduces gain by inserting attenuation at the amplifier input. OLC threshold is set at the factory so that power per carrier does not exceed the maximum specified by proposed EIA standard PN2009.

Power Supplies

Repeater amplifiers may be equipped with internal AC power supplies, DC regulators or converters for operation with external DC supplies or batteries on floating charge, or they may operate with DC supplied via the radiating coaxial cable. Because of the mission-critical nature of repeater amplifier systems, careful attention must be paid to selecting the most reliable method of supplying power to individual repeater amplifiers.

TX RX Systems provides internal AC power supplies of the highest quality, and they are operated at a fraction of their maximum output capability. Transient suppression at the AC input, current foldback and overvoltage protection are standard. Built-in circuitry is included in many standard repeater amplifier systems for automatically switching to emergency batteries in case of AC power outages. As an additional layer of protection against supply-induced damage, TX RX repeater amplifiers utilize linear voltage regulators to provide operating voltage to amplifiers, OLC and other circuitry. DC-to-DC switching converters may be supplied on request for applications where an uninterruptible DC supply of some kind is already available. 48 to 72 VDC input voltages can be accommodated.

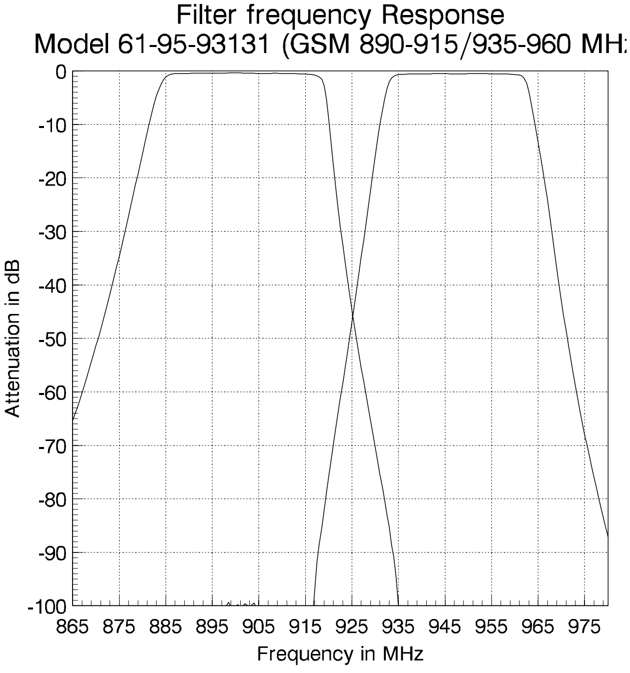


Figure 14

Supplying DC through the coaxial cable is a method that has worked well in systems utilizing a limited number of low-power repeater amplifiers. Special "choke boxes" are required at each repeater amplifier to separate DC and RF while maintaining a high degree of input-to-output RF isolation. A "choke box" is also needed to inject DC power into the first unit in the chain. The method is not attractive for systems where many high-level repeater amplifiers operate at individual current drains of several amperes. High resistance in long cable segments causes large DC voltage drops. The need to apply a high voltage to the cable input may require the use of DC-to-DC switching converters instead of linear regulators in individual repeater amplifiers. This may prove to be very costly.

Supervisory and Backup Facilities

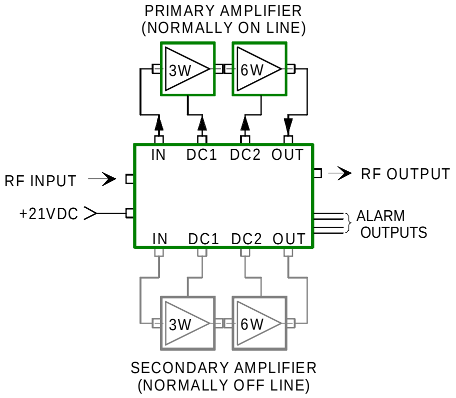


Figure 15 - TX RX Systems' ***Auto-Backup*** ™ System (U.S. & Other Patents Pending)

A reasonable degree of system monitoring is desirable, but common sense dictates that fault prevention is a more worthwhile investment than sophisticated fault detection and reporting. For example, the failure of a single power supply may put an entire system out of commission. It would make much more sense to operate repeater amplifiers with external telecommunication grade batteries on floating charge, instead of using elaborate A/D converters, microprocessors and modems to report temperatures, voltages, currents and, ultimately, system failures. The 8-bit industrial microprocessor is a fine technological achievement, but using it for inappropriate purposes is not necessarily good engineering. TX RX Systems' experience indicates that the probability of low-level amplifier failure is astronomically small. Therefore it makes little sense to increase system cost with low-level stage monitoring facilities. Besides, monitoring amplifier RF output power, VSWR and system signal integrity requires complicated transponder, intermittent carrier or pilot carrier monitoring arrangements.

As an alternative, TX RX Systems recommends using its ***Auto-Backup*** ™ system (U.S. and foreign patents pending) in applications that demand maximum reliability. ***Figure 15*** shows a typical ***Auto-Backup*** arrangement. In normal operation, the *primary amplifier* is connected to the RF chain and system DC power, and the *secondary amplifier* is completely disconnected from the RF and DC paths. Because amplifiers are usually damaged by high RF levels or power supply anomalies, the isolated secondary amplifier in the ***Auto-Backup*** system has a very high probability of surviving events that are likely to damage both the primary and the secondary in "hot standby", hybrid-coupled arrangements. The ***Auto-Backup*** system intelligently takes advantage of the fact that Class-A linear amplifiers are designed to operate at an essentially constant current. A simple analog circuit in the supervisory module monitors supply current and actuates switching relays in response to excursions above or below preset limits, since current anomalies are a sure indication of amplifier failure. If the primary fails, the secondary is brought on line within milliseconds. In the unlikely case of a secondary failure, the supervisory module entirely bypasses both amplifiers and allows the repeater amplifier to continue operating at reduced power. Dry contact closures provide a positive indication of system status and can be easily interfaced with system supervision facilities.

TX RX Systems can provide optional analog circuitry for DC voltage, DC current and RF level monitoring and alarm functions. Outputs can be either a dry contact closure at a specified threshold, or a standard current loop. Both can be easily interfaced with monitoring equipment.

Enclosures

TX RX Systems offers a variety of enclosures for its repeater amplifier systems. For installation in benign environments, such as heated and air-conditioned office buildings, systems can be built on inexpensive open shelves suitable for mounting in 19" cabinets or open racks. Wall-mounted metal enclosures with gasketed front access doors are a popular choice for many applications. Stainless steel enclosures rated to NEMA 4X standards are recommended for operation in hostile environments. For less hostile environments, painted steel or aluminum enclosures are available at lower cost. High-quality, weatherproof cabinets of special design, with sealed heat exchangers to prevent exposure of the equipment to extreme environments, are available on request.

PART II - REPEATER AMPLIFIER APPLICATIONS

Repeater amplifier system applications can be grouped into three different categories:

- Type I: Tunnels.
- Type II: Buildings or enclosed structures.
- Type III: Shadowed areas behind high terrain or structures.

The above categories cover a wide variety of specific applications ranging from high-rise office buildings to aircraft carriers. The difference lies in the type of signal distribution system utilized to provide radio coverage inside the enclosed or blocked area.

TYPE I APPLICATIONS: TUNNELS

General Description

Tunnels are long, narrow underground or interior spaces, bounded by lossy materials such as reinforced concrete, soil, rock or others. The following spaces belong in this category:

- Mine access shafts and tunnels
- Hydroelectric plant shafts and ducts
- Railway and vehicular tunnels, the "Chunnel" being the longest by far
- Long passageways in airport terminals and commercial buildings
- Underground transportation system tunnels (metros, subways, etc.)

Radio Signals in Tunnels

Radio signals do not propagate well in narrow tunnels bounded by lossy walls. Attempts at coupling 30 to 960 MHz radio signals into tunnels by means of antennas have typically resulted in longitudinal propagation ranging from poor to very bad. For this reason, "leaky feeder" systems, consisting of transmission lines that are deliberately made to radiate along their length, have been developed to generate relatively uniform RF fields inside tunnels. At low frequencies (30-50 or 66-88 MHz), transmission line longitudinal loss is small and it is feasible to provide communication inside long tunnels with relatively small input RF power. At higher frequencies, however, transmission line loss severely limits communication range, and the brute-force application of high RF power may cause problems of a different kind.

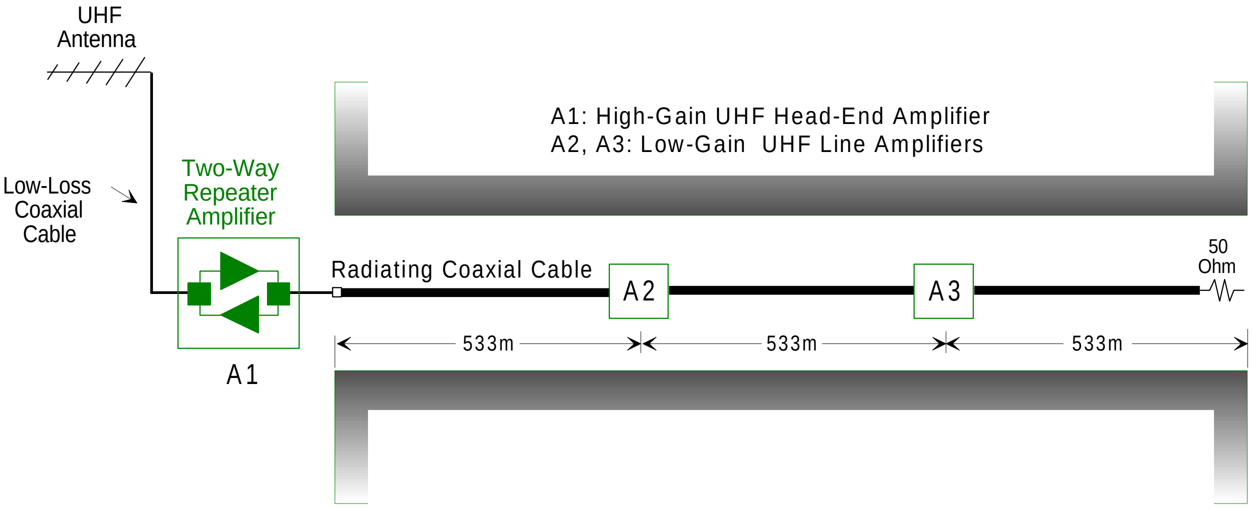


Figure 16 - Vehicular Tunnel UHF Communication System

Figure 16 illustrates two basic functions of repeater amplifiers in tunnel communication systems. *Head-end amplifier* A1, installed in this case at one end of the tunnel, and a high-gain directional antenna provide an air interface with an external base or repeater station. A single radiating coaxial cable carries RF signals to and from radios inside the tunnel. The far end of the cable is terminated with a 50-ohm RF load resistor to assure proper impedance matching. The head-end amplifier boosts signals to levels appropriate for reliable communication with transceivers at a point just before A2. *Line amplifiers* A2 and A3, installed at intervals of 533 meters in the tunnel, are low-gain units that compensate for cable longitudinal transmission loss. The use of two-way amplifiers requires that the base or repeater station be full duplex or semiduplex, and that the separation between frequencies be sufficient to achieve high isolation between repeater amplifier branches, as discussed in **Part I**.

Twin-Lead vs. Coaxial "Leaky Feeders"

A leaky feeder can be either a balanced transmission line (twin lead), or a coaxial transmission line with openings, both designed to "leak" signal along their entire length. Of the two, radiating coaxial cable is nearly always chosen for tunnel communication systems, for several good reasons:

- Radiating coaxial cable is available from several recognized manufacturers in the U.S., Europe, Japan and other countries around the world.
- Radiating coaxial cable is commercially available in a variety of sizes, configurations and materials to suit virtually all applications.
- The availability of excellent product application documentation and reliable specifications have led to consistent successes in large and small installations.

By contrast, twin lead systems have not been frequently seen in credible commercial applications. Contributing factors are reports of environment-related twin-lead system failures, as well as a general lack of support by recognized manufacturers.

Radiating Coaxial Cable Types

Three types of radiating coaxial cable have been used over the years. Loose-braided, large-diameter coaxial cable was used early in the history of underground communication systems. It provides a combination of low longitudinal loss and coupling factor that is not affected by cable orientation relative to the mounting surface. One cause of concern to the system designer is the possibility that contacts between loose strands may become sources of intermodulation, if they become oxidized or corroded as a consequence of long exposure to the environment. A second type of radiating coaxial cable is made by cutting a series of small, close-spaced oval apertures or diagonal slots along the solid shield of a low-loss coaxial cable. The size, shape and orientation of the apertures or slots can be adjusted to optimize coupling factor in a variety of ways. A third type of radiating coaxial cable has a solid shield and two continuous longitudinal slits, or an equivalent thereof. Both multiple-slot and continuous-slot cable produce a relatively homogeneous field when properly installed in accordance with the manufacturer's recommendations. Excellent data sheets and applications notes are available from all major manufacturers of radiating cable.

Long-term deterioration of metal-to-metal contacts is undoubtedly the leading cause of intermodulation problems in radiating coaxial cable systems. Long-term experience in multiband, multichannel systems and laboratory tests confirm that the materials used in the construction of RF connectors have a significant effect on their intermodulation performance. In general, connectors with large-diameter, gold- or silver-plated non-ferrous center contacts perform better. The use of ferrous metals or nickel plating in connectors has been recognized as one of the leading sources of intermodulation. Dissimilar-metal interfaces have a high potential for becoming intermodulation sources after long-term exposure to corrosive environments. Aluminum and copper produce a particularly bad electrolytic pair. Therefore, there is a valid reason for concern about the reliability of connector joints on radiating cable made with an aluminum shield. However, field experience indicates that silver-plated connector bodies and proper connector waterproofing techniques go a long way towards preventing long-term problems, regardless of the type of cable or connectors. Also, properly-designed connectors utilize attachment methods that produce high-pressure, inherently hermetic metal-to-metal interfaces.

Feeding the Radiating Cable System

Radiating cable systems can be either connected directly to base station radios or repeaters in the tunnel or its vicinity, or they may operate with remote base stations or repeaters radios via air interfaces or optical fiber links. Each method has its advantages and disadvantages.

I. Base Station Radios in Tunnels

On superficial examination, it appears that coupling high-power base transmitters and high-sensitivity receivers into a radiating cable system could be a cost-effective system solution, as satisfactory signal levels can be achieved without amplification over considerable cable lengths. However, there are two drawbacks:

- Means are still required to carry digital or analog signals between the tunnel base station equipment and remote or local control facilities. Leased telephone lines, microwave and fiber optic links may be very costly propositions in the long run.
- Experience indicates that cable and connector joint deterioration is only a matter of time, and it can only be postponed by choosing the best components, materials and installation method. When cable system intermodulation and noise rear their ugly head, 60- to 100-watt transmitters will cause much worse problems than low-level sources operating at powers of a few watts or less. It is a well-known fact that the magnitude of third-order intermodulation products, regardless of their source, decreases 3 dB when carrier power is reduced by 1 dB. Reducing carrier power from 100 watts to only 1 watt, for example, may decrease intermodulation levels by as much as 60 dB. That may be the crucial difference between a system that works and one that is a chronic nightmare. For these reasons, the best strategy is to use low-power base station radios and low-level, low-gain repeater amplifiers to boost signals as required. ***Figure 17*** shows a UHF system that has been configured in accordance with this recommendation.

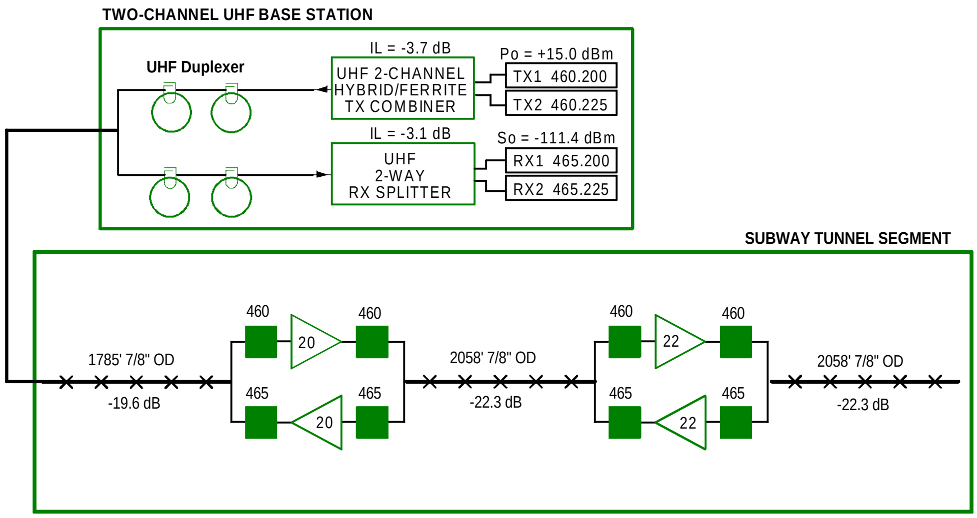


Figure 17 - Recommended Low-Power Tunnel Communication System Configuration

II. Air Interface with Base Station Radios

An air interface is often the most economical way to provide radio signals in a tunnel, as it does not require additional radio equipment or the high cost of installing it inside the tunnel. The tunnel system depicted in ***Figure 16*** and the in-building system in Figure 19 utilize air interfaces with external system base stations or repeaters. The head-end repeater amplifier provides bidirectional amplification for signals traveling from the base station to the radios inside the tunnel or building (downlink) and in the opposite direction (uplink).

Air interfaces work best when base transmitter power and propagation loss to the head-end amplifier are such that repeater amplifier input signal levels exceed -70 to -90 dBm. Reliable operation at lower levels may not be possible, depending on site noise, fading margins, repeater amplifier noise floor and other system design considerations. Using high-gain antennas at the head-end repeater amplifier site is always advantageous, as each decibel of antenna gain reduces amplifier gain and dynamic range requirements by an equal amount. Decibel for decibel, antenna gain may be less expensive than amplifier gain and may reduce amplifier dynamic range requirements.

III. Fiber Optic Interface

Fiber optic technology has advanced to the point that off-the-shelf transmitters and receivers for broadband RF transmission are available from several sources. Complete links have been specifically optimized for operation at relatively high levels with multiple carriers, as required, for example, for trunking radio and cellular radiotelephone system service.

Figure 18 shows a link that provides RF from 20 trunking transmitters to a tunnel site 20 miles away. The output of two ten-channel **T-Pass** multicouplers is connected to the fiber optic transmitter via directional couplers, fixed RF pads and a 4-way hybrid that provide ample isolation between systems and reduce the potential for intermodulation. Fiber optic links are extremely noisy, due to the nature of the devices involved in their operation (laser diodes at one end and photodiodes at the other end). Noise figures of 30 to 40 dB are not unusual. However, a high noise figure is not necessarily objectionable, as long as system output signal-to-noise ratio is satisfactory. At the levels shown in ***Figure 18***, commercially available links provide in the order of 50 to 60 dB signal-to-noise and signal-to-intermodulation ratios. For duplex radio operation, a second link is required to bring signals from the remote location to the radio system receivers. Because linear RF amplifiers are used at the input and output of the link, their combined third-order intercept point sets definite power limits as a function of the number of carriers in the system.

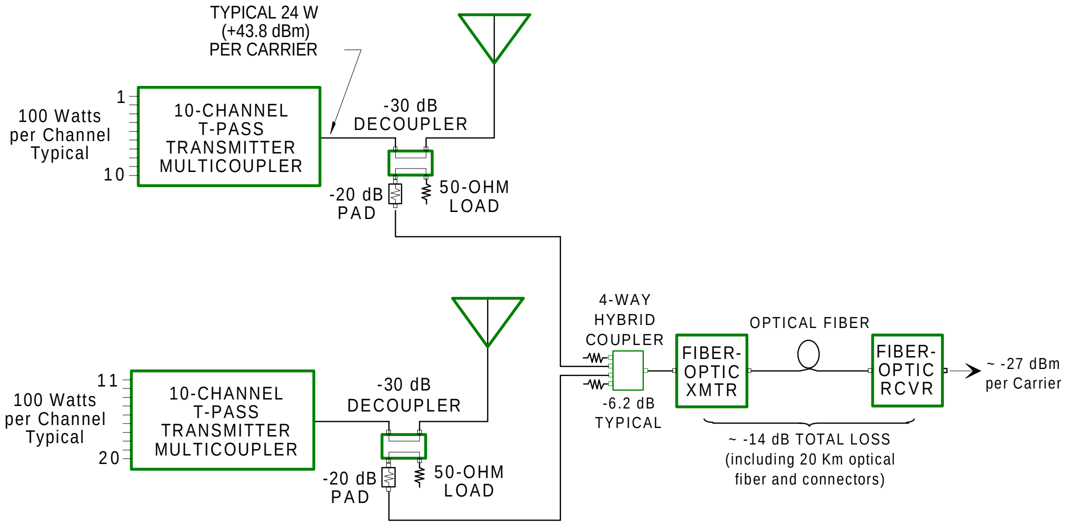


Figure 18 - Typical 20-Channel Tx Optical Fiber Link

Fiber optic link manufacturers often talk about the low cost of optical fiber ("pennies per foot!") as one of the significant advantages of their technology. By the time optical fibers are wrapped in protective layers suitable for burial or exposure to weather, the cost of fiber optic cable has risen to levels comparable to low-loss coaxial cable. Furthermore, the cost of installing optical fiber cable can easily be in the order of tens of thousands of dollars per mile, and there may be significant right-of-way problems. As of this writing, the cost of one-way fiber optic links is still in the order of many thousands of dollars, and other RF link technologies may be far more attractive from the standpoint of total installed cost. The main advantage of fiber optic technology lies in its phenomenal bandwidth and information carrying capacity. As a means to carry thousands of data or voice channels, it may be quite reasonably priced. As a means to carry only a few narrowband RF channels, it may be too expensive for practical purposes.

Type II Applications: Buildings

Buildings require three-dimensional signal distribution systems to provide coverage in relatively open spaces, narrow corridors, staircases and ventilation or elevator shafts. A high-gain, head-end repeater amplifier usually provides an interface between an external radio system and the interior of the building. In large building complexes with many users (hospitals or large factories, for example), it may be preferable to use an internal, dedicated base station to provide communication service to users in the facility. Two-way line amplifiers may then be required to overcome signal distribution losses within the complex.

Figure 19 shows an in-building 800 MHz communication system that operates with an external trunking base station. A high-gain directional antenna links the head-end amplifier with the base station. The signal distribution system consists of a number of branches fed by RF decouplers and splitters. Each branch utilizes a different combination of low-loss coaxial cable, radiating coaxial

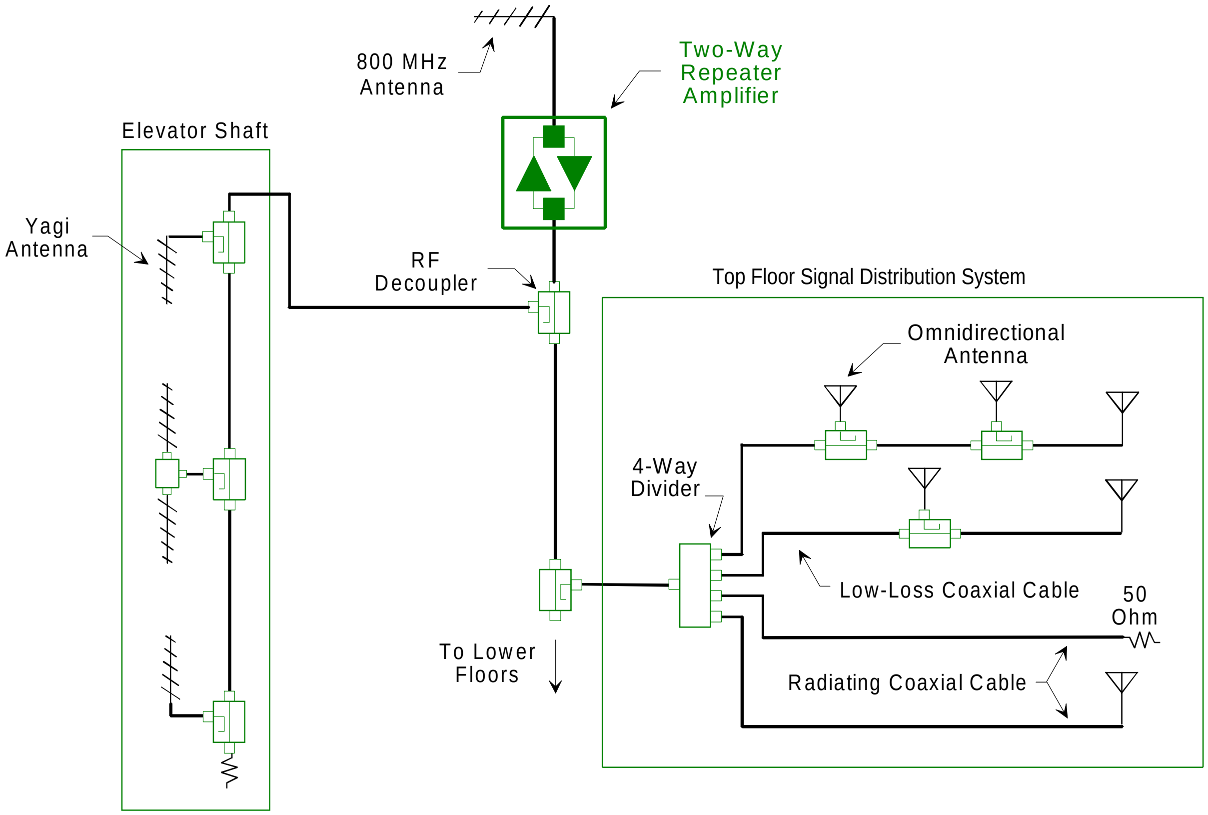


Figure 19 - Typical 800-MHz In-Building Communication System

cable, directional and omnidirectional antennas to achieve optimum coverage of elevator shafts, corridors and open areas.

Propagation loss inside buildings may be significantly higher than free-space propagation loss. Diffraction, attenuation by structural elements and complex multipath effects cause anomalies which make it difficult to accurately predict signal levels. TX RX Systems strongly recommends that signal level measurements be made throughout the areas to be covered, using a modulated RF signal generator or handheld transceiver with an output attenuator as a source. A spectrum analyzer, communications service monitor or handheld transceiver with a SINAD meter can be used to measure levels in different floors or areas, with the source at a fixed location. Experience indicates that it is possible to achieve uniform, reliable coverage by judiciously distributing relatively few radiating elements throughout the various spaces in a building.

Type III Applications: Shadowed Areas

Shadowed areas behind high terrain or man-made structures can be covered with a repeater amplifier with two antennas. One antenna links the system base station or repeater with the repeater amplifier. The other antenna is aimed at and provides coverage in the shadowed area.

Figure 20 illustrates an application of this kind. The two-way repeater amplifier boosts base and mobile or portable transmit signals to the level required for reliable coverage of the area blocked by high terrain. To prevent amplifier instability due to input-to-output feedback, the two antennas must be carefully located to provide space isolation 10 to 15 dB greater than amplifier gain. Stable antenna isolation in excess of 60 to 70 dB is very difficult to achieve. This imposes an upper limit of 50 to 60 dB on amplifier gain in this kind of application. In general, this implies relatively short distances between the base station and the repeater amplifier site, as well as between the repeater amplifier site and the shadowed area.

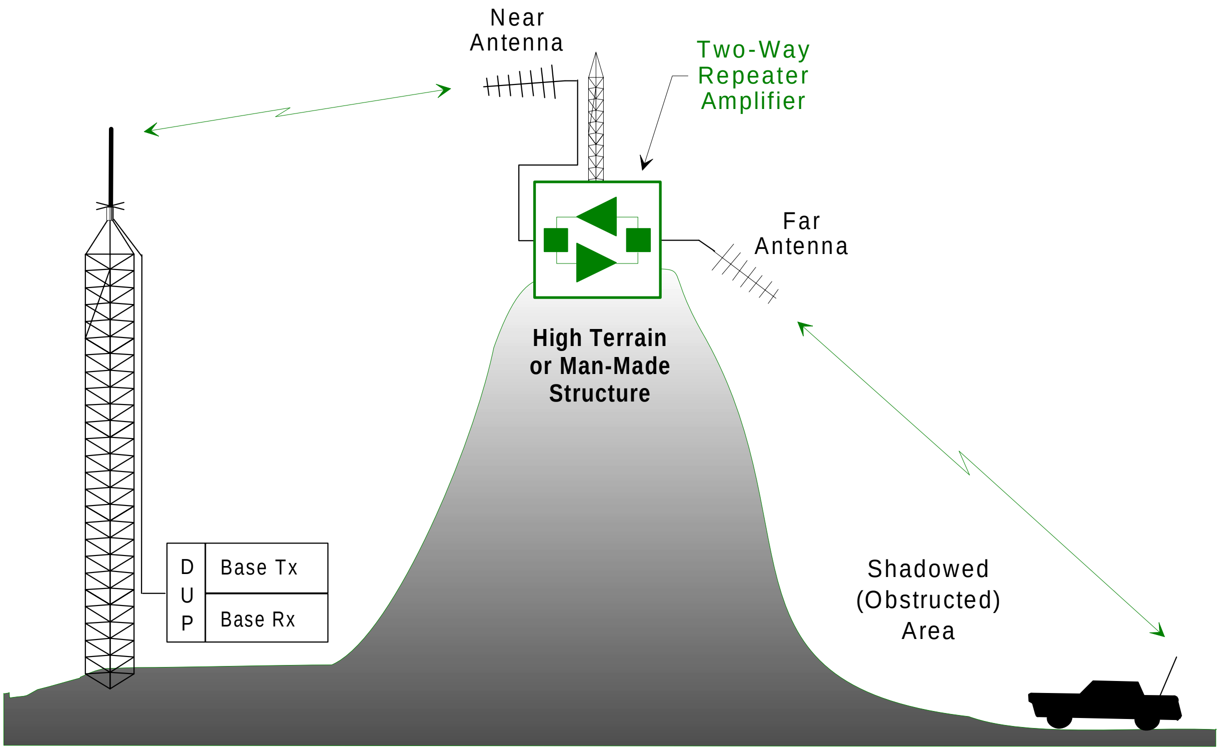


Figure 20 - Shadowed-Area Repeater Amplifier System Application

Conventional radio repeaters or heterodyne repeater amplifiers that operate on different input and output frequencies have few limitations on output power and maximum gain. Non-heterodyne repeater amplifiers should be used for shadowed-area applications only when there is no possibility of operating on frequencies different from or additional to existing base frequencies.

Real-World Applications

Real-world applications usually contain elements of more than one of the above categories. For example, an airport terminal may have long underground passageways that are treated as tunnels, as well as large open concourses that are best covered with discrete antennas. Underground transportation systems typically require communication coverage in train tunnels, passenger platforms, service areas, control and administrative spaces. Optimal designs for such applications involve a combination of different types of signal distribution systems.

Compatible Radio Services

All types of radio services can be extended with repeater amplifier systems:

- Repeater-based or semiduplex VHF and UHF two-way radio
- VHF to 900 MHz trunking
- VHF or UHF duplex radiotelephone
- UHF to GSM cellular radiotelephone (in the U.S., A- and B-band cellular control channels must be individually selected and amplified by heterodyne single-channel amplifiers)
- Telemetry or SCADA
- Paging
- Data transmission

Stable bidirectional amplification requires that uplink and downlink branch signals be on different frequencies, to make it possible to provide isolation between branches by means of appropriate filters. The great majority of modern radio applications are two-way duplex or semiduplex, except paging systems, which are one-way. Two-way simplex systems can only be handled in very limited ways with repeater amplifiers.

PART III - AMPLIFIER NOISE, INTERMODULATION AND DYNAMIC RANGE

Introduction

The preceding section provided a general overview of non-heterodyne repeater amplifier systems and their applications. We now turn our attention to the application of linear amplifier theory to the estimation of repeater amplifier system performance. We will take the theory for granted, as it has been extensively covered in many classical textbooks and technical papers. We will focus, instead, on the impact of linear amplifier parameters on system power, noise and intermodulation levels.

The concepts, formulas, data and graphs presented here are eminently practical. In fact, we use them in our daily work.

NOISE

Noise deserves special attention in repeater amplifier systems, because amplifier noise defines the system noise floor. A fundamental system design objective is to achieve receiver input signal-to-noise ratios high enough to produce prescribed output signal-to-noise-ratios or bit error rates. Additionally, amplifier output noise levels must comply with U.S. or international spurious radiation standards. An understanding of noise figure and its application is essential.

Amplifier Noise Figure

Non-ideal amplifiers add noise to signals passing through them. The amplifier noise contribution can be measured as a ratio of input to output signal-to-noise ratio, as follows:

$$\mathbf{NF\ (dB) = 10\ log\ [(S/N)_I/(S/N)_O]} \qquad [\textit{Eq. 1}]$$

where NF is the *noise figure* and $(S/N)_I$ and $(S/N)_O$ are the amplifier input and output signal-to-noise ratios.

The noise figure is 0 dB for a noiseless amplifier or lossless passive device, and is always positive for non-ideal devices. The noise figure of lossy passive devices is numerically equal to device insertion loss. The typical noise figure of linear amplifier stages ranges from 2 dB or less in low-noise stages, to about 10 dB in power amplifiers.

If the input of a non-ideal amplifier of gain G dB and noise figure NF dB were connected to a matched resistor, amplifier output noise power would be

$$\mathbf{P_{No}\ (dBm) = 10\ log\ (kT) + 10\ log\ (B) + G + NF} \qquad [\textit{Eq. 2}]$$

where k is Boltzmann's constant (1.38×10^{-20} milliwatts/°K), T is the resistor temperature in degrees Kelvin and B is the noise bandwidth in Hz. At room temperature ($T = 290^{o}$ K), and over the 30-KHz noise bandwidth that is frequently used for channel noise power measurements,

$$\mathbf{P_{No}\ (dBm) = -174 + 10\ log\ (30{,}000) + G + NF = -129.2 + G + NF} \qquad [\textit{Eq. 3}]$$

With NF = 6 dB and G = 100 dB, amplifier noise output power would be -23.2 dBm over a 30-KHz bandwidth. Noise output power is the same over the same noise bandwidth in heterodyne and non-heterodyne amplifiers of the same gain and noise figure. The noise power advantage of heterodyne repeater amplifiers arises from the use of narrowband IF filters that sharply reduce system noise bandwidth.

Noise Figure of Cascaded Amplifiers

When amplifiers are cascaded, noise power rises towards the output as noise from succeeding stages is injected into the system. Under the assumption that noise powers add non-coherently, the noise figure NF_T of a cascade consisting of two stages of numerical gain A_1 and A_2 and noise factor N_1

and N_2, is given by Friis' equation:

$$\mathbf{NF_T = 10\log[N_1 + (N_2 - 1)/A_1]} \qquad [Eq.\ 4]$$

where noise factor is $N = 10^{(NF/10)}$ and numerical gain is $A = 10^{(G/10)}$. Repeated application of Equation 4 yields the noise figure of a multistage system.

System noise figure is therefore largely determined by first stage noise figure when A_1 is large enough to make $(N_2-1)/A_1$ much smaller than N_1. For example, if $A_1 = 100$ ($G_1 = 20$ dB); $A_2 = 10$ ($G_2 = 10$ dB); $N_1 = 2$ ($NF_1 = 3$ dB); and $N_2 = 10$ ($NF_2 = 10$ dB), equation 4 yields $NF_T = 3.2$ dB, whereas if A_1 were reduced to only 3 ($G_1 = 4.8$ dB), the noise figure of the cascade would become $NF_T = 7.0$ dB.

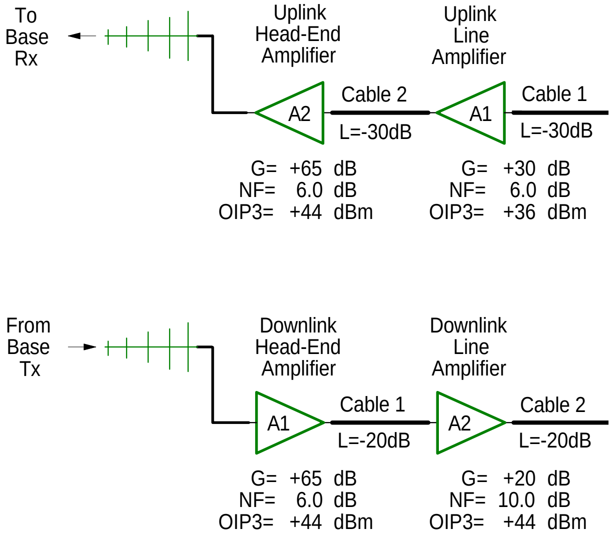


Figure 21 - Two-Stage Repeater Amplifier Cascade

It is important to apply the above formulas correctly, and to interpret results in ways that make practical sense. The total noise figure of the uplink cascade in ***Figure 21*** is $NF_T = 39$ dB, an alarmingly large number, when the loss of cable 1 is included in the calculation. Net cascade gain is +35 dB, and A_2 output noise power (measured over a 30 KHz bandwidth) is $P_{No} = -129.2 + 39 + 35 = -55.2$ dBm. Let us now compute NF_T for the cascade exclusive of cable 1 loss, and then compute P_{No} on that basis. We obtain $NF_T = 9$ dB, which is intuitively more appealing than 39 dB. However, net cascade gain is now 65 instead of 35 dB, so that $P_{No} = -55.2$ dBm as before. The 30-dB noise figure increment due to cable loss ahead of the first amplifier simply means that a larger *signal* is required at the cable input to produce a specified output signal-to-noise ratio. Seen from that viewpoint, a 39-dB noise figure is not so objectionable. In this case, either a -110.2 dBm signal at the input of A_1 or a -80.2 dBm signal at the input of cable 1 will produce an output signal-to-noise ratio of 10 dB.

In the downlink cascade in *Figure 1*, the worst-case (highest) noise level occurs at the output of downlink amplifier A_2. Cable attenuation after that point causes an equal decrease in both signal and noise power, so that no further deterioration of S/N ratio occurs. Cascade noise figure to the output of A_2 is $NF_T = 6$ dB, with a net cascade gain of +65 dB. Therefore $P_{No} = -58.2$ dBm at the output of A_2. The minimum signal power required at the input of A_1 to produce a 10-dB output signal-to-noise ratio is -113.2 dBm. Much higher input levels would be available in a well-designed practical system.

INTERMODULATION

The Importance of Intermodulation Analysis

Intermodulation is a process whereby unwanted signals are produced through the interaction of two or more wanted signals in non-linear system elements. Thousands of potential low-order intermodulation products may exist, for example, in a multiband 40-channel system. In multichannel radio sites, trouble-free operation is achieved through a combination of careful frequency planning and the use of transmitter combiners, receiver multicouplers, high-selectivity cavity filters, and separate transmit and receive antennas with ample space isolation. In repeater amplifier systems, it is often necessary to couple all receive and transmit channels into a single cable or complex signal distribution network where all transmit and receive channels coexist everywhere. Under those conditions, extreme care must be exercised in predicting potential intermodulation problems.

All multichannel repeater amplifier system designs should begin with an exhaustive intermodulation analysis. In systems where all signals flow through a single cable with bidirectional amplifiers, it is mandatory to examine all possible intermodulation products on base transmit and receive channels, and the analysis should extend to high intermodulation orders. In low-power systems with separate downlink and uplink cables and one-way amplifiers, it is generally sufficient to analyze low-order products on base transmit and receive frequencies.

Two-Carrier Intermodulation and Output Third-Order Intercept Point

A non-ideal linear amplifier with two input carriers on frequencies F_1 and F_2 generates intermodulation products on frequencies $(mF_1 \pm nF_2)$ and $(mF_2 \pm nF_1)$, where m and n are positive integers. The sum (m+n), an odd integer, defines the order of a product. Third-order intermodulation products on frequencies $(2F_1 \pm F_2)$ and $(2F_2 \pm F_1)$ have the largest magnitude and are the basis for worst-case analyses. Higher-order products, especially those on frequencies near system receive channels, must be considered in systems where multiple repeaters or base station transceivers are connected to signal distribution networks.

When the two carrier frequencies are in the same range, products of the form $(2F_1+F_2)$ and $(2F_2+F_1)$ fall completely outside the amplifier passband, on frequencies near the third harmonic of the carriers. Those products may not need to be considered in single-band systems. In multiband systems, they may interfere with radio equipment operating in another band. For example, third-order products of two transmitters operating on 150.600 and 150.900 MHz would interfere with receivers operating on 452.100 and 452.4 MHz. If the transmitters had a 1-watt output stage and transmitter intermodulation rejection were -135 dBc, the intermodulation products would appear at a level of -105 dBm, approximately 14 dB above typical receiver sensitivity. This is one of the reasons why the use of separate downlink and uplink cables is recommended in multiband repeater amplifier systems.

Output third-order intercept point (OIP_3), a linear amplifier figure of merit, establishes a relationship between P_o, the individual power of two equal carriers that generate third-order intermodulation products, and IMD, the ratio of carrier to intermodulation product power, both measured at the amplifier output. It is defined as:

$$\mathbf{OIP_3\ (dBm) = P_o + IMD/2} \qquad [\mathit{Eq.\ 5}]$$

OIP_3 can be easily measured by applying two carriers of equal power to the amplifier and observing its output with a spectrum analyzer. Carrier power P_o is normally set to a level 10 dB or more below the 1-dB compression point of the amplifier under test.

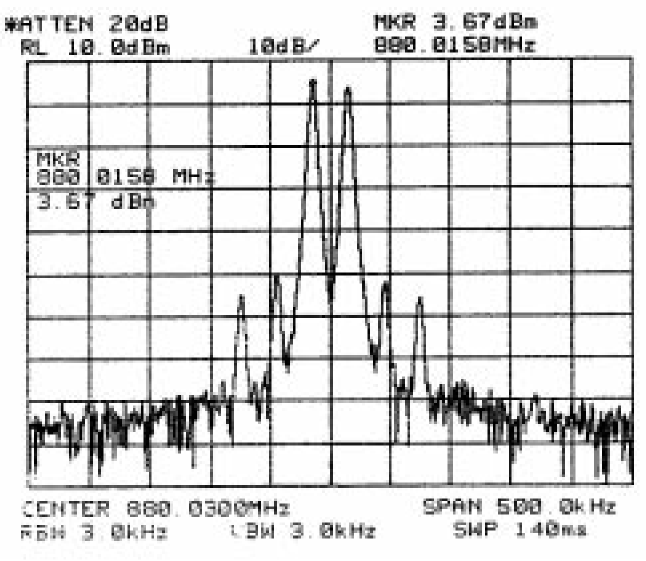


Figure 22 - Measuring OIP_3 with a Spectrum Analyzer

Figure 22 is a spectrum analyzer screen plot showing the third- and fifth-order intermodulation products on the output of a high-performance amplifier which has been driven to an output level of +33.7 dBm per carrier. Because a 30-dB power attenuator was used to put signals within the dynamic range of the spectrum analyzer, absolute signal levels are obtained by adding +30 dB to measured levels. The third-order products on either side of the two carriers are 42.5 dB below the carriers. Therefore P_O = +33.7 dBm, IMD = 42.5 dB and OIP_3 = 33.7 + 42.5/2 = +54.9 dBm.

From the above definition of OIP_3, a useful equation can be derived for IM_3, third-order intermodulation output power:

$$\mathbf{IM_3\ (dBm) = 3P_o - 2OIP_3} \qquad [\textit{Eq. 6}]$$

Equation 6 states that there is a 3:1 relationship between third-order intermodulation product power and carrier power P_o . Thus, a 1-dB change in carrier power causes a 3-dB change in intermodulation product power. Equation 6 also states that there is a 2:1 relationship between output intercept point and intermodulation product power. Thus, at a fixed output power, a 1-dB reduction of intermodulation power requires a 2-dB increase of output intercept point. Output third-order intercept point can be increased by using either higher-power amplifiers or amplifiers with feedforward or other intermodulation cancellation techniques. High-power and feedforward linear amplifiers are expensive and require larger, costly power supplies and power backup equipment. Operation at lower carrier power has tangible cost, reliability and system performance advantages.

The 3:1 relationship between carrier and third-order intermodulation power also holds for intermodulation caused by any non-linearities in cable joints, connectors, corroded cable clamps, etc. Radio site operators in the U.S. have long known that all systems eventually develop physical flaws that produce intermodulation. The repeater amplifier system designer should therefore view with suspicion any suggestions to couple high-power transmitters directly into a cable system. High-power signal sources may reduce the number of repeater amplifiers required, but the potential for increased long-term trouble is very real. For instance, operating with 100-watt transmitters (Po = +50 dBm) in a cable system with connector or hardware non-linearities will result in third-order intermodulation products 39 dB higher than those produced by 5-watt transmitters (Po = +37 dBm), because 3 x (50-37) = 39 dB.

Interestingly enough, when intermodulation problems arise in systems where transmitters and receivers are directly coupled to a cable, the very first action taken by their operators is to lower transmitter output power until the problem (hopefully!) disappears. This is not a satisfactory solution to a problem that can and should be prevented to begin with.

Third-Order Intermodulation Products in Multiple-Carrier Systems

In a system where N carriers are present on frequencies $F_1, F_2, \ldots, F_N$, two types of third-order intermodulation products need to be considered. Two-carrier products will fall on frequencies given by (2Fi±Fj), where i and j are not equal and vary from 1 to N. Their individual amplitude is given by

$$\mathbf{IM_{3(2)}\ (dBm) = 3(P_0) - 2(OIP_3)} \qquad [\textit{Eq. 7}]$$

Three-carrier products may also occur on frequencies ($F_i \pm F_j \pm F_k$), where i, j and k are not equal and vary from 1 to N. Products of this type are much more numerous than the two-carrier products described above. They occur at a level approximately 6 dB higher than 2-carrier product levels. Therefore their level can be estimated from

$$\mathbf{IM_{3(3)}\ (dBm) = (3P_o) - 2(OIP3) + 6\ dB} \qquad [\textit{Eq. 8}]$$

In multiple-carrier systems, several two- and three-carrier products may occur on the same frequency. ***Table 1*** shows the results of an intermodulation analysis for eight carriers on frequencies from 879.925 to 880.135 MHz, equally spaced at 30 KHz intervals. Even in a simple case like this, there are 224 intermodulation products. Eighteen third-order products occur on each of two of the carrier frequencies, and sixteen occur on frequencies immediately above and below the carriers.

***TABLE 1* - Estimated In-Band Third-Order Intermodulation Products**

8 Carriers, 879.925 to 880.135 MHz, Equal 30 KHz Spacing

Channel	**2-Carrier IM Products**			**3-Carrier IM Products**			**$IM_{3(2)}$** (dBm)	**$IM_{3(3)}$** (dBm)	**$IM_{3(T)}$** (dBm)	**$IM_{3(T)}$** (dBc)
	F(MHz)	n_2	10log(n_2)	F(MHz)	n_3	10log(n_3)				
	879.715	1.00	0.00	879.715			-50.00		-50.00	-70.00
	879.745	1.00	0.00	879.745	1.00	0.00	-50.00	-4400	-43.03	-63.03
	879.775	2.00	3.01	879.775	2.00	3.01	-46.99	-40.99	-40.02	-60.02
	879.805	2.00	3.01	879.805	4.00	6.02	-46.99	-37.98	-37.47	-57.47
	879.835	3.00	4.77	879.835	6.00	7.78	-45.23	-36.22	-35.7	-55.7
	879.865	3.00	4.77	879.865	9.00	9.54	-45.23	-34.46	-34.11	-54.11
	879.895	4.00	6.02	879.895	12.00	10.79	-43.98	-33.21	-32.86	-52.86
TX1	879.925	3.00	4.77	879.925	9.00	9.54	-45.23	-34.46	-34.11	-54.11
TX2	879.955	3.00	4.77	879.955	12.00	10.79	-45.23	-33.21	-32.94	-52.94
TX3	879.985	3.00	4.77	879.985	14.00	11.46	-45.23	-32.54	-32.31	-52.31
TX4	880.015	3.00	4.77	880.015	15.00	11.76	-45.23	-32.24	-32.03	**-52.03**
TX5	880.045	3.00	4.77	880.045	15.00	11.76	-45.23	-32.24	-32.03	**-52.03**
TX6	880.075	3.00	4.77	880.075	14.00	11.46	-45.23	-32.54	-32.31	-52.31
TX7	880.105	3.00	4.77	880.105	12.00	10.79	-45.23	-33.21	-32.94	-52.94
TX8	880.135	3.00	4.77	880.135	9.00	9.54	-45.23	-34.46	-34.11	-54.11
	880.165	4.00	6.02	880.165	12.00	10.79	-43.98	-33.21	-32.86	-52.86
	880.195	3.00	4.77	880.195	9.00	9.54	-45.23	-34.46	-34.11	-54.11
	880.225	3.00	4.77	880.225	6.00	7.78	-45.23	-36.22	-35.7	-55.7
	880.255	2.00	3.01	880.255	4.00	6.02	-46.99	-37.98	-37.47	-57.47
	880.285	2.00	3.01	880.285	2.00	3.01	-46.99	-40.99	-40.02	-60.02
	880.315	1.00	0.00	880.315	1.00	0.00	-50.00	-44.00	-43.03	-63.03
	880.345	1.00	0.00	880.345			-50.00		-50.00	-70.00
	Total:	56		**Total**:	168					

OIP3 = +55.0 dBm	N = 8 carriers	Po(max) = + 22.8 dBm (EIA)	Po= + 20.0 dBm

Estimating Third-Order Intermodulation Product Levels

The total power of intermodulation products on one frequency can be estimated by treating them as non-coherent signals and adding their power. Total power is then approximately nP, where P is the power of a single intermodulation product and n is the number of products on a specified frequency. Under the additional assumption that the power contribution of higher-order products is negligible relative to third-order product levels, total third-order product power can be estimated as

$$\mathbf{IM_{3(2)}\ (dBm) = 3(P_0) - 2(OIP_3) + 10\ log\ n_2} \qquad [Eq.\ 9]$$

for two-carrier products, and

$$\mathbf{IM_{3(3)}\ (dBm) = 3P_o - 2OIP_3 + 6\ dB + 10\ log\ n_3} \qquad [Eq.\ 10]$$

for three-carrier products. n_2 and n_3 are the number of two- and three-carrier products on one particular frequency. To compute total intermodulation power on one frequency, $IM_{3(2)}$ and $IM_{3(3)}$ are first converted to milliwatts and added together, and the sum is then converted back to dBm. In other words,

$$\mathbf{IM_{3(TOTAL)}\ (dBm) = 10\ log\ \{10^{[IM3(2)/10]} + 10^{[IM3(3)/10]}\}} \qquad [Eq.\ 11]$$

To verify the above method, eight carriers on the frequencies listed in ***Table 1*** were applied to a high-performance linear amplifier. Carrier level was adjusted to +20 dBm per carrier at the amplifier output, and output intermodulation product levels were measured. Amplifier OIP_3 = +55 dBm were verified by measurement as explained on page 21. ***Figure 23*** is a spectrum analyzer screen plot showing eight +20 dBm carriers at the output of the amplifier, with a worst-case intermodulation product at approximately -54 dBc on 880.165 MHz.

The intermodulation analysis indicates that there are four two-carrier and twelve three-carrier products at 860.165 MHz. With OIP_3 = +55 dBm, P_o = +20 dBm, n_2 = 4 and n_3 = 12, equations 9, 10 and 11 predict the following intermodulation levels:

$IM_{3(2)} = 3(20) - 2(55) + 10\log(4) = -44.0$ dBm
$IM_{3(3)} = 3(20) - 2(55) + 6 + 10\log(12) = -33.2$ dBm
$IM_{3(TOTAL)} = 10\log\{10(-44/10) + 10(-33.2/10)\} = 10\log(0.00051841) = -32.8$ dBm
$IMD = P_o - IM_{3(TOTAL)} = +20 - (-32.8) = 52.8$ dBc.

The prediction is therefore slightly on the pessimistic side of the measurements in ***Figure 23***. Even with this high-performance amplifier, operation at +20 dBm per carrier would result in intermodulation levels not in compliance with the -36 dBm CEPT rule. Compliance would be assured by lowering carrier power by (-36+32.8)/3 = -1.07 dB. +18 dBm per carrier would be a safe operating level.

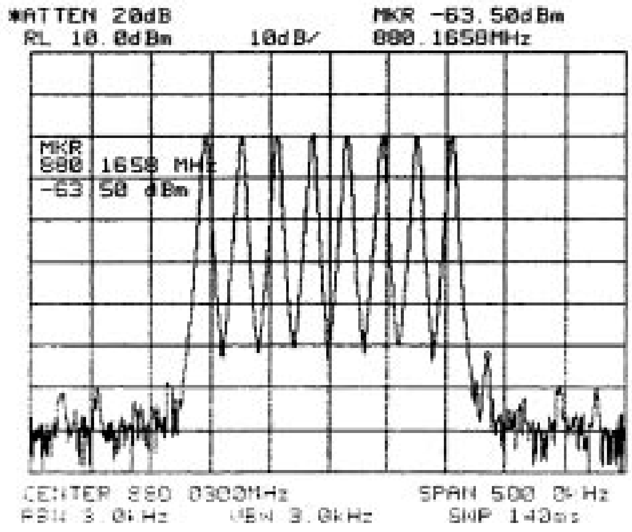


Figure 23 - Eight- Carrier Output Intermodulation Products

Equally-spaced carriers cause the worst accumulation of in-band, third-order intermodulation products. If conditions permit, unevenly-spaced frequencies should be chosen for operation with repeater amplifiers.

Intermodulation in Cascaded Amplifier Systems

In cascaded amplifier systems, another complication arises from the fact that each amplifier in the chain sees an input consisting of wanted signals plus intermodulation products from previous stages. In the worst case, products generated in each amplifier add coherently with amplified products of previous amplifiers, thereby causing a gradual rise of intermodulation levels towards the system output.

In systems consisting of cascaded stages of different gain and output intercept point, a practical way to estimate intermodulation levels is to compute the OIP_3 for the entire system, based on the worst-case assumption of coherent addition of intermodulation product power at each stage. In a system consisting of two cascaded stages of gain G_1 and G_2 dB, with output intercept points $OIP_{3(1)}$ and $OIP_{3(2)}$, overall output intercept point $OIP_{3(T)}$ is given by

$$\mathbf{OIP_{3(T)}\ (dBm) = -10\ \log\{1/[10^{[OIP3(1)\ +\ G2]/10}] + 1/[10^{OIP3(2)/10}]\}} \qquad [\mathit{Eq.\ 12}]$$

Repeated application of equation 12 will yield the output intercept point of a multiple-stage system. Total intermodulation product levels can then be estimated on the basis of $OIP_{3(T)}$ for the amplifier chain, with corrections for multiple carriers in accordance with the methods described above. This approach has the advantage of taking into consideration the effect of all system losses, gains and intercept points.

Consider again the amplifier system in ***Figure 21*** on page 20. Downlink cascade OIP_3 is +41 dBm, 3 dB less that the OIP_3 of the individual stages. In this case, two stages of equal OIP_3 operate at the same output power and contribute equal amounts of intermodulation power at the system output. The underlying assumption in the calculation is that intermodulation powers add in phase, causing a

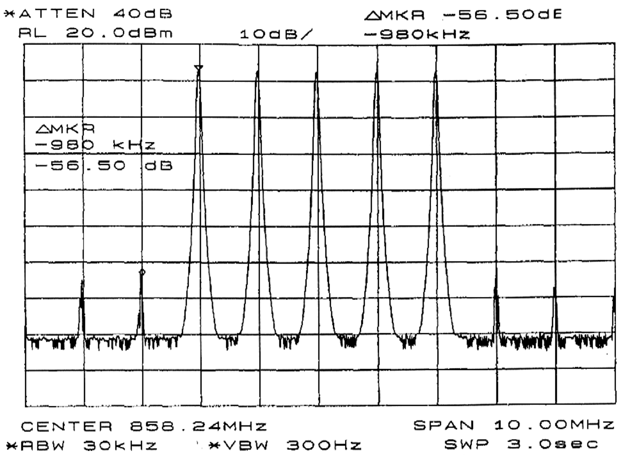


Figure 24 - Intermodulation Products in a Single Amplifier

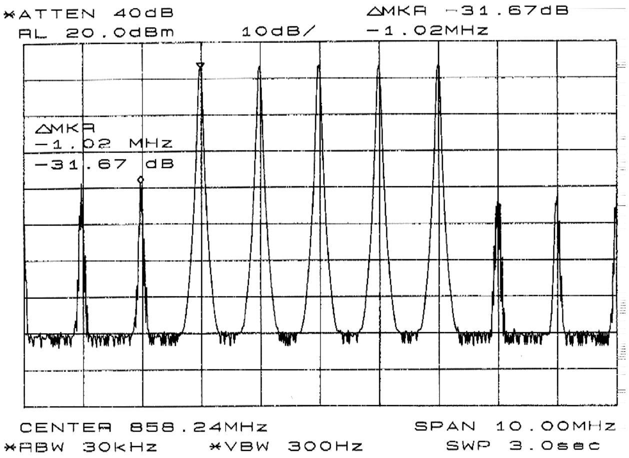


Figure 25 - Intermodulation Products in a Thirteen-Amplifier Cascade

6-dB increase in intermodulation power, which translates into a 3-dB reduction in cascade output intercept point. In the uplink branch, the head-end amplifier is at the end of the cascade. The aggregate OIP_3 is +44 dBm. In this case, the high-gain stage at the end of the cascade causes the amplitude of intermodulation products from that stage to be much larger than products from previ-ous stages. The intercept point of the last stage therefore "dominates" the intercept point of the chain. It can be easily verified that increasing the OIP_3 of A_1 from +36 to +44 dBm has no effect on system intermodulation performance.

Figure 24 shows the output of an 800-MHz amplifier consisting of three low-level and two high-level linear stages. At +12.5 dBm per carrier, worst-case intermodulation is 56.5 dBc with 5 carriers. ***Figure 25*** shows the result of cascading thirteen amplifiers and attenuators to simulate a long tunnel system. Amplifier gain was set to 47 ± 3 dB, just enough to offset the loss between stages. At the same power per carrier as in **Figure 24**, intermodulation power rises to 31.7 dBc, an 24.8-dB increase relative to the single-amplifier case.

Regulatory Carrier-to-Intermodulation Limits

In the United States, FCC regulations stipulate that spurious power must be (43+10log P) dB below P, the maximum authorized output power per carrier. Stated in another way, spurious power must not exceed -13 dBm regardless of carrier power. Proposed EIA standard No. PN 2009 provides a formula for calculating the maximum authorized power per carrier that meets the -13 dBm criterion, as a function of amplifier output intercept point OIP_3 and number of carriers N:

$$\mathbf{P_c(max) = (2/3)[OIP + 0.409 - 24.75\,\log_{10}N + 1.437\,(\log_{10}N)^2]\ dBm} \quad \textit{[Eq. 13]}$$

where **OIP = Third Order Output Intercept Point of the Booster, Expressed in dBm, as Type Accepted for the Particular Linear Amplification Path for the Channel's Spectrum (i.e. base Tx or mobile Tx).**

N = Number of Authorized Signals for the Particular Spectrum (all signals having equal power)

It is convenient to lump together the terms after OIP_3 in equation 13, to obtain

$$\mathbf{P_c(max) = (2/3)OIP_3 + (2/3)C,} \quad \textit{[Eq. 14]}$$

$$\textit{where}\ \mathbf{C = 0.409 - 24.75\,\log_{10}N + 1.437\,(\log_{10}N)^2}$$

The simplified formula simply states that, in order to meet FCC specifications, an amplifier must operate at an output power no higher than two thirds of the output intercept point in dBm, minus a

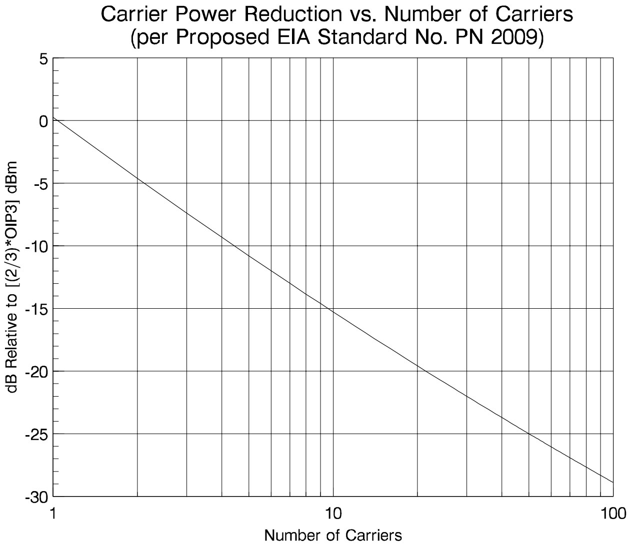


Figure 26

margin that is a function of **N**, the number of carriers. ***Figure 2*6**, a plot of the function **C** vs. **N**, the number of carriers, makes it easier to visualize the substantial power reduction required to operate within regulatory limits as the number of carriers increases. ***Figure 26*** indicates that, for operation with two carriers, power per carrier should be -4.6 dB relative to (2/3)OIP$_3$. If OIP$_3$ is +48 dBm, maximum output power per carrier is (2/3)(48)-4.6 = +27.4 dBm. If the number of carriers is increased to 10, maximum power per carrier becomes (2/3)(48)-15.5 = +16.5 dBm.

CEPT standards impose a more stringent limit of -36 dBm on spurious power. Because of the 3:1 relationship between carrier and third-order intermodulation product power, this implies that repeater amplifier systems of a specified OIP$_3$ should be operated in CEPT countries at carrier levels (23/3) = 7.67 dB lower than those allowed by U.S. standards. Alternatively, amplifier OIP$_3$ would have to be (23/2) = +11.5 dB higher to meet CEPT standards at the same carrier levels allowed by U.S. standards. Some PTTs (Postal, Telephone and Telecommunication authorities) have already opted for establishing equipment standards based on high output intercept points in the +50 to +55 dBm range, which may require the use of expensive high-power or feedforward linear amplifiers regardless of the application. With care, however, it is possible to design well-behaved, reliable repeater amplifier systems that operate at lower power levels and do not require esoteric amplifiers.

AMPLIFIER DYNAMIC RANGE

The *two-tone dynamic range* is a useful figure of merit that facilitates the comparison of two amplifers, on the basis of easily measurable parameters. It is defined as

$$\mathbf{DR = 2/3\ (OIP_3 - MDS)} \quad \text{[Eq. 13]}$$

where MDS is the minimum detectable output signal level, that is, the level of a signal equal to the amplifier output noise floor given by equation 3 on page 20. Dynamic range is simply the difference, in dB, between the minimum detectable signal and the level of two equal signals that produce a third-order intermodulation product of the same level as the MDS.

Substituting equation 3 into equation 13,

$$\mathbf{DR = 2/3\ (OIP_3 + 129.2 - G - NF)} \quad \text{[Eq. 14]}$$

over a noise bandwidth of 30 KHz. Equation 14 indicates that dynamic range is a function of amplifier OIP$_3$, decreasing amplifier gain, noise figure and noise bandwidth. For example, the dynamic range of an amplifier that has a noise figure of 10 dB, a gain of 55 dB and a third-order output intercept point of +44 dBm is

$$DR = 2/3\ (44 + 129.2 - 55 - 10) = 72.1 \text{ dB}$$

If the gain of this amplifier were reduced to only 24 dB, its dynamic range would increase by 20.7 dB to 92.8 dB. In practice, other criteria may define maximum and minimum system signal levels. For example, good design practice requires that minimum signal levels should be at least 10 dB above the MDS, and maximum signal levels are either set by regulatory considerations, or limited to levels below the squelch sensitivity of system receivers.

PART IV - REPEATER AMPLIFIER SYSTEM ARCHITECTURE

The Repeater Amplifier System Design Process

The primary objective of the repeater amplifier system design process is to provide RF signals to all receivers in the specified coverage area, at levels that satisfy communication reliability, noise and spurious suppression requirements. Simulcast paging, data transmission, spread-spectrum, TDMA and CDMA systems impose additional time-domain requirements, usually expressed in terms of time and group delay limits within a specified passband. Each repeater amplifier system must be configured in accordance with those system design objectives.

As in all radio system engineering work, repeater amplifier system design is an iterative process. It should begin with a complete description of the radio service in which the repeater amplifier system is intended to operate. As a minimum, the following must be specified:

- Type of service (conventional two-way radio, trunking radio, paging, etc.)
- Nature of the application (mining, government installation, shopping center, etc.)
- Radio to repeater amplifier system interface (air interface with external base/repeater via antennas, or local radio base station with repeater amplifiers)
- System frequency plan (individual channel transmit and receive frequencies)
- Base, mobile and portable radio equipment specifications: transmitter power, receiver sensitivity, receiving and transmitting antenna gain, feedline losses, transmitter combiner loss, receiver multicoupler gain, etc.)
- If the system operates with a remote base or repeater, measured propagation loss between sites and fading margin (a firm system design can only be based on accurately measured signal levels at key locations)
- Minimum required signal levels at base, mobile and/or portable receivers

Each of the listed specifications is essential to the design process. Differences between estimated and actual specifications can be expected to cause significant changes in equipment configuration, performance and price.

A detailed description is also needed of the area in which radio coverage is to be provided by the repeater amplifier system. This should include, as a minimum:

- Detailed drawings of the area
- The results of a physical survey indicating how cable can be routed and where equipment and antennas can be installed
- System performance objectives

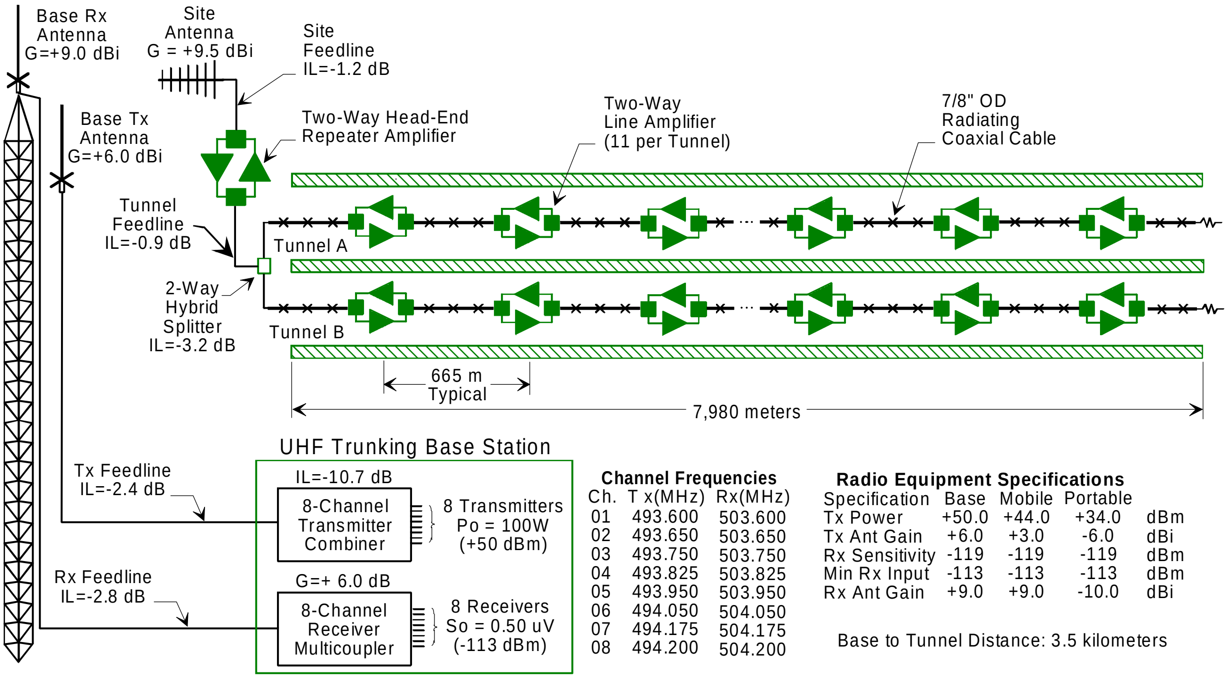
General statements, such as "the system shall provide a 95% probability of two-way voice communication in 95% of the coverage area", or "the bit error rate at 9600 baud shall not be greater than 1×10^{-6} anywhere in the coverage area", should be preferably translated into minimum receiver input levels at specified worst-case locations. Unrealistic or impractical system design objectives should be avoided. Specifications such as "The system shall provide 95% reliability at 95% of the locations, with the user's body in a prone position and completely covering the handheld radio and antenna" impose system power and gain requirements beyond the limits of feasibility. Reasonable alternatives should be considered, such as equipping portable radios with a microphone/antenna accessory to be worn at shoulder level.

With those facts on hand, a tentative system design is laid out and preliminary calculations are made to verify worst-case signal, intermodulation and noise levels. The preliminary analysis usually leads to design change recommendations (for example, change one transmitter frequency to eliminate a problematic low-order intermodulation product). Design adjustments are made and the process is repeated until a design is achieved that satisfies all operating requirements.

System Design Example: A Tunnel System

System Specification

Figure 27 provides a summary description of a UHF communication system for a 7,980-meter vehicular tunnel. The repeater amplifier system is required to provide radio communication inside two separate vehicular tunnel branches, at the minimum levels specified in the drawing. The system is to operate with an existing eight-channel trunking repeater station located 3.5 kilometers from the nearest tunnel entrance. Spurious products must meet FCC specifications everywhere in the system.



Channel Frequencies

Ch.	T x(MHz)	Rx(MHz)
01	493.600	503.600
02	493.650	503.650
03	493.750	503.750
04	493.825	503.825
05	493.950	503.950
06	494.050	504.050
07	494.175	504.175
08	494.200	504.200

Radio Equipment Specifications

Specification	Base	Mobile	Portable	
Tx Power	+50.0	+44.0	+34.0	dBm
Tx Ant Gain	+6.0	+3.0	-6.0	dBi
Rx Sensitivity	-119	-119	-119	dBm
Min Rx Input	-113	-113	-113	dBm
Rx Ant Gain	+9.0	+9.0	-10.0	dBi

Base to Tunnel Distance: 3.5 kilometers

Figure 27 - Vehicular Tunnel Repeater Amplifier System Design

In order to specify repeater amplifier equipment for an application, the following questions must be answered:

1. What input signal levels are available at both branches of the head-end repeater amplifier?
2. How much head-end amplifier gain is required to boost base and portable transmit signals to a level that satisfies minimum receiver input requirements?
3. What filter configuration provides the isolation required by head-end amplifier gain requirements?
4. What type of radiating coaxial cable should be used?
5. How far apart should the line amplifiers be installed along the tunnels?
6. How many line amplifiers are required?
7. At what gain should the line amplifiers be operated?
8. What is the minimum amplifier output third-order intercept point that meets system intermodulation level objectives?

Intermodulation Analysis Results

The specified base transmit frequencies do not produce intermodulation products of the thirty-first or lower order on any of the base receive frequencies. There are a total of 224 third-order, two- and three-carrier intermodulation products ±2 MHz from 493.900 MHz. Because of the uneven frequency spacing between channels, the number of two- and three-carrier products on any frequency is

TX RX SYSTEMS INC.
TUNNEL/BUILDING SYSTEM WITH HEAD-END AND SIGNAL DISTRIBUTION AMPLIFIERS

Customer:	Seminar Subjects - Repeater Amplifiers and Applications	**Prepared by:**	Ernesto A. Alcivar
Application:	UHF System for Dual Vehicular Tunnel	**Date:**	October 19, 1994
Design Conditions:	Head-end amp & first line amplifier; portable at far end of second 2,182' cable segment (worst-case low levels).		

TALK-OUT (DOWNLINK) PATH	8.00	Carriers		
1. Base Tx Frequency (F1)	493.600	MHz		
2. Base Tx Power	100.00	W		
3. Portable/Mobile Rx Sensitivity	-119.00	dBm		
BASE TO HEAD-END DOWNLINK AMPLIFIER				
4. Base Tx Power	+50.00	dBm		
5. Base Tx Combiner/Filter Loss	-10.70	dB		
6. Base Tx Feedline Loss	-2.40	dB		
7. Base Tx Antenna Gain	+6.00	dBi		
8. Base->Site Free-Space Loss	**-97.21**	dB @	3.50	Km
9. Shadow and Other Path Losses	-10.00	dB		
10. Site Antenna Gain	+9.50	dBi		
11. Site Feedline Loss	-1.20	dB		
12 Other Loss		dB		
13. Total Base -> Downlink Amp Loss	**-106.01**	dB		
14. Head-End Amplifier Input Power	**-56.01**	dBm		
15. Head-End Downlink Gain	+65.00	dB		
16. Head-End Downlink Output Power	**+8.99**	dBm		
17. Downlink Head-End Amp OIP3	+44.00	dBm		
18. Maximum Allowable Power per Carrier	**+15.50**	dBm		
Carrier Power Below Maximum by	**-6.51**	dB		
HEAD-END TO DOWNLINK DISTRIBUTION AMPLIFIER				
17. Cable Loss	-25.90	dB		
18. 2-Way Hybrid Splitter Insertion Loss	-3.20	dB		
19. Total Head-End -> Distribution Amp Loss	**-29.10**	dB		
20. Distribution Amplifier Input Power	**-20.11**	dBm		
21. Distribution Amplifier Gain	+29.00	dB		
22. Distribution Amplifier Output Power	**+8.89**	dBm		
23. Downlink Distribution Amp OIP3	+44.00	dBm		
24. Maximum Allowable Power per Carrier	**+15.50**	dBm		
Carrier Power Below Maximum by	**-6.61**	dB		
DOWNLINK DISTRIBUTION AMPLIFIER TO PORTABLE				
25. Other Loss		dB		
26. Signal Distribution Cable Type:	7/8" OD	L:	665.00	m
27. Cable Transmission Loss	-23.99	dB		
28. Cable Coupling Loss	-63.00	dB @	20.00	ft
29. Inside Antenna Decoupler Loss		dB		
30. Inside Antenna Gain		dBi		
31. Space Loss to Inside Antenna @ F1		dB @		
32. Design Margin	-15.00	dB		
33. Portable/Mobile Antenna Gain (Rx)	-10.00	dBi		
34. Inward -> Mobile/Portable Loss	**-111.99**	dB		
35. Portable/Mobile Rx Input	**-103.10**	dBm		
36. Portable/Mobile Rx Sensitivity	-119.00	dBm		
37. Signal Margin at Mobile/Portable Rx	**+15.90**	dB		

TALK-BACK (UPLINK) PATH		
38. Portable Tx Frequency (F2)	503.600	MHz
39. Portable/Mobile Tx Power	2.50	W
40. Base Rx Sensitivity	-119.00	dBm
PORTABLE TO UPLINK DISTRIBUTION AMPLIFIER		
41. Portable Tx Power	+34.00	dBm
42. Portable Antenna Gain (Tx)	-6.00	dBi
43. Space Loss to Inside Antenna @ F2		dB
30. Inside Antenna Gain		dBi
29. Inside Antenna Decoupler Loss		dB
44. Cable Coupling Loss @ F2	-63.00	dB
45. Cable Transmission Loss @ F2	-23.99	dB
25. Other Loss		dB
32. Design Margin	-15.00	dB
46. Portable -> Uplink Distribution Amp Loss	**-107.99**	dB
47. Uplink Distribution Amp Input Power	**-73.99**	dBm
48. Uplink Distribution Amp Gain	+29.00	dB
49. Uplink Distribution Amp Output Power	**-44.99**	dBm
50. Uplink Distribution Amp OIP3	+44.00	dBm
51. Maximum Allowable Power per Carrier	**+15.50**	dBm
Carrier Power Below Maximum by	**-60.49**	dB
DISTRIBUTION AMP TO HEAD-END UPLINK AMPLIFIER		
18. 2-Way Hybrid Splitter Insertion Loss	-3.20	dB
17. Cable Loss	-25.90	dB
19. Total Head-End -> Distribution Amp Loss	**-29.10**	dB
52. Uplink Head-End Amplifier Input Power	**-74.09**	dBm
53. Uplink Head-End Amplifier Gain	+57.00	dB
54. Uplink Head-End Amp Output Power	**-17.09**	
55. Uplink Head-End Amp OIP3	+44.00	dBm
56. Maximum Allowable Power per Carrier	**+15.50**	dBm
Carrier Power Below Maximum by	**-32.59**	dB
HEAD-END UPLINK AMPLIFIER TO BASE		
57. Other Loss		dB
11. Site Feedline Loss	-1.20	dB
10. Site Antenna Gain	+9.50	dBi
9. Shadow and Other Path Losses	-10.00	dB
58. Site -> Base Free-Space Loss @ F2	**-97.38**	dB
55. Base Rx Antenna Gain	+9.00	dBi
56. Base Rx Feedline Loss	-2.80	dB
57. Base Rx Multicoupler/Filter Loss	+6.00	dB
58. Total Uplink Head-End -> Base Loss	**-86.88**	dB
59. Base Receiver Input Power	**-103.97**	dBm
60 Base Rx Sensitivity	-119.00	dBm
61. Signal Margin at Base Rx	**+15.03**	dB

REMARKS:

2. F1, F2 specify frequency range for purposes of cable attenuation and coupling loss ONLY.
3. Distances, losses and margins arbitrarily adjusted to match measured data provided by customer.

relatively small (3 and 6). The worst-case on-channel intermodulation product accumulation occurs on TX5 (493.950 MHz), where 3 three-carrier products appear. The worst-case off-channel accumulation occurs on 493.900 MHz, where 3 two-carrier and 4 three-carrier products appear. Intermodulation level calculations are based on those worst cases.

System Layout

Good design practice requires that no more than 24 to 30 dB of loss be allowed between repeater amplifiers on a cable system. This rule of thumb results in low power, intermodulation and noise levels. The rule influences the choice of radiating coaxial cable and the number of repeater amplifiers required. Small-diameter cable is less expensive, but its higher loss decreases the maximum allowable length for 24 dB loss, and this in turn requires a larger number of amplifiers. Large-diameter radiating coaxial cable is very expensive, but it allows the use of longer cable segments and reduces the number of amplifiers. Depending on the price of the specific cable and repeater amplifiers under consideration, a cable/amplifier cost analysis generally favors the use of more amplifiers with smaller-diameter cable. Where maximum performance in a concern, as in multichannel systems, the use of larger diameter cable should be favored.

In this case in particular, 7/8"-diameter cable is an optimal choice for operation in the 493-504 MHz frequency range. 665 meters of cable have a longitudinal transmission loss of approximately 24 dB. The 7,980-meter tunnel could therefore be covered by twelve 665-meter cable segments and eleven two-way line amplifiers to compensate for cable losses.

Approval of a design recommendation of this kind normally depends on the availability of physical space and electrical power in the tunnels. The need to install repeater amplifiers in cross-passages or equipment rooms makes it necessary to modify cable lengths and losses accordingly.

Head-End and Line Amplifier Gain Calculation

Page 29 is a printout of one of TX RX Systems' worksheets for repeater amplifier system design calculations. It provides a detailed list of estimated signal levels at key points in the system. Line 9 on both columns (Shadow and Other Path Losses) has been arbitrarily adjusted to match the measured signal levels reported by the customer. Other parameters are in accordance with the specifications in ***Figure 27***.

The calculation indicates that head-end downlink amplifier gain should be +65 dB to produce worst-case signal margins of +15.9 dB at a portable receiver at the far end of a cable segment. Because of more favorable antenna gain conditions, an uplink amplifier gain of +57 dB produces a similar margin at the base station receiver, with a portable transmitter at the far end of a cable segment. The resulting amplifier output levels would satisfy FCC standards.

Calculations were also made of maximum signal levels under the following conditions:

1. Portable 1 meter away from the near end of a cable segment
2. Mobile 3.3 meters away from near end of a cable segment

Case 2 results in maximum uplink amplifier levels that are above the limits suggested by EIA PN2009. The use of output level control is therefore indicated in both the uplink and downlink branches of the head-end amplifier.

Cascaded Amplifier Performance Calculations

The downlink amplifier chain consists of the head-end amplifier (G=+65 dB, NF=+8.0 dB, OIP_3=+44 dBm), 12 cable segments and 11 low-gain line amplifiers (NF=8.0 dB, OIP_3 = +44.0 dBm). Each cable segment has an insertion loss of -24 dB, except the first, where hybrid splitter and other losses increase total loss to -29.1 dB. The gain of each line amplifier is numerically equal to the cable loss preceding it. The uplink chain is the same as the downlink chain, but in reverse order.

The OIP_3 of the complete downlink chain +33.2 dBm. If the OLC of the head-end downlink amplifier were set to +9.0 dBm, the level required for satisfactory operation with portables in the tunnels,

TABLE 2 -ESTIMATED IN-BAND THIRD-ORDER INTERMODULATION PRODUCTS
11-Amplifier Cascade, Downlink

	2-Carrier IM Products			**3-Carrier IM Products**			$IM_{3(2)}$	$IM_{3(3)}$	$\mathbf{IM_{3(T)}}$	$\mathbf{IM_{3(T)}}$
Channel	F(MHz)	n_2	$10\log(n_2)$	F(MHz)	n_3	$10\log(n_3)$	(dBm)	(dBm)	(dBm)	(dBc)
TX1	**493.600**	1	0.00	**493.600**	2	3.01	-39.40	-30.39	**-29.88**	**-38.88**
TX2	**493.650**			**493.650**	1	0.00		-33.40	**-33.40**	**-42.40**
TX3	**493.750**			**493.750**	2	3.01		-30.39	**-30.39**	**-39.39**
TX4	**493.825**			**493.825**	3	4.77		-28.63	**-28.63**	**-37.63**
Worst Case	**493.900**	3	4.77	**493.900**	4	6.02	-34.63	-27.38	**-26.63**	**-35.63**
TX5	**493.950**			**493.950**	3	4.77		-28.63	**-28.63**	**-37.63**
TX6	**494.050**			**494.050**	3	4.77		-28.63	**-28.63**	**-37.63**
TX7	**494.175**			**494.175**	2	3.01		-30.39	**-30.39**	**-39.39**
TX8	**494.200**			**494.200**	1	0.00		-33.40	**-33.40**	**-42.40**
Conditions:	OIP_3 = + 33.2 dBm			N = 8 Carriers		P(max)=+8.3 dBm		P_O = +9.0 dBm		

Table 2 shows that regulatory intermodulation criteria would be easily met.

The OIP_3 for the uplink amplifier chain is +44.0 dBm. Amplifier output levels in this branch could be set to a maximum of 0 dBm, resulting in intermodulation levels at least 32 dB lower than downlink levels. This is desirable to operate at externally radiated spurious levels that satisfy FCC requirements by a wide margin.

Noise figure is 8.0 dB and 18.8 dB for the downlink and uplink chains. Output noise power, calculated over a 30-KHz noise bandwidth, is -56.3 dBm for the downlink and -43.7 dBm for the uplink chain. At the specified carrier levels, signal-to-noise ratio would be +43.7 dB for the uplink branch and +65.3 dB for the downlink branch. Both satisfy regulatory and design requirements.

Output filters in all repeater amplifiers provide a significant amount of broadband noise and intermodulation product attenuation. Noise and spurious attenuation of at least 40 dB can be expected at frequencies as close as 1 MHz from the system band edges.

Repeater Amplifier Configuration

With the information available at this point in the design process, it is possible to select "catalog" equipment for the application, or to design entirely new head-end and line amplifiers.

For the relatively narrow pass bandwidth required in this system, a configuration similar to Model 61-68-03-OLC in ***Figure 5*** would be satisfactory, with filters of the type shown in ***Figure 6.*** Because of the lower gain required, the line amplifiers would have fewer amplifier stages and could operate with four-section, 2-inch filters only.

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