NTIA Technical Report TR-11-480

In-Building Radio Enhancement Systems for Public Safety

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report series

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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ACRONYMS

AGC	Automatic gain control
BDA	Bi-directional amplifier
BTS	Base transceiver station
CIU	Cable interface unit
COAX	Coaxial cable
DAQ	Delivered audio quality
dB	Decibel
dBd	Decibels relative to a dipole antenna
dBi	Decibels relative to an isotropic antenna
dBm	Decibels relative to a milliwatt
IBRES	In building radio enhancement system
ICC	International Code Council
INR	Interference to noise power ratio
FCC	Federal Communications Commission
FLM	Frequency loop margin
FO	Fiber optic cable
FOI	Fiber optic interface
MGC	Manual gain control
NFPA	National Fire Protection Association
NPSAC	National Public Safety Radio Advisory Committee
NPSTC	National Public Safety Telecommunications Council
P25	Project 25
SNR	Signal to noise power ratio
TP	Twisted pair cable

EXECUTIVE SUMMARY

The purpose of public safety radio is to provide reliable communications over a jurisdiction. Industry standards recommend that 97 percent of a jurisdiction area have radio coverage. Unfortunately, because of building attenuation, this availability ends once public safety professionals enter buildings within the jurisdiction where a significant amount of their work lies.

Building attenuation varies widely with the variety of construction materials, how the materials are used architecturally, the location of the building, type of building, and position within the building. It is particularly high in the lower floors of buildings in urban areas.

A number of approaches have been used to overcome building attenuation such as reducing repeater coverage areas, enabling portable radios to bypass the repeater and talk directly to each other, and using mobile repeaters. However, the most reliable approach is to use an in-building radio enhancement system (IBRES).

IBRESs circumvent building attenuation by guiding the signal between indoor and outdoor antennas over a robustly designed distribution network. Loss of radio coverage is virtually eliminated by the judicious placement of the indoor antennas. These systems are typically designed to provide coverage greater than 90 percent in most areas of the building and 95 percent in critical areas such as lobbies, stairs, and elevators.

The technology used in today's IBRESs has been developed over a long period of time. Considerable strides in its development were made in the 1950s for communications in mining and transportation tunnels and again in the 1980s for the burgeoning cellular phone industry. A renewed interest has developed in the past decade for the continued expansion of the cellular phone industry, proliferation of wireless local area networks, and our Nation's resolve to provide public safety professionals with the best possible radio systems.

Although this is a mature technology, it is not without problems. Firefighters have noted that IBRESs are vulnerable to both fire and fire-fighting operations. IBRES designers are confronted with a difficult and often unpredictable in-building radio wave propagation environment. Building owners would like to reduce installation and maintenance costs. In addition, the bi-directional amplifier (BDA) used in the IBRES to overcome losses in the radio wave propagation paths and distribution network can create a number of problems if not used properly. Most notably, it can cause radio interference by introducing intermodulation, feedback, noise, and delay.

This report is intended to be used by public safety professionals tasked with assisting building owners to fulfill IBRES requirements mandated by their jurisdiction. The information used in writing this report was collected through interviews with public safety professionals, designers, installers, and equipment manufacturers. The report has two sections. The first section describes current IBRES technology and the second section discusses the problems described above and common methods that mitigate them.

Appendices provide building attenuation tables, radio-wave propagation theory, link budget calculations, and BDA measurements necessary to understand results cited in the main body of the report. The link budget calculations demonstrate the utility of the IBRES by comparing received power in buildings with and without an IBRES against the power required for reliable operation. They also show how noise transmitted by an IBRES can desensitize another system's repeater several hundred meters away. The BDA measurements show spectrum of a BDA experiencing feedback. Sufficient detail is provided to allow the reader to replicate the measurements using ordinary radio laboratory equipment.

IN BUILDING RADIO ENHANCEMENT SYSTEMS FOR PUBLIC SAFETY

Robert J. Achatz, Roger A. Dalke, and John J. Lemmon

Reliable public safety communications between system repeaters outside a building and portable radios inside a building is often not possible due to building attenuation. To circumvent this problem, increasing numbers of municipalities are requiring building owners to provide in-building radio enhancement systems (IBRESs) for public safety communications. This report is intended to be used by public safety communications professionals who are tasked with assisting building owners to fulfill this requirement. The main body describes IBRES technology, problems endemic to it, and solutions to these problems. Appendices provide detailed data tables, theory, calculations, and measurements that support assertions made in the main body.

Keywords: Bi-directional amplifiers; building attenuation; distributed antenna system; in-building radio enhancement system; land mobile radio; link budget; public safety radio; radio-wave propagation

1 INTRODUCTION

The purpose of public safety radio is to provide reliable communications over a jurisdiction. Industry standards recommend that 97 percent of a jurisdiction area have radio coverage [1]. Unfortunately, because of building attenuation, this availability ends once public safety professionals enter buildings within the jurisdiction, where a significant amount of their work lies.

Understanding building attenuation begins by studying how construction materials attenuate the radio signal. As shown in Figure 1, construction material attenuation decreases the power of a signal each time it passes through a wall. The magnitude of this attenuation depends on the frequency of the radio wave, the type of material, and the angle of incidence. Construction material attenuation has been comprehensively evaluated by the National Institute of Standards and Technology (NIST) through laboratory measurements [2] and [3]. These measurements show that at 800 MHz, a commonly used public safety frequency, a radio wave striking a concrete wall “head on” (i.e., at a 0-degree angle of incidence) can be attenuated by up to 30 dB (i.e. to 0.1 percent of its initial power). Examples for other materials are provided in Appendix A. Increasing the angle of incidence attenuates the signal even more. For example, a radio wave striking the same wall at a 70-degree angle of incidence is attenuated by 40 dB (i.e. to 0.01 percent of its initial power) [4].

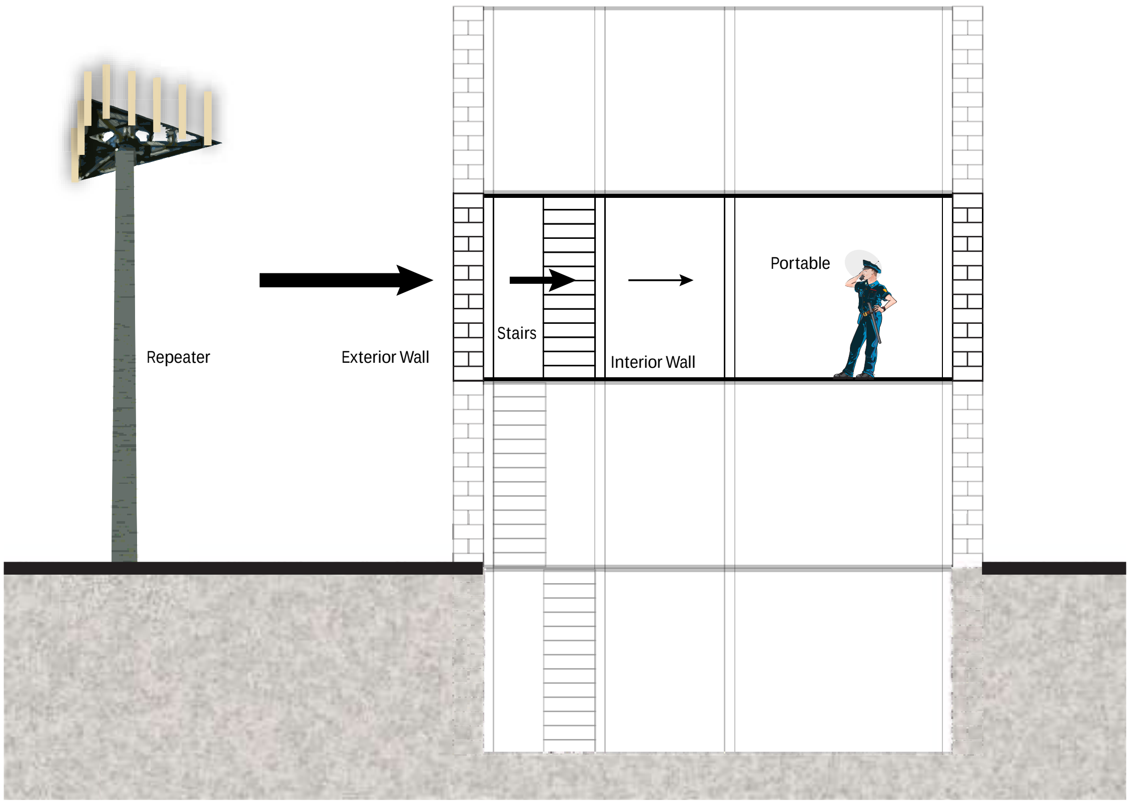

Figure 1. Signal transmission into building is represented as arrows. Narrowing arrow widths correspond to diminishing signal power caused by construction material attenuation.

But building attenuation, the ratio of the signal power inside the building to the signal power outside the building, is more complex than the construction material attenuation described above. The building's surroundings, the variety of materials, and how they are used architecturally contribute to the complexity of building attenuation. This complexity causes building attenuation to vary widely with building location (i.e., urban or suburban), building type (i.e., office or warehouse), and position within the building. Radio system engineers address this variability by characterizing building attenuation statistically in terms of its mean and standard deviation [5], [6].

We now consider some common approaches public safety organizations use to overcome building attenuation [7]. For the purposes of this discussion, the public safety radio system signal is assumed to originate from a simulcast radio repeater system that operates in the 800 MHz National Public Safety Advisory Committee (NPSAC) band with full-duplex, narrow-bandwidth signals. With simulcast systems, repeaters strategically located throughout the metropolitan area receive the relatively weak signal from mobile and portable radios on one frequency, f_1, and retransmit it over the entire metropolitan area on another, f_2. Channel bandwidths can be 25, 12.5, or 6.25 kHz wide—which are all narrow in comparison to the 800 MHz carrier frequency.[1] A table of state and local narrowband public safety mobile radio frequency bands is provided in Appendix A.

[1] In 2013, the maximum channel bandwidth will be 12.5 kHz.

Figure 2 illustrates how in-building communications are provided by the repeater system. By design, the system overcomes building attenuation by reducing the coverage areas of repeaters in urban areas where it is expected to be highest. With smaller coverage areas, portable radio power normally budgeted to overcome loss due to distance can be used to overcome loss due to building attenuation.

A number of researchers have comprehensively measured building attenuation for this high-site scenario, in which a repeater antenna is mounted high above ground level and radiates over a large portion of a metropolitan area [6], [8], [9]. Analysis of the measurements showed that building attenuation was high and widely variable in urban areas in the lower floors of buildings. As an example, building attenuation at 850 MHz on the first floor of a building in an urban area was found to have a mean of 18 dB and a standard deviation of 8 dB. Other examples of these measurements are provided in Appendix A. The high mean attenuation and wide variability in this scenario is likely to cause loss of radio coverage.

Another strategy for overcoming building attenuation is to use direct or simplex communications between radios at the incident site as shown in Figure 3. With direct communications, everyone transmits and receives on an additional frequency, f_3, not used by the repeater system. If two radios are unable to connect due to an obstruction within the building, they may be able connect to other radios free of the obstruction. This diversity reduces the likelihood that anyone will be completely cut off from radio communications.

Since direct communications are performed at a frequency that is not used by the repeater system, interactions with those outside the incident site (such as dispatch) are not possible. To circumvent this, direct communications is replaced by mobile repeater communications, shown in Figure 4, as soon as a vehicle with a mobile repeater arrives at the incident site. In this mode, the portable radios operate in full duplex with a pair of frequencies, f_4 and f_5, not used by the repeater system. The mobile repeater converts these frequencies to those used by the repeater system. In other words, signals received on f_4 are transmitted to the repeater on f_1 and signals received on f_2 are transmitted to the portable radio on f_5.

NIST has performed comprehensive measurements of building attenuation for this low-site scenario, where a repeater antenna is mounted low and radiates into a nearby building [10], [11]. These measurements also found high and widely variable amounts of attenuation in several different types of buildings. For example, attenuation at 867 MHz in an office building had a mean of 38 dB with a standard deviation of 14 dB. Other examples of these measurements are provided in Appendix A. As in the previous scenario, there is likely to be loss of radio coverage.

The most reliable strategy for overcoming building attenuation, which is the subject of this report, is to use an in-building radio enhancement system (IBRES) [12]. The IBRES, shown in Figure 5, distributes a radio signal more uniformly throughout the building by providing alternate guided paths.

Outside the building, a donor antenna establishes a link with the donor repeater site. Inside the building, a distribution network guides signals to and from indoor antennas located throughout the building. Between the donor antenna and the distribution network, a bi-directional amplifier

(BDA) provides signal amplification necessary to overcome distribution network and radio-wave propagation losses.

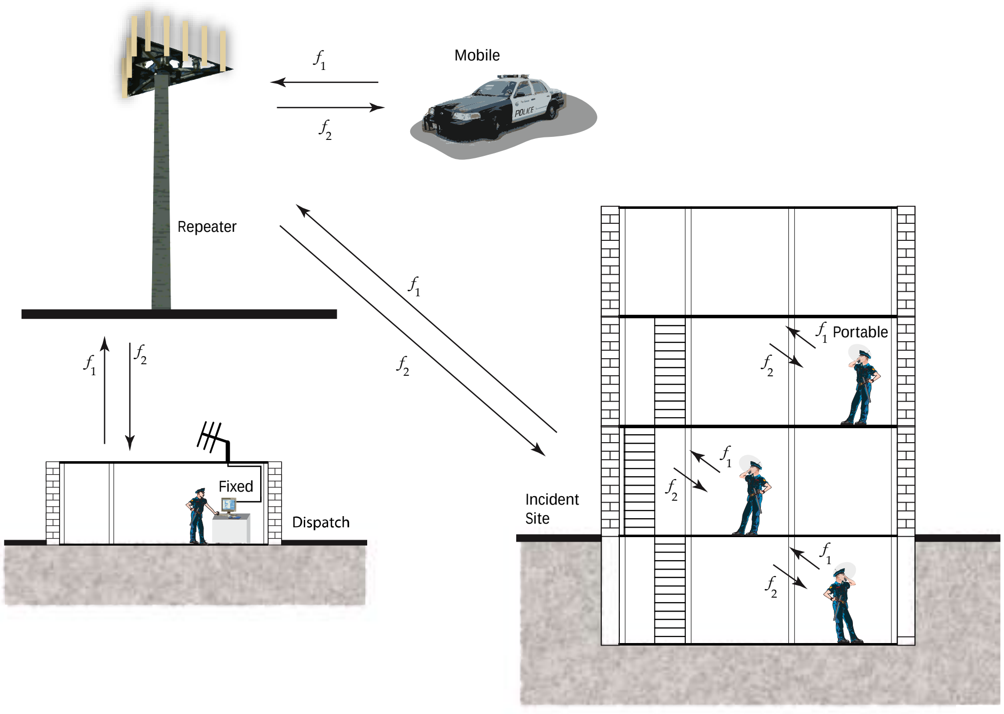

Figure 2. In-building communications using the repeater system.

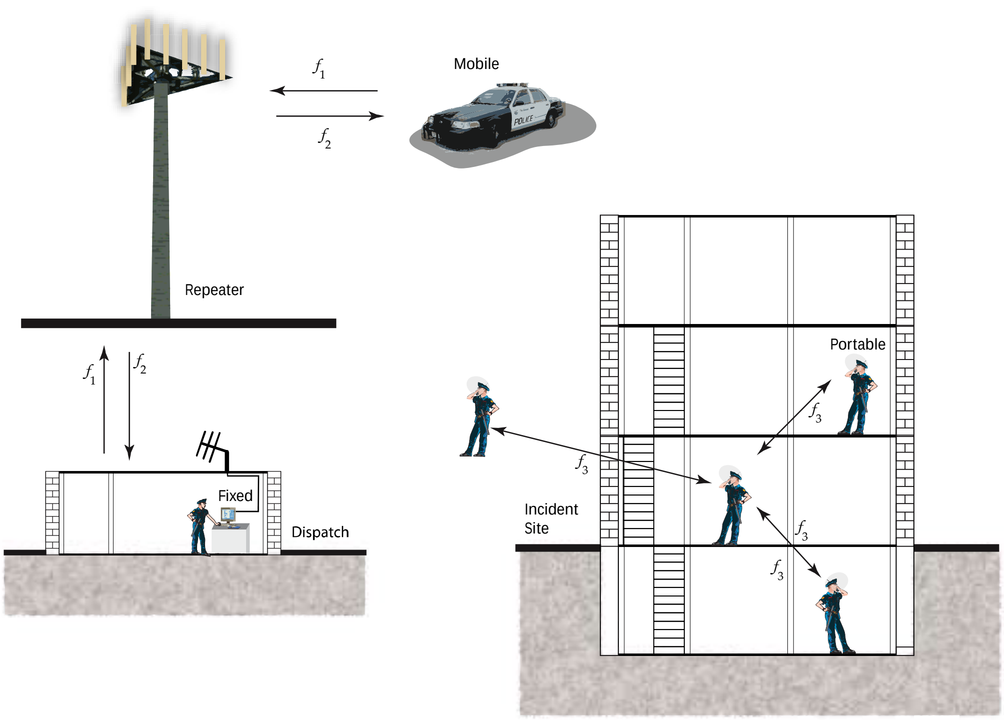

Figure 3. In-building communications using direct communications.

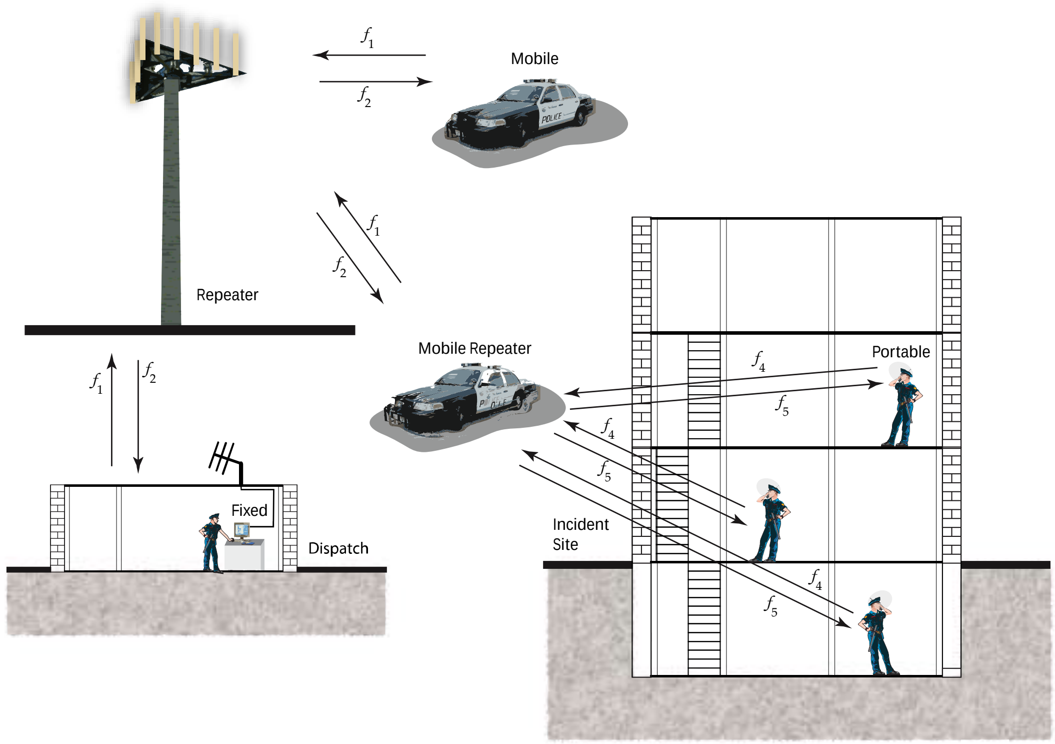

Figure 4. In-building communications using a mobile repeater system.

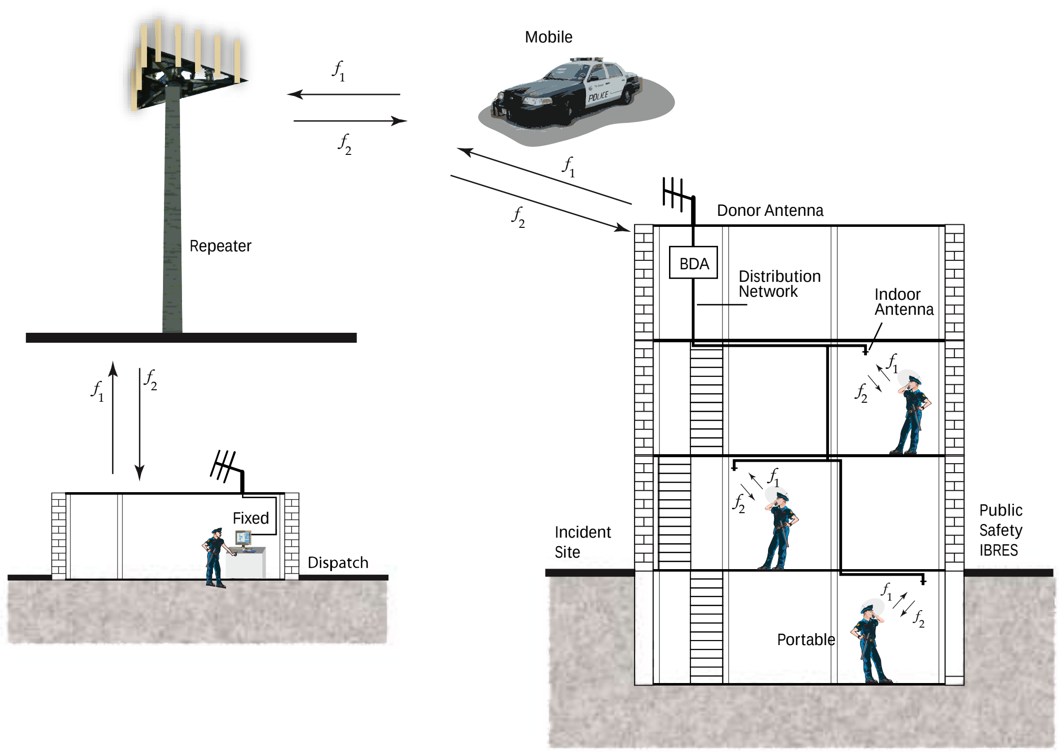

Figure 5. In-building communications using an IBRES.

IBRESs have none of the deficiencies of the first two approaches. Loss of radio coverage can be virtually eliminated by the judicious placement of indoor antennas and no new frequencies are needed to maintain communications with those outside the incident site. Because of these advantages, more and more municipalities are requiring buildings to have IBRESs for public safety communications. This strategy is completely different from the others because the equipment is provided by the building owner rather than the public safety organization. This report is intended to be used by public safety communications professionals tasked with assisting building owners to fulfill this requirement.

The information used in writing this report was collected through interviews with public safety professionals, designers, installers, and equipment manufacturers as well as through the more traditional literature search. The report has two sections. The first section describes current IBRES technology and the second section discusses problems endemic to the IBRES and common methods for mitigating them. Appendices provide details necessary to understand results cited in the main body of the report.

2 IBRES TECHNOLOGY

The technology used in today's IBRESs has been developed over a long period of time. Considerable strides in its development were made in the 1950s for communications in mining and transportation tunnels [13] and again in the 1980s for the burgeoning cellular phone industry [14]. A renewed interest has developed in the past decade due to the continued expansion of the cellular phone industry, proliferation of wireless local area networks, and our Nation's resolve to provide public safety professionals with the best possible radio systems [15].

This section provides an overview of today's IBRES technology. It is organized in terms of the IBRES components introduced previously: the BDA, the distribution network, and the antennas. The section culminates with examples of IBRESs and link budget analysis results that demonstrate their utility.

2.1 BDA

The purpose of the BDA is to amplify signals to overcome distribution network and radio-wave propagation losses. Signals from the donor antenna are amplified for transmission by the indoor antenna and signals from the indoor antenna are amplified for transmission by the donor antenna. Unlike repeaters, BDAs do not shift frequencies. Signals are transmitted on the same frequencies at which they were received.

Signal amplification and retransmission is highly regulated by the Federal Communications Commission (FCC) because of its interference potential. The FCC controls this interference potential through regulations and a certification process [16].

One consequence of signal amplification is intermodulation. Intermodulation creates interfering signals at frequencies that are sums and differences of input signal frequencies and their harmonics. These signals can affect channels across the entire BDA bandwidth. Intermodulation can be caused by non-linear amplification due to excessively high input powers and BDA gains. Intermodulation is mitigated by careful control of BDA gain.

BDA gain is set, by manual gain control (MGC) or by computer, to a level that assures optimal performance during normal operating conditions. The amount of gain needed is dependent on the input power of all the signals in the BDA bandwidth and the output power required for reliable service. In general, gain is set to as low a level as possible. Automatic gain control (AGC) limits output power to a level that minimizes intermodulation by introducing attenuation when higher than normal input powers are experienced. The higher input powers may be due to strong signals from mobile radios outside the building or a larger number of channels being used during an incident.

Another consequence of signal amplification is the possibility of amplifying another system's channels and causing interference in that system. The FCC separates BDAs into two classes by whether or not they can avoid this. Class A BDAs avoid this by being able to filter and selectively amplify a specific channel. Class B BDAs do not have this capability. In many cases, Class B BDAs filter and amplify an entire band of channels. The FCC restricts the use of Class B BDAs to closed spaces such as in tunnels and buildings to reduce this source of interference potential. In the IBRES industry, Class A and Class B BDAs are referred to as narrowband and broadband BDAs, respectively.

While Class A BDAs have the least interference potential, their implementation is typically more complicated than that of Class B BDAs. This complexity is due to the need to shift the signal to a lower intermediate frequency to achieve narrow filter bandwidths [17].

In the past, BDA signal processing operations such as filtering and frequency shifting were implemented solely in hardware. With the advent of modern digital signal processors, some manufacturers have chosen to perform these signal processing tasks with software algorithms. With this approach, the BDA can operate as Class A or Class B depending on the circumstances. Custom channel filtering and gain configurations can be implemented with software that can be updated over a radio link. This is clearly advantageous when channel assignments need to be changed.

Figure 6 illustrates three BDA filtering schemes. It is important to note that the choice of BDA class and implementation must be evaluated in the context of the radio environment in which the BDA will be operating. As an example, the added complexity of a Class A BDA may be unnecessary if there are no other system's signals in the BDA bandwidth.

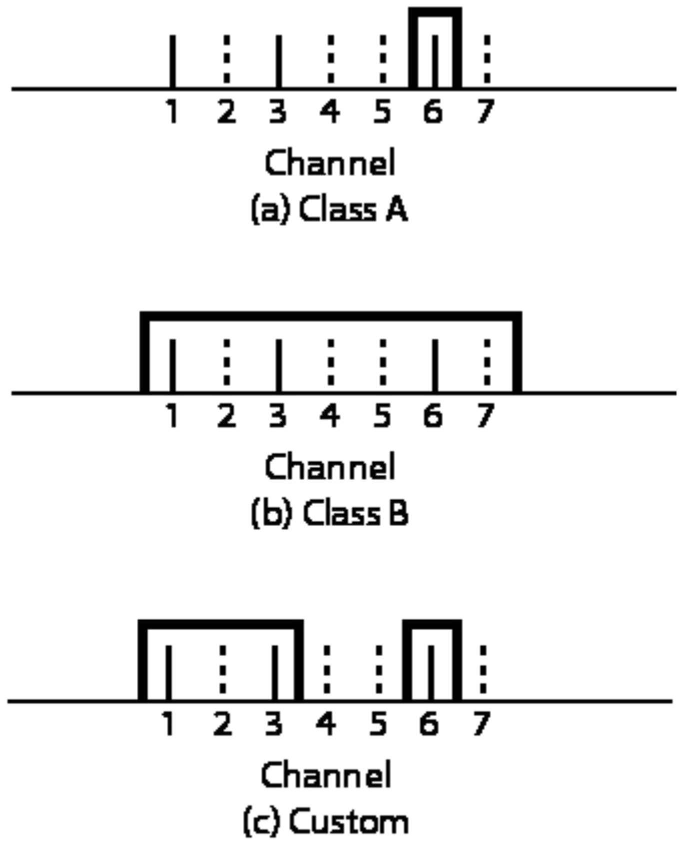

Figure 6. Class A, Class B, and custom BDA filtering. Solid lines represent the user's channels. Dashed lines represent channels from another system. Rectangles over the channels represent the BDA filter bandwidth. The Class A BDA amplifies only one of the user's channels. The Class B BDA amplifies all channels indiscriminately. The custom filtered BDA amplifies any combination of channels. As configured, this would be classified as Class B.

Figure 7 shows a BDA and Figure 8 is a functional block diagram of its operation showing filtering and gain control. Alarm circuits notify the system operator when events that affect operation occur. These events would include line-power loss, low battery power, amplification problems, and donor antenna malfunction.

Figure 7. BDA showing front panel with donor antenna socket, distribution network socket, A/C power plug, and power indicator light.

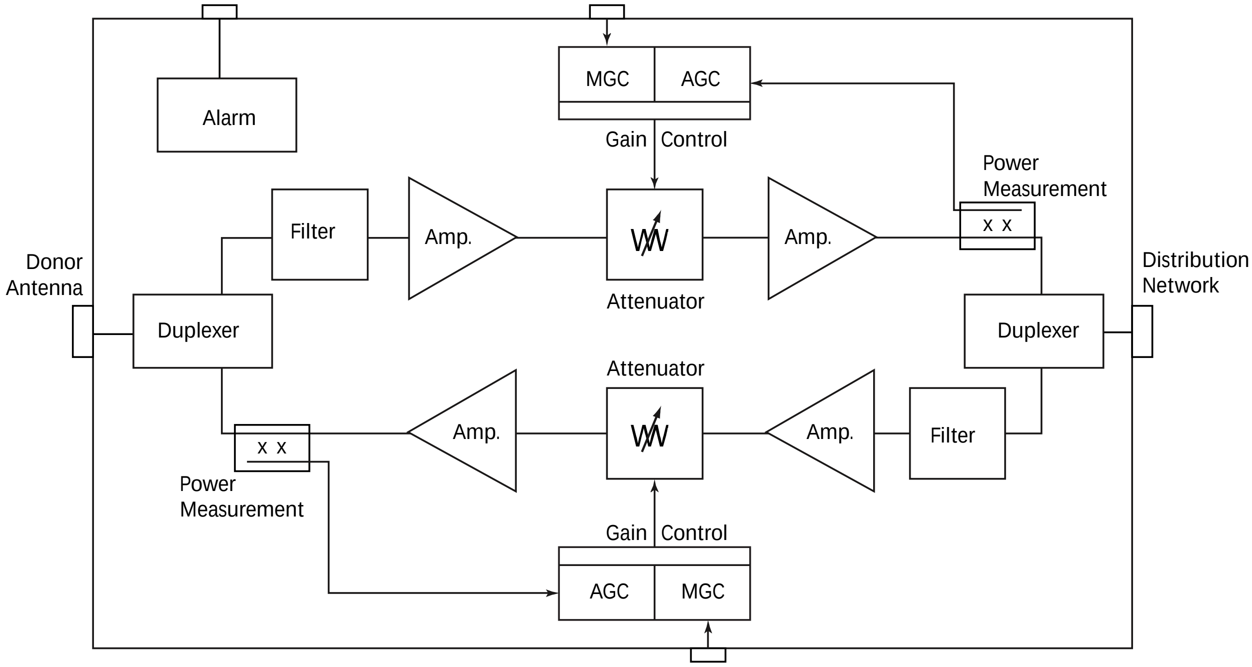

Figure 8. BDA functional block diagram.

2.2 Distribution Network

The distribution network consists of the cables and associated components needed to guide the signals between the BDA and the indoor antennas throughout the building. Cable types include coaxial (Figure 9), optical (Figure 10), and twisted-pair (Figure 11). These cables all have different characteristics that are exploited in a number of ways. Cable components enable signal splitting, combining, coupling, attenuation, and amplification.

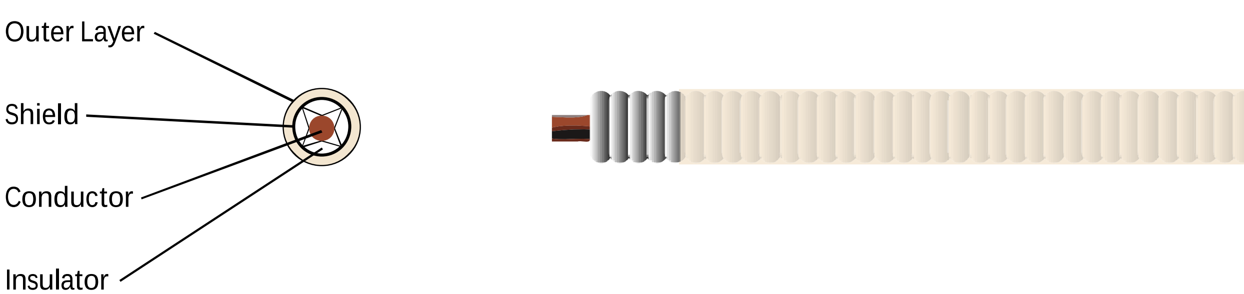

Figure 9. Coaxial cable cross-section (left) and profile (right).

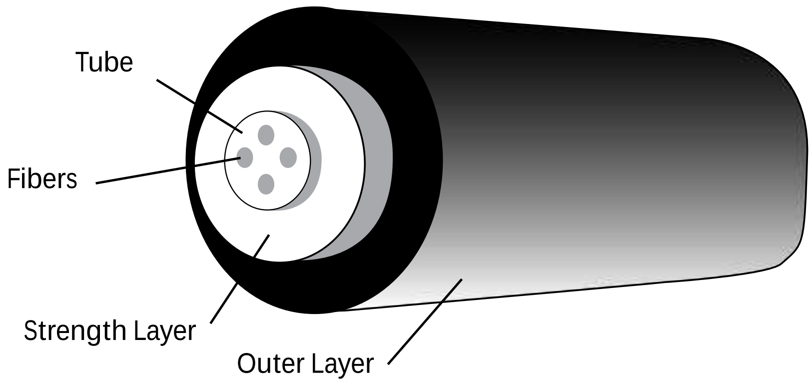

Figure 10. Optical cable.

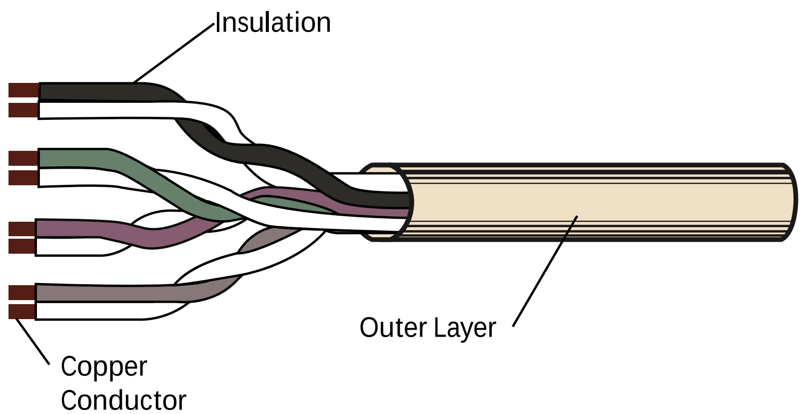

Figure 11. Twisted-pair cable.

The most significant difference between coaxial cable and the others is that coaxial cable can carry narrowband public safety signals at the same frequency at which they were transmitted over the air. In other words, the over-the-air transmission frequencies are within the coaxial cable frequency range. Fiber-optic and twisted-pair cables require cable interference units (CIU) to shift over-the-air transmission frequencies to cable frequency ranges. While the CIUs are an extra expense, they are often used advantageously to monitor and report system status.

Coaxial cable is composed of a center conductor, an insulator, a corrugated metal shield, and a protective outer layer. The most common type used for public safety bands is fairly rigid and ½ in. (12.7 mm) in diameter. Typical losses for an air-insulated ½-inch cable are approximately 0.4 to 4.0 dB per 100 feet (30.5 meters) over the frequency range of 30 MHz to 2 GHz. Extremely long lengths of coaxial cable need periodic, in-line amplification. However, because in-line amplifiers introduce noise, the number of amplifiers that can be used is limited.

Fiber-optic cable is composed of thin light-carrying fibers and layers needed for strength and protection. A 4-fiber cable is flexible and approximately ⅙ in. (4.24 mm) in diameter. Fiber-optic cable transmits monochromatic 1310 and 1550 nm wavelength light corresponding to 229 and 193.5 THz frequencies, respectively, which are well above those used by public safety. CIUs are needed to modulate the signal to and from the fiber-optic frequency range [18], [19]. The main advantages of fiber-optic cable are its extremely low loss and its wide bandwidth. Fiber optics are also immune to interference from RF signals. Loss is approximately 1 and 0.4 dB per mile (1.8 km) for 1310 and 1550 nm wavelength cables, respectively. CIUs with 2 GHz bandwidths are available. Fiber-optic cable is commonly used over the long distances needed to distribute the signals within large buildings or between buildings.

Twisted-pair cable is composed of twisted wire pairs wrapped in a protective layer. Both shielded and unshielded types are available. A cable with four twisted wire pairs is flexible and approximately ⅙ in. (4.24 mm) in diameter. Twisted-pair cable is classified by a category identifier. Category 5e and 6 twisted-pair cable is used to transmit up to 125 MHz and 250 MHz, respectively. CIUs are needed to shift the signal to and from the cable frequency range. Category 5e cable has losses of 0.6 to 7 dB per 100 feet (30.5 meters) from 1 to 125 MHz. Its flexibility makes it easier to install than coax and, in many cases, twisted-pair cable has already been installed for computer networking. If computer networks are already using the cable, the CIU merely needs to shift the over-the-air transmission frequencies to cable frequencies not used by the computer network.

2.3 Antennas

The donor antenna is typically a directional antenna whose beam is pointed directly at the repeater site. The directionality reduces the chances of interference with other systems as well as feedback from its own indoor antennas. Typical directional antenna designs include the Yagi, corner reflector, parabolic reflector, and panel.

The IBRES designer takes the antenna's gain, beam-width, and front-to-back ratio characteristics into consideration when choosing the donor antenna type. The most commonly used donor antenna is the Yagi depicted in Figure 12. The other antennas are chosen when there is a need for more gain to compensate for a weak signal, a narrower beamwidth to attenuate signals that are close in bearing, or a higher front-to-back ratio to provide more attenuation of signals out of the main beamwidth. Representative characteristics of each antenna type are provided in Appendix A.

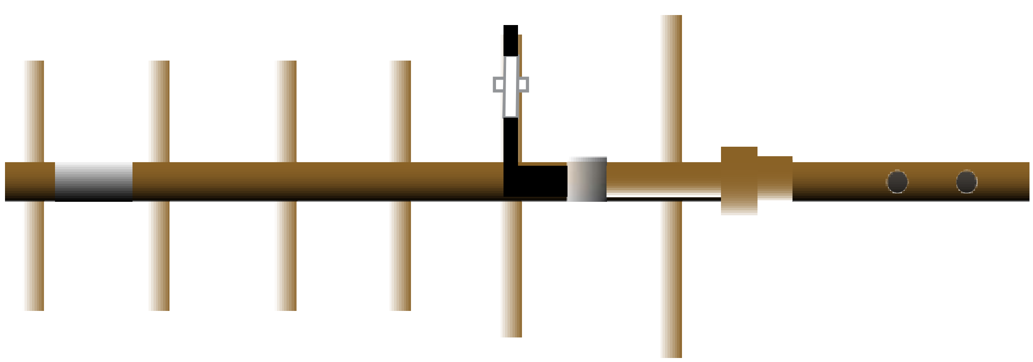

Figure 12. Yagi antenna.

Indoor antennas are either discrete or continuous. The discrete antenna is typically an omnidirectional, short monopole antenna on a ground plane. These elements are shown mounted in a typical plastic housing in Figure 13. This antenna has a 360-degree azimuthal beamwidth. Hung from the ceiling, this antenna creates a circular coverage area.

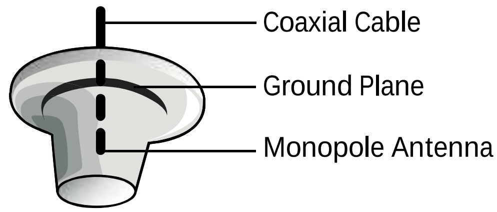

Figure 13. Omnidirectional antenna.

Narrower beamwidth discrete antennas are used when it is necessary to avoid radiating in certain directions. For example, panel antennas with beamwidths less than 90 degrees can be used to avoid radiating towards exterior wall areas with low attenuation, such as windows and doors.

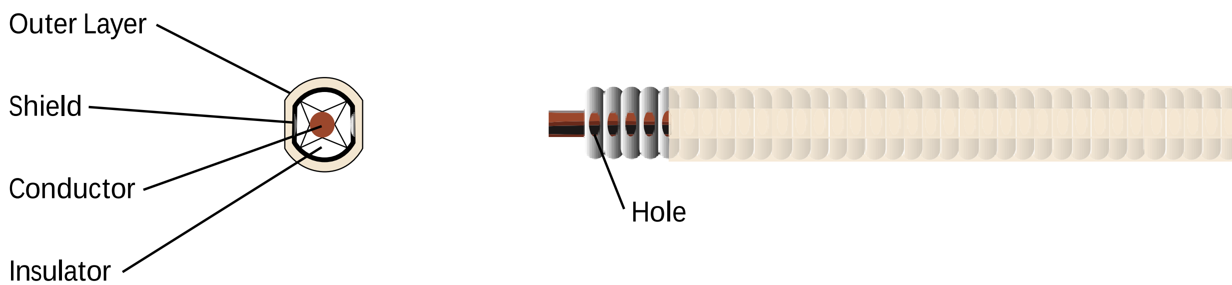

Figure 14. Leaky coax, cross section (left) and profile (right). Periodic holes are present on the flattened side.

The continuous antenna is commonly referred to as leaky coax. Leaky coax has a 360-degree lateral beamwidth. Hung from the ceiling, it creates a linear coverage area wherever the cable is run. The properties of leaky coax have been studied extensively [20], [21], [22], [23] and many types are manufactured. A commonly used type, shown in Figure 14, looks remarkably like the coaxial cable shown previously. The difference is the presence of periodic holes in the corrugated metal shield.

The main disadvantage of leaky coax is its high coupling loss, i.e., the ratio of the power received by a standard antenna a fixed lateral distance away from the cable and the power in the cable. Measurements made 2 meters away show coupling losses in excess of 70 dB at 500 MHz. In spite of this disadvantage, leaky coax is commonly used in long, narrow areas such as stairwells and elevator shafts.

2.4 Design, Installation, Testing, and Commissioning

The design, installation, testing, and commissioning of IBRESs are complex processes best left to experienced professionals. These professionals are guided by a number of organizations including, but not limited to, the National Public Safety Telecommunications Council (NPSTC), the Federal Communications Commission (FCC), the International Code Council (ICC), and the National Fire Protection Association (NFPA).

The NPSTC develops telecommunication policy on behalf of public safety organizations and companies that manufacture public safety telecommunications equipment. Among their publications is a report outlining best practices for the design and installation of IBRESs [24]. The FCC issues regulations to minimize interference in other radio systems.

Local authorities adopt into law building codes that specify how IBRESs are to be designed and installed. These codes are based on consensus standards developed by the ICC [25], [26] and the NFPA [27], [28]. Although these standards could be adopted in whole, they are generally amended to fit local circumstances [29].

Despite the fact that standards vary among municipalities, some general statements can be made in their regard. For example, codes usually only require public safety IBRESs in the areas of large buildings that do not have adequate coverage from outside. Existing buildings are often excluded unless they undergo renovation. Whether the building is new or is being renovated, building owners are free to wait until the construction is finished before determining whether an IBRES is necessary. However, provisions for installing the IBRES, such as vertical cable risers, are often required. If the IBRES is needed, the certificate of occupancy can be delayed until it is commissioned. The fire marshal reviewing the building plans prior to construction may recommend installing the IBRES during construction to avoid delays.

Firefighters have noted that IBRESs are vulnerable to both fire and fire-fighting operations [30]. IBRES designers readily acknowledge that cables and antennas directly exposed to flame will quickly become useless. However, when fighting fires it is also important that communications be possible in other parts of the building that are not on fire. Consequently, many municipalities are adopting codes for minimizing the effect of the fire on IBRES operation in other parts of the building. For example, some municipalities require that active electronics such as BDAs, CIUs, and uninterruptable power supplies be enclosed by water-resistant NEMA-4 cabinets and fire-protected rooms. In addition, some municipalities require that cables running through the building to remote locations be able to withstand some degree of water and fire exposure.

Finally, BDAs and CIUs are vulnerable to power outages. Most municipal codes require that they be connected to battery backup systems capable of supplying power for an extended period of time.

Prior to design, it is highly recommended that a radio spectrum survey be performed. Results from the survey are used to determine the best donor repeater site and whether signals from other systems will need to be mitigated.

IBRESs are often designed with the aid of graphical computer-aided design software. The software uses building architectural design information and specifications for various IBRES components including BDAs, cables, cable components, CIUs, and antennas. These components can be interactively located while designing the system. Once the system has been designed, the software can be used to calculate transmitted powers and radio coverage. Bills of material, installation labor, and cost reports can also be generated.

Municipalities often require that the IBRES be installed by certified technicians. Certification is typically acquired through the equipment manufacturers. Once installed, the IBRES is inspected for code compliance. If it passes, the system is commissioned by the municipality. Once commissioned, the IBRES is periodically tested.

Radio system coverage tests are part of the code compliance inspection. Coverage tests are similar to channel performance criterion (CPC) tests developed by the Telecommunications Industry Association [31]. The coverage test divides each building floor into a rectangular grid pattern as shown in Figure 15. To pass the coverage test, the building must have a specified percentage of cells with coverage, i.e., covered area availability. In most cases, this percentage equals or exceeds 90 percent. For critical areas, such as exit stairs, this percentage equals or exceeds 95 percent.

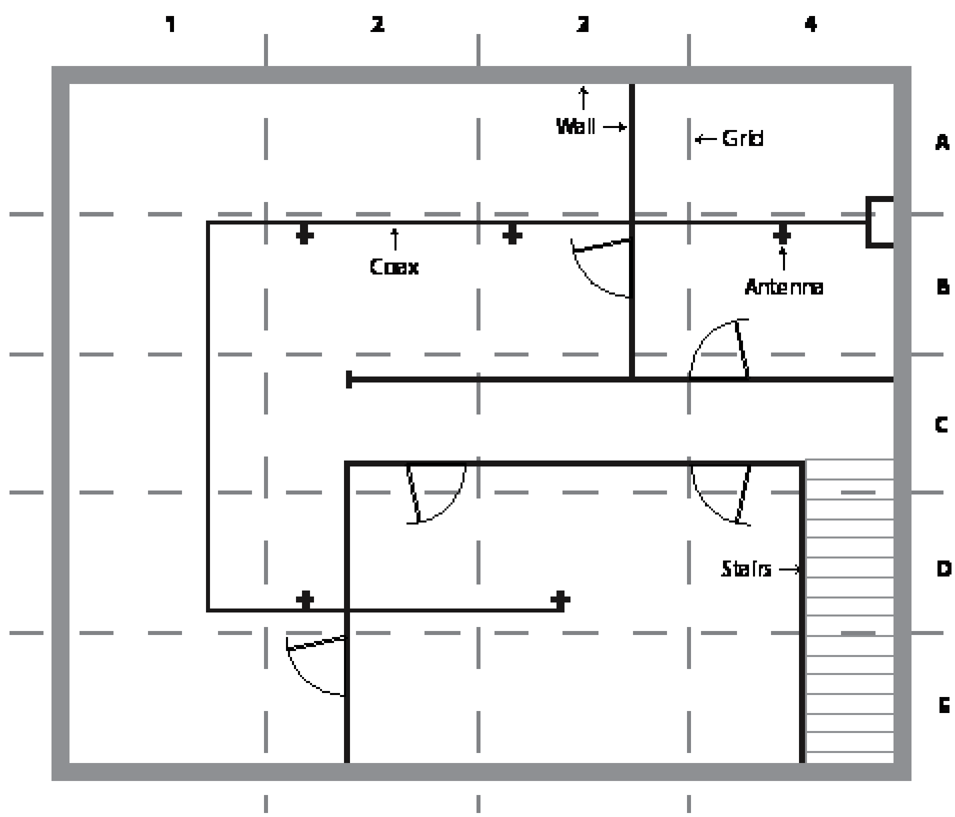

Figure 15. Floor plan gridded for coverage test.

In many municipalities, the cells of the grid are deemed to have coverage if the signal meets or exceeds a minimum power level. In others, a more stringent subjective speech quality metric called delivered audio quality (DAQ) is used. The scale ranges from 1 to 5, with 1 being unintelligible to 5 being perfect. Public safety radio uses a DAQ of 3.4, which corresponds to speech that is understandable and rarely needs repetition.

2.5 Examples

The components described above are used to build IBRESs in a number of ways [32], [33], [34]. Figures 16-18 show how IBRESs are implemented in buildings with small and large numbers of floors. In all three examples, the donor antenna is mounted on the roof so that it points at the donor repeater station. After passing through the building exterior, the antenna cable is connected to the BDA. All of the buildings have stairwells on the right and one floor below ground level.

Figure 16 depicts an IBRES in a building with a small number of floors. The distribution network is composed of coaxial cable alone. The floor area is serviced by discrete antennas and the stairway uses leaky coax. Figure 17 depicts an IBRES in a building with a larger number of floors. Coaxial cable loss is too high for the long distances needed to distribute the signal between floors. Hence, optical cable and fiber-optic/coaxial (FO/COAX) CIUs are needed. Figure 18 depicts a system where the coaxial cable is replaced by twisted-pair cable. This requires additional twisted-pair/coaxial (TP/COAX) CIUs.

The IBRES in Figure 16 is considered passive because it has neither signal amplifiers nor CIUs in the distribution network. The other two IBRESs with CIUs are referred to as active. In addition to buildings with large numbers of floors, active IBRESs are often used in buildings with large areas, such as shopping malls or convention centers.

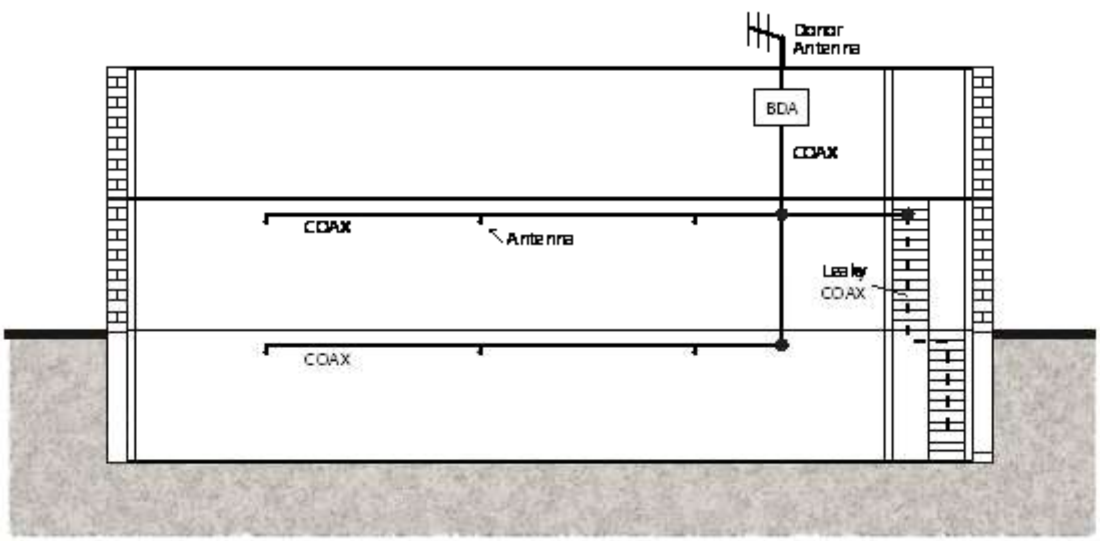

Figure 16. IBRES implemented with coaxial (COAX) cable in a building with a small number of floors.

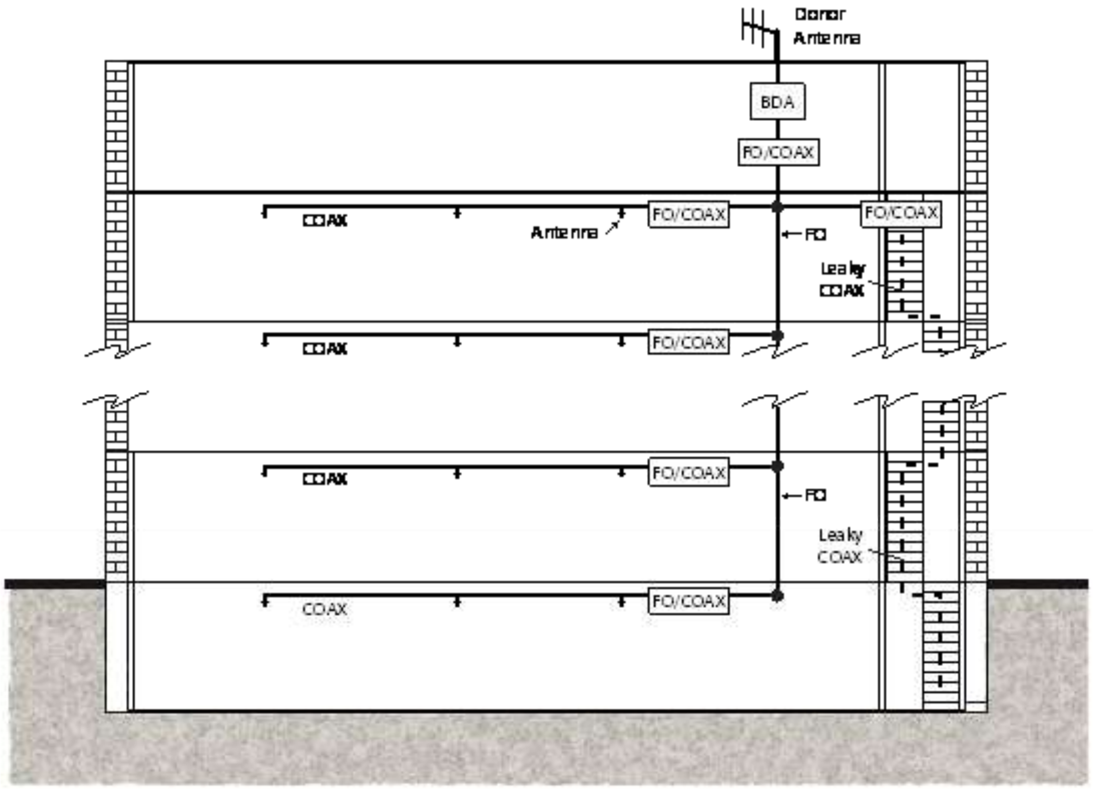

Figure 17. IBRES implemented with coaxial (COAX) cable, fiber-optic (FO) cable, and corresponding CIUs in a building with a large number of floors.

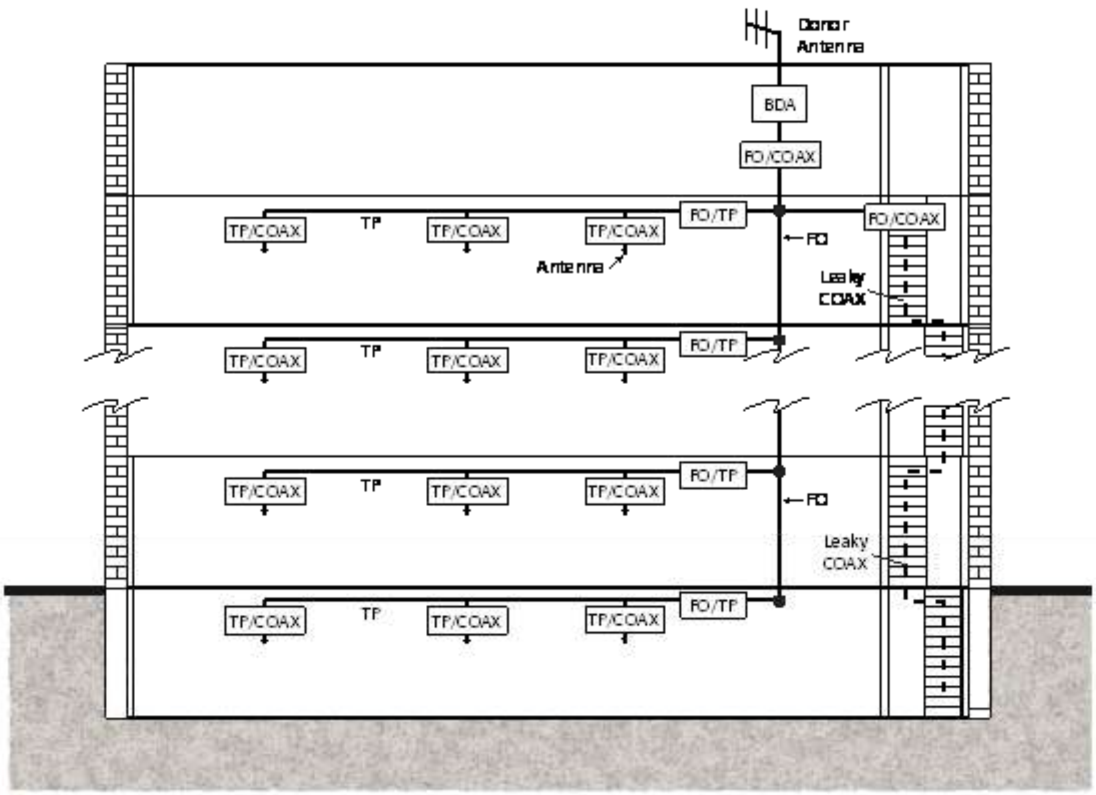

Figure 18. IBRES implemented with coaxial (COAX) cable, fiber-optic (FO) cable, and twisted-pair (TP) cables and corresponding CIUs in a building with a large number of floors.

2.6 Link Power Budgets

This section analyzes the utility of an IBRES with an example that compares the power received by a portable radio operated at ground level inside a building with and without an IBRES. The portable radio is assumed to be an analog frequency-modulated public safety portable radio operating in the 800 MHz NPSAC band with 12.5 kHz channel spacing. The IBRES is assumed to be similar to the one illustrated in Figure 16.

The methodology used in this section is straightforward. We first calculate the minimum power required outside the building, $P_{req,OUT}$, to achieve a 3.4 DAQ with 97 percent covered area availability performance level. We then calculate the power inside the building, P_r, and compare that to the minimum power required inside the building, $P_{req,IN}$, to achieve a 3.4 DAQ with 90 percent covered area availability performance level. If P_r is greater than or equal to $P_{req,IN}$ the link meets the performance level objective.

It is important to note that links not meeting the objective may still “work”. For example, the link may be operating with a DAQ of 3.0, which means that greater effort is needed to understand speech and more repetition is required.

The powers $P_{req,OUT}$, $P_{req,IN}$, and P_r are calculated with link power budgets. Detailed explanations of the propagation phenomenon involved and link power budget calculations are provided in Appendices B and C, respectively. It is important to note that these calculations assume high losses of a hip-mounted portable radio antenna and are expressed in terms of power received by a dipole antenna commonly used for conformance tests. Results for this example are provided in Table 1. These results clearly show that the performance objective can only be met if the building is equipped with an IBRES.

Table 1. Results for buildings with and without the IBRES

	P_r	$P_{req,IN}$	**Performance Objective Met**
Without IBRES	-91.0	-74.0	No
With IBRES	-78.2	-78.2	Yes

There are two reasons for the effectiveness of the IBRES. First, the donor antenna is typically mounted on the roof, which provides relief from attenuation by nearby buildings or urban clutter. Second, there are a number of ways to increase gain and decrease losses when designing the IBRES. For example, if more gain is needed a designer can install high-gain BDAs or antennas. If less loss is needed the designer can reduce indoor antenna spacing.

3 COMMON PROBLEMS AND THEIR SOLUTIONS

This section focuses on problems commonly found in IBRESs. These problems include feedback, gain reduction, noise transmission, delay, complex radio-wave propagation, and cost. The problems are described, specific examples are identified, and solutions are discussed. Two other problems commonly found in IBRESs, intermodulation and vulnerability to fire and firefighting operations, are not discussed in this section as they were addressed in Sections 2.1 and 2.4, respectively.

3.1 Feedback

BDAs receive on the same frequency as they transmit. This leaves IBRESs vulnerable to the effects of unwanted signals created by feedback. Feedback occurs when there is insufficient isolation between the BDA output and its input [35], [36]. The path the signal takes from the output of the BDA to its input is referred to as the feedback loop, and it consists of the distribution network, indoor antenna, propagation path, donor antenna, and cable between the donor antenna and BDA input.

Feedback can cause either oscillation or distortion. Oscillation occurs when the BDA gain equals or exceeds feedback loop attenuation, resulting in either a non-existent or negative feedback loop margin (FLM). Distortion occurs when BDA gain is less than feedback loop attenuation. The FLM is positive, which prevents oscillation, but it is not large enough to protect the signal from interfering with itself. Spectrum measurements showing the effects of oscillation and distortion are described in Appendix D.

Feedback signals can occur in both the portable radio and repeater transmit frequency ranges. Both signals are transmitted from the donor and indoor antennas. However, only the signal in the portable radio transmit frequency range can be received by the repeater and cause outages throughout the system when retransmitted.

Feedback outages are rarely caused by high-quality BDAs deployed in well-designed, correctly installed, and properly-maintained IBRESs. They are more commonly due to substandard BDAs installed in an ad hoc fashion. For example, substandard BDAs have caused feedback when installed in vehicles where it is difficult to obtain sufficient isolation. These outages can put civilians and public safety professionals at risk and be difficult to correct [37].

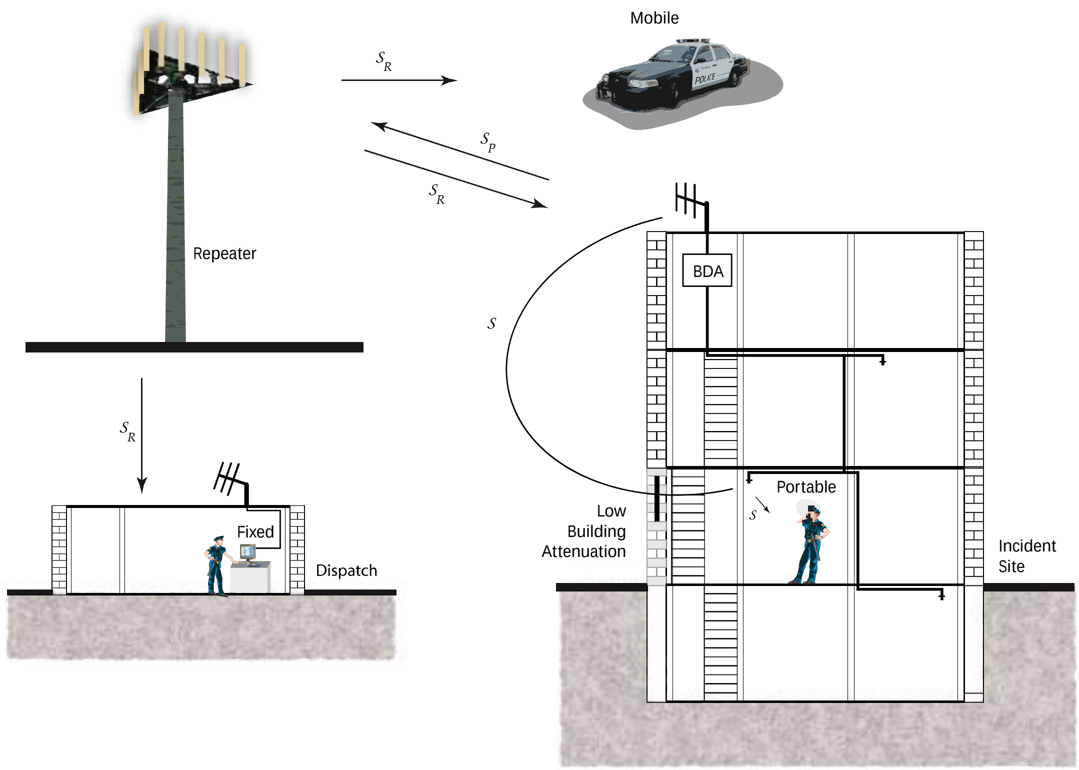

Figure 19. Insufficient isolation between the BDA output and its input causes feedback. Feedback, labeled S, can occur in both the portable and repeater transmit frequency ranges. The feedback signal in the portable radio transmit frequency range, S_P, is transmitted to the repeater. The repeater frequency shifts S_P to S_R, which is retransmitted throughout the entire system.

Example: A BDA oscillates when the door to a building is opened.

Solution: Opening the door reduces propagation loss between the indoor and outdoor antenna. The FLM can be increased by decreasing BDA gain, increasing the separation between indoor and donor antennas, relocating the indoor antenna away from the door, using a directional indoor antenna to point the signal away from the door, or adding attenuation to the distribution network prior to the indoor antenna.

Example: A windstorm knocks a roof-mounted donor antenna over, leaving it pointed directly at an indoor antenna.

Solution: The BDA can be designed to detect oscillations and reduce gain when present. If oscillations persist, the BDA can turn off amplification and activate an alarm. As shown in Appendix D, a BDA with AGC can still oscillate. Hence, the gain reduction required for oscillation mitigation must be addressed in addition to the gain reduction used by AGC.

3.2 Gain Reduction

Class B BDAs amplify all signals within their bandwidth. Once AGC is engaged, the addition of more channels reduces gain and channel output power. At some point, it is possible to have so many channels that some may no longer be received at powers that can meet the performance-level objective. A strong signal can also aggravate this situation, as shown in Figure 20.

Consider the example of the building with an IBRES in Section 2.6 and Appendix C. It would take approximately 114 channels to drive P_r below $P_{req,IN}$. Far fewer channels can be driven below $P_{req,IN}$ if there is a strong channel. For example, seven channels can be driven below $P_{req,IN}$ if one of the channels is allowed to increase its power to more than -52.6 dBm outdoors or -57.8 dBm indoors.

Example: A strong undesired signal from another system causes the other signals to go below the received power threshold.

Solution: Minimize BDA gain to avoid engaging AGC. Reduce the undesired signal power by pointing the donor antenna to a repeater in another direction. If this is not possible, reduce the undesired signal power by additional filtering.

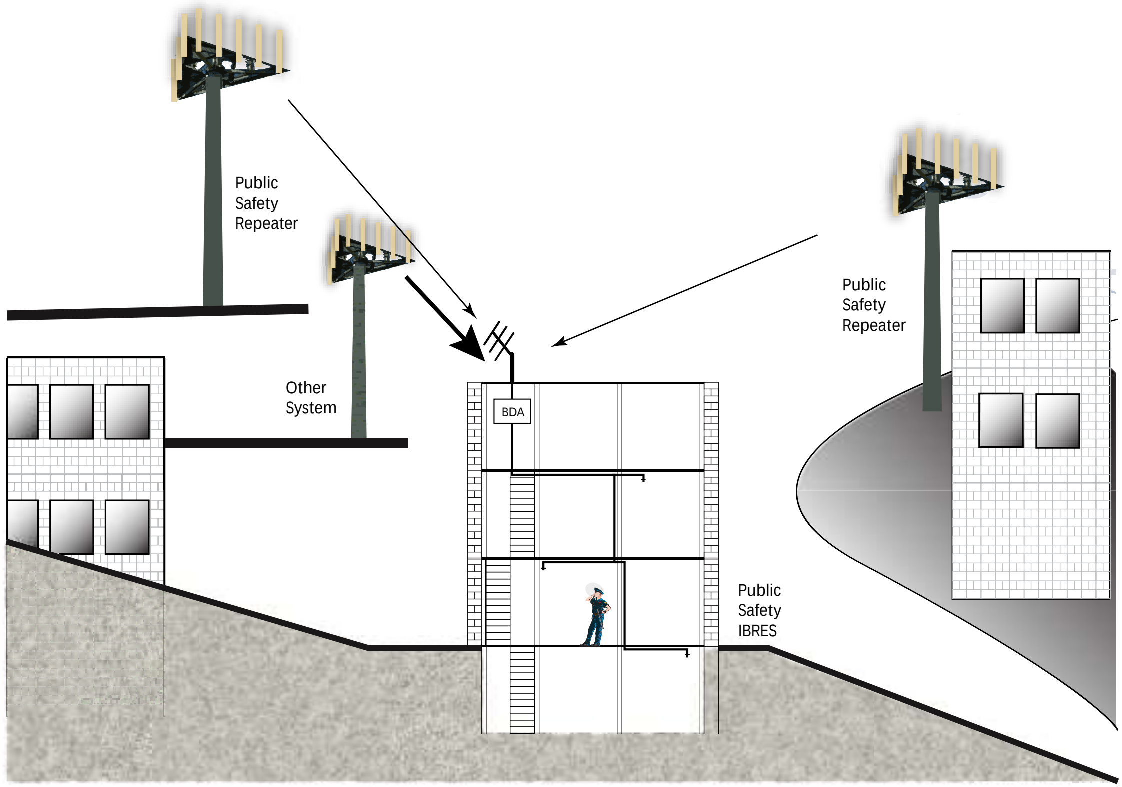

Figure 20. Strong signal from another system is received by public safety IBRES causing gain reduction.

3.3 Noise Transmission

BDAs amplify and transmit the noise the IBRES generates[2] through the donor antenna. The transmitted noise power can cause repeater receiver desensitization. Desensitization can occur over significant distances. For example, an IBRES uplink can desensitize another system's repeater operating at a 3.4 DAQ to a 3.0 DAQ as far away as 1447 feet (441 meters). Calculation details are provided in Appendix C.

Example: Another system's repeater is being desensitized by noise transmitted from a nearby public safety IBRES using a Class B BDA.

Solution: Reduce BDA gain as much as possible, attenuate the noise in the other system's channels by filtering, and point the donor antenna toward a public safety repeater in another direction.

Example: A public safety repeater is being desensitized because a number of public safety IBRES donor antennas from different buildings are pointed at it.

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[2] In addition, a BDA amplifies the natural and man-made noise in the environment, which is substantial in the VHF band.

Solution: Reduce BDA gain as much as possible, point donor antennas at other public safety repeaters, and reduce the number of BDAs by connecting distribution networks in different buildings together.

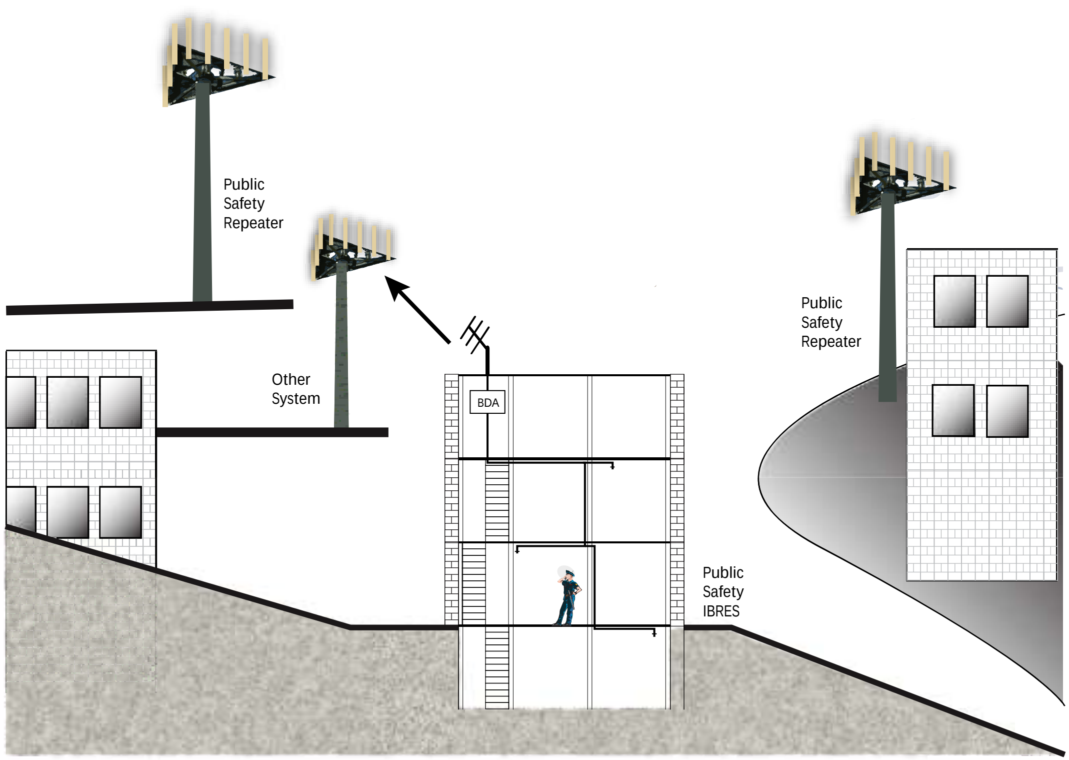

Figure 21. IBRES is transmitting noise into another system's repeater.

3.4 Delay

Narrow bandwidth filters and long runs of fiber-optic cables can introduce significant delays in the signal. Radio system performance can be degraded when signals delayed by the IBRES are combined with signals that did not go through the IBRES. Tests have shown that radios can tolerate this delay if there is a sufficient difference in power between delayed and undelayed signals[17]. More delay can be tolerated with larger differences in power levels. For example, Phase 1 P25 analog FM and digital C4FM radios operating in a 12.5 kHz bandwidth can tolerate a 40 µs delay with a 6 dB difference, but only 33 µs with 0 dB.

Example: An indoor antenna is placed near a window. The signal from the repeater enters the building through the window and interferes with the signal from the indoor antenna.

Solution: Larger differences in signal power can be obtained by increasing the power to the indoor antenna. To ensure that the increased power does not cause problems to a radio outside the building, the indoor antenna must be moved away from windows and doors. Directional panel antennas are also useful for increasing the power difference. The directional antenna should be mounted on the wall between the indoor coverage area and the repeater site [38].

If the delay is caused by narrow bandwidth filters and the problem persists after increasing the difference in signal powers, then the delay must be reduced by widening the filter bandwidth. A 12.5 kHz channel filter has a minimum of $1/12{,}500$ s or 80 µs of delay. Increasing the bandwidth to 200 kHz can decrease this minimum to $1/200{,}000$ s or 5 µs.

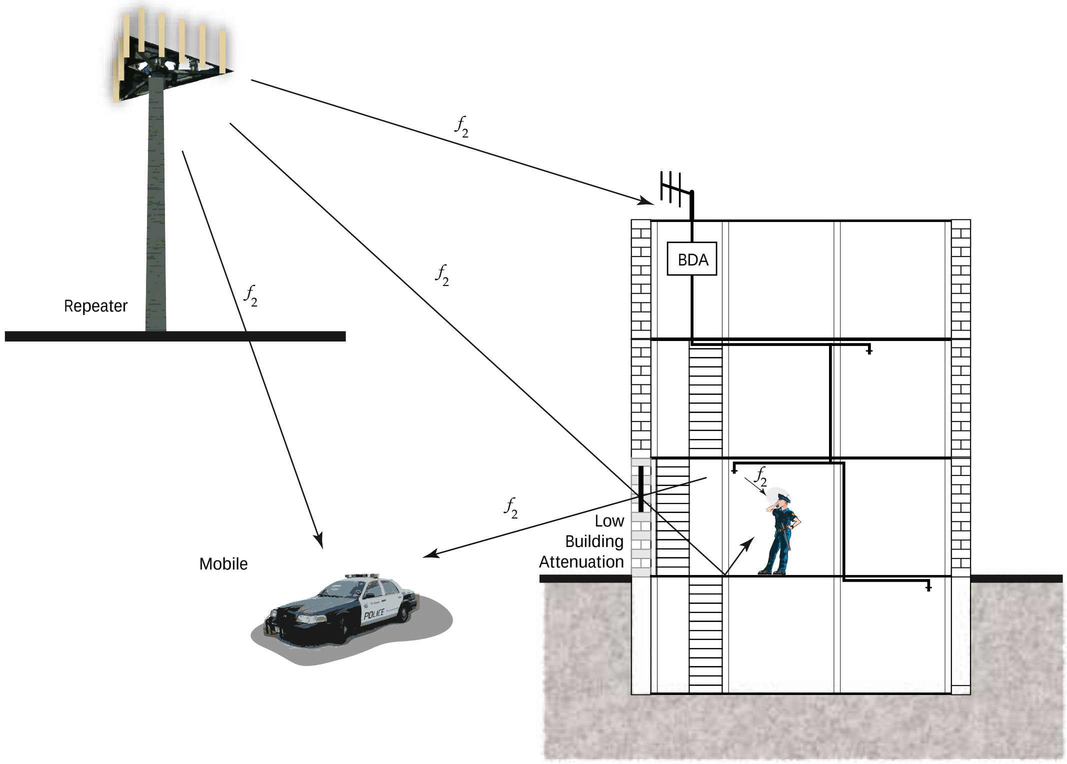

Figure 22. Performance degradation due to reception of delayed IBRES signal.

3.5 Radio-Wave Propagation

Building walls, floors, and furnishings create complex radio-wave propagation conditions that make radio coverage difficult to predict and test.

Example: Indoor antenna location is usually determined by the judgment of an experienced RF engineer using a path loss model [39]. An example of this prediction is shown in Figure 23. The approach is prone to error because the model predicts path loss for a generic type of building, for example, an office or warehouse. Specific architectural details of the actual building are not considered. Appendix B contains a description of some commonly used path loss models.

Solution: Measure coverage after installation and add additional antennas if necessary. Another solution is to “saturate” the building with antennas spaced closer than what the path loss model recommends. Research has shown that a saturated design is less dependent on the floor plan and antenna location [40].

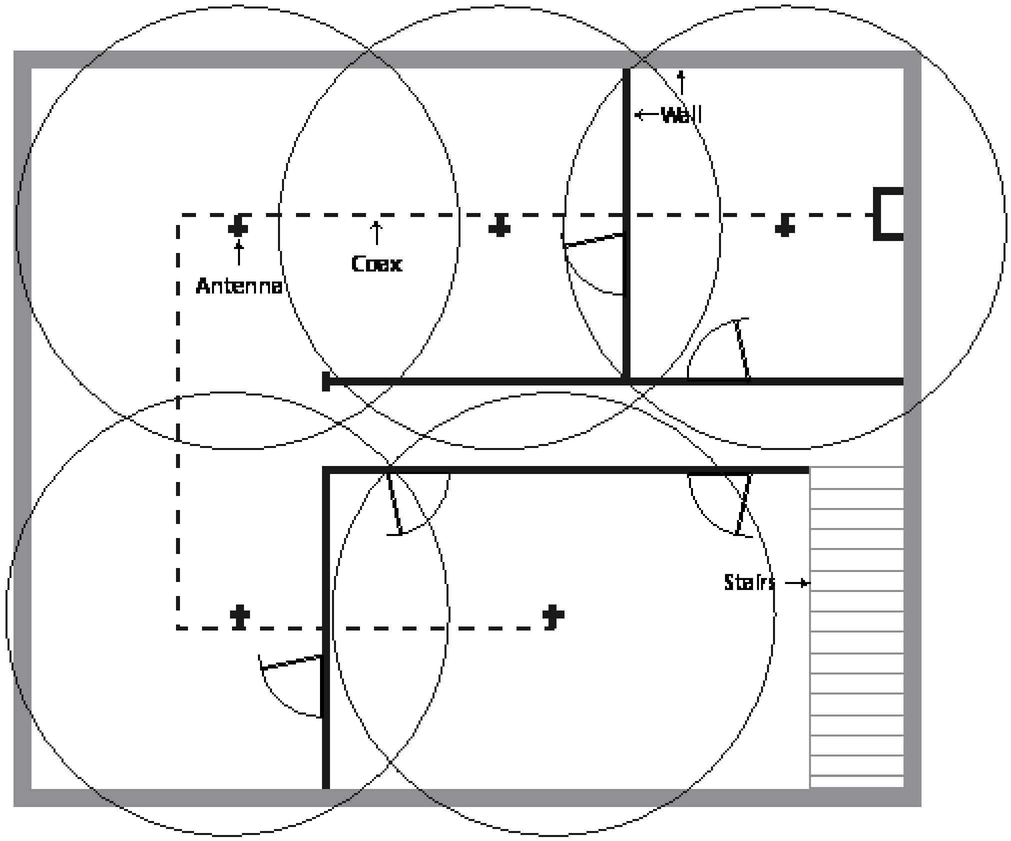

Figure 23. Radio coverage prediction using a path loss model. The circles surrounding the antennas represent the antenna's radio coverage area.

Finally, the designer can use site-specific models that consider the effect of the building's architectural details on radio-wave propagation. An example of such a prediction is shown in Figure 24. Although error cannot be eliminated, it can be reduced. Advanced algorithms are being developed for site-specific models to determine the optimal antenna location [41], [42], [43], [44]. Appendix B contains supplemental material on site-specific modeling methods.

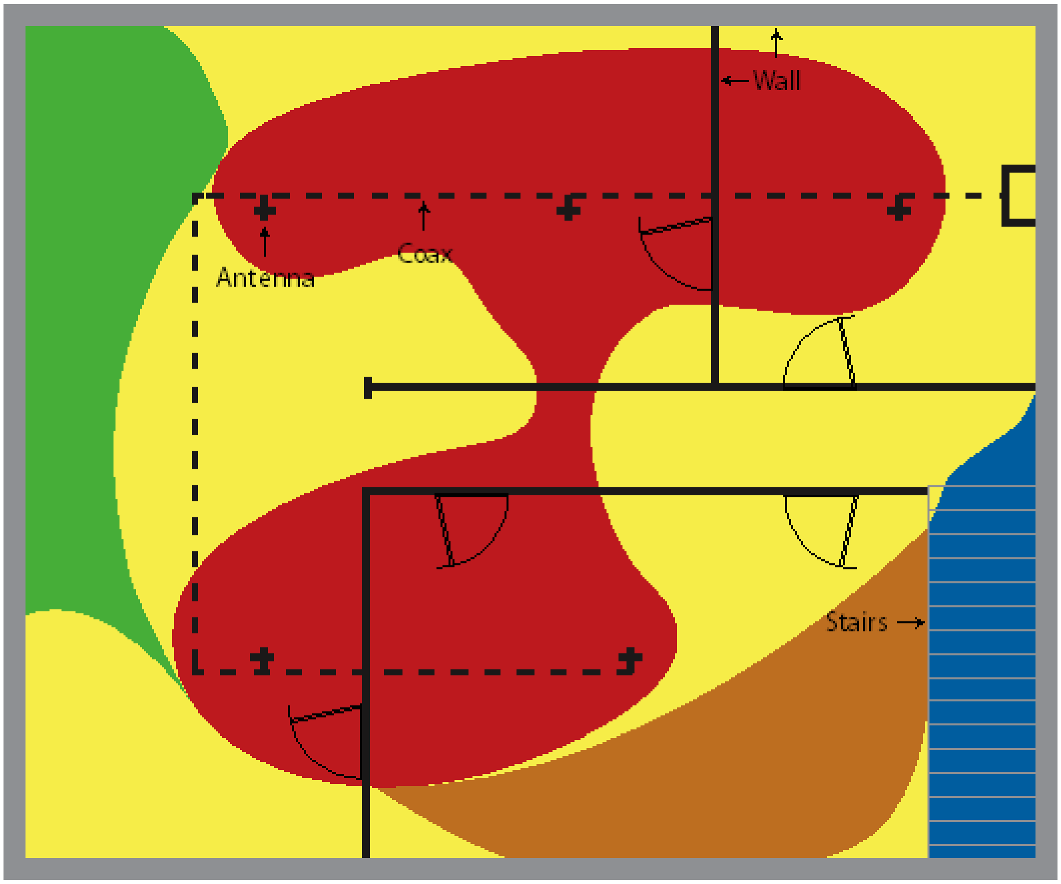

Figure 24. Radio coverage prediction using a site-specific radio-wave propagation model. Differing colors represent various received signal power levels.

Example: IBRES coverage tests require that a building be divided into a grid pattern and that a certain percentage of the grid cells have powers that equal or exceed a minimum level. However, multipath fading can cause the signal power to fluctuate over small changes in position within the cell making it hard to assign a power level.

Solution: Measure grid cell signal power by averaging (in watts) a number of power measurements collected over a small area within the cell. NFPA code specifies the number of measurements that must be made over an x-shaped pattern. This guarantees statistical confidence in the average power estimate. As an example, averaging 50 power samples over 40 wavelengths produces an average power estimate that is accurate to within 1 dB with a 90-percent confidence level. At 800 MHz, 40 wavelengths equal a distance of 49.2 feet (15 meters) [45].

Example: Multipath delay can cause poor speech quality even when the specified received signal strength is met.

Solution: Measure signal quality in terms of delivered audio quality (DAQ) in addition to received signal strength.

3.6 Cost

Issue: Designing, installing, and maintaining public safety IBRESs increases the costs of constructing, remodeling, and operating a building.

Solution: IBRESs are now being installed in buildings to distribute cellular, WLAN, telemetry, and building automation signals. These systems are referred to as neutral host systems because they are not owned by the telecommunications services provider [46].

Adding public safety communications to the neutral host system can reduce the cost of designing, installing, and maintaining public safety IBRESs [47]. Continued interest in providing public safety communications with state-of-the-art wideband communication capability over commercial cellular carrier networks also makes this approach attractive [48], [49], [50].

Figure 25 shows how public safety communications can be added to a neutral host system. This configuration has a public safety BDA and cellular system base transceiver stations (BTS). The public safety BDA is connected to a donor antenna pointed at a repeater. The BTS can be connected by radio link or cable to the cellular master-switching station. The units use signal conditioning (SC) circuits, which independently control BDA and BTS signal powers so that intermodulation in the fiber optic interface (FOI) is minimal.

The disadvantage of adding public safety communications to a neutral host system is losing control over system modifications or maintenance which, if done poorly, can severely degrade system performance [12]. This disadvantage can be overcome by monitoring system performance information over the Internet.

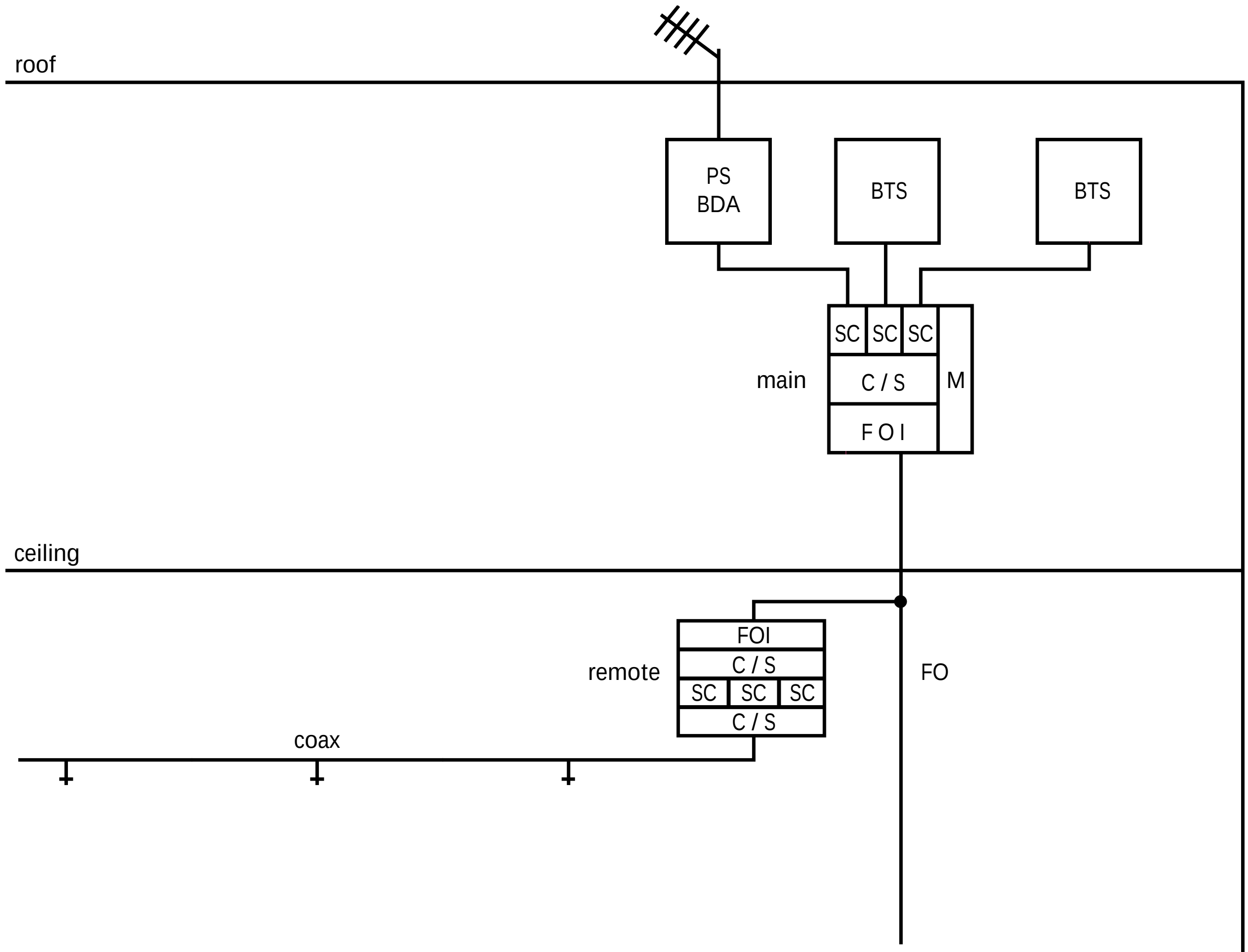

Figure 25. Public safety communication system BDA shares a neutral host system with two cellular system BTSs. The main and remote interface units include signal conditioning (SC), combiner/splitter (C/S), fiber optic interface (FOI) functions. The management (M) function in the main interface unit allows system performance to be monitored over the Internet.

4 CONCLUSION

IBRES technology is a mature art that was refined in response to a myriad of challenges over the past several decades. When designed, installed, and maintained by experienced professionals, these systems are considered reliable. As a testament to IBRES reliability, many municipalities across the United States are requiring buildings to have IBRESs for public safety communications.

Link budget calculations in the Appendices below show how installing an IBRES provided reliable communications in a building which, without the IBRES, was unable to meet performance objectives. There are two reasons for the effectiveness of the IBRES. First, the donor antenna is typically mounted on the roof, which provides relief from attenuation by nearby buildings or urban clutter. Second, there are a number of ways to increase gain and decrease losses when designing the IBRES. For example, if more gain is needed a designer can install a higher gain BDA or antenna. If less loss is needed the designer can reduce indoor antenna spacing.

IBRES technology has a number of common problems, but none have proven to be insurmountable. These problems, listed in the order discussed, include intermodulation, vulnerability to fire and fire-fighting operations, feedback, gain reduction, noise transmission, delay, complex radio-wave propagation, and cost.

Of these problems, the most commonly encountered are feedback, gain reduction, and noise transmission. In general, an experienced professional can mitigate these problems with simple measures such as reducing BDA gain, repointing the donor antenna towards a different repeater, choosing a different donor antenna, relocating the indoor antenna, using a directional indoor antenna, or filtering.

These problems are also being addressed through telecommunications policy. For example, in a number of cases, these problems were due to public safety radio systems with high-site land mobile radio architectures sharing the same band as systems with low-site cellular radio system architectures [51]. The FCC mitigated these problems by moving the two types of radio systems into separate frequency bands [52]. In addition, the FCC is working diligently to eliminate harmful interference caused by substandard BDAs [37].

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APPENDIX A: TABLES

A.1 Building Material Attenuation

Table A-1 contains a list of typical construction materials and their corresponding attenuation at 800 MHz and 0-degree angle of incidence. Variations are due to differences in thickness, density, or composition of the material samples. Values in this table are derived from [A-1].

Table A-1. Construction material attenuation

Construction Material	Attenuation (dB)
Drywall	0.2
Plywood	0.3 – 1.1
Glass (non-metalized)	0.5 – 2.75
Wood	2.2 – 5.4
Brick	3.0 – 5.5
Brick/Masonry-block	10.1
Brick/Concrete-wall	13.0 - 23.0
Masonry block	11.0 – 27.0
Concrete wall (Type 1)	11.0 – 35.0
Reinforced concrete wall	25.0 – 29.0

A.2 High-Site Building Attenuation

Table A-2 contains a list of building attenuation statistics where the outside antenna is mounted high above the ground. The attenuation is the ratio of average power in the streets surrounding the building to the average power measured over a small distance inside the building. The test signals were radiated by seven advanced mobile phone system (AMPS) cellular radio sites, operating at 850 MHz, spaced approximately 15 miles (24 km) apart throughout a metropolitan area. The inside antenna was omnidirectional. Values are derived from [A-2].

Table A-2. High- site building attenuation at 850 MHz

Environment	Floor	No. of Bldgs.	Mean (dB)	Standard Deviation(dB)
Urban	1	3	18.0	7.7
Suburban	1	10	13.1	9.5
All	1	13	14.2	9.3
	2	8	10.6	8.5
	3	6	6.8	9.8
	4	4	-0.8	10.7
	5	3	2.9	9.2

A.3 Low-Site Building Attenuation

Table A-3 contains a list of building attenuation statistics where the outside antenna is mounted low near the ground. Attenuation is the ratio of the average power measured outside the building on the wall nearest the transmitter to the average power measured over a small distance inside the building. The outside antenna is directional and mounted approximately 13 feet (4 meters) off the ground. The inside antenna is omnidirectional. Values are derived from [A-3].

Table A-3. Low-site building attenuation

Building	Frequency (MHz)	Mean (dB)	Standard Deviation (dB)
Apartment building, New Orleans, LA	902	34.2	13.8
Apartment building Boulder, CO	908	27.0	10.9
Office, Phoenix, AZ	867	37.9	13.5
Office, Gaithersburg, MD	902	57.7	14.1
Office, Silver Spring, MD	902	70.4	10.5
Hotel, Colorado Springs, CO	902	34.1	18.8
Shopping Mall, Bethesda, MD	902	44.6	6.3
Convention Center, Washington, DC	902	61.8	14.5

A.4 Narrowband Public Safety Mobile Radio Frequency Bands

Table A-4 contains a list of frequency bands for narrowband radios used by state and local public safety agencies [A-4]. Mobile and base frequencies are not always specified for the 150 and 450 MHz bands. The 800 MHz interleaved band has both public safety and non-public safety licensees. The 800 MHz National Public Safety Advisory Committee (NPSAC) band is licensed solely by public safety agencies.

Table A-4. Narrowband public safety mobile radio frequency bands

Band	Mobile Transmit (MHz)	Base Transmit (MHz)
150 MHz - VHF High	150-162	Same
450 MHz - UHF	450-470	Same
700 MHz	799-805	769-775
800 MHz - NPSAC	806-809	851-854
800 MHz - Interleaved	809-816	854-861

A.5 Donor Antenna Characteristics

Table A-5 lists four commonly used donor antenna types and their characteristics. Gain in dBi is obtained by adding 2.15 dB to the dBd value shown.

Table A-5. Representative characteristics of several types of donor antenna

Antenna type	Freq. (MHz)	Bandwidth (MHz)	Gain (dBd)	Beam width (deg)		F/B (dB)	Dim. (in)
				H	V		
Yagi (6-element)	806-866	60	9	42	40	16	28" L
Corner reflector	806-960	90	8.5	45	56	23	68" W 38" H 18" D
Parabolic	806-896	90	16	12	24	25	68" W 36" H 18" D
Panel	806-900	94	14.5	102	7	20	95" H 8" W 6" D

A.6 References

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APPENDIX B: RADIO-WAVE PROPAGATION

Variable names are consistent within the Appendix. Unless otherwise stated, upper case variables are the decibel equivalents of their corresponding lower-case variables and logarithms are base 10.

B.1 Ideal Radio Wave Propagation Path Loss Models

Radio propagation models are often used to determine how much signal attenuation or loss there is between antennas. These models are based on the fundamental definition that loss, l, is the ratio of transmitted and received powers, i.e.

$$l = \frac{p_t}{p_r}, \tag{B-1}$$

where p_t is power at the input to the transmitting antenna and p_r is the output of the receiving antenna.

For free-space propagation, where transmit and receive antennas are far removed from any obstruction, the received power is

$$p_r = p_t \frac{g_t}{4\pi d^2} a, \tag{B-2}$$

where g_t is the transmitting antenna gain, d is the distance between transmitter and receiver, and a is the effective area of the receiving antenna which captures the radiated field. The effective area is

$$a = \frac{\lambda^2 g_r}{4\pi}, \tag{B-3}$$

where g_r is the receiving antenna gain and λ is wavelength. Substituting (B-3) into (B-2) we obtain

$$p_r = p_t \frac{g_t g_r}{\left(\frac{4\pi d}{\lambda}\right)^2} . \tag{B-4}$$

Rearranging terms we find that

$$l = \frac{1}{g_t g_r}\left(\frac{4\pi d}{\lambda}\right)^2 . \tag{B-5}$$

Basic transmission path loss is often used to express path loss independent of antenna gains

$$l_p = l g_t g_r \tag{B-6}$$

yielding the expression

$$p_r = \frac{p_t g_t g_r}{l_p}, \tag{B-7}$$

or in decibels

$$P_r = P_t + G_t + G_r - L_p (dBm). \tag{B-8}$$

Hence, *free-space loss* is

$$l_p = \left(\frac{4\pi d}{\lambda} \right)^2. \tag{B-9}$$

In land mobile and cellular radio systems, loss is invariably influenced by reflections off the earth's surface. Because of this, their path loss cannot be predicted by free-space loss. However, assuming that the distance between transmit and receive antennas is small compared to the curvature of the earth, and large compared to the height of the antennas, their path loss can be predicted by *plane earth loss*

$$l_p = \left(\frac{4\pi d}{\lambda} \right)^2 \left(\frac{1}{4\sin^2\left(\frac{2\pi h_r h_t}{\lambda d} \right)} \right) = \left(\frac{2\pi d}{\lambda \sin\left(\frac{2\pi h_r h_t}{\lambda d} \right)} \right)^2, \tag{B-10}$$

where h_t is height of transmitter antenna and h_r is height of receiver antenna. This function produces a scalloping pattern when h_r increases. In other words, l_p alternately increases and decreases with height because of interference from the ground reflected wave. If the angle created by $\frac{2\pi h_r h_t}{\lambda d}$ is small, i.e. ≤ 0.3 radians, then $\sin\left(\frac{2\pi h_r h_t}{\lambda d} \right) = \frac{2\pi h_r h_t}{\lambda d}$ and

$$l_p = \left(\frac{d^2}{h_t h_r} \right)^2. \tag{B-11}$$

Plane earth loss at small angles differs from free-space loss in that it increases by the 4th power of distance instead of the 2nd power. This means plane earth loss increases by 12 dB each time distance is doubled as compared to 6 dB for free-space loss.

B.2 Practical Path Loss Models

The propagation of signals used by narrowband land mobile and cellular radio systems is very complex [B-1]. Its complexity is due to the myriad of interactions a radio wave has with the cluttered environment. In the outdoors, the clutter includes building exteriors, terrain, and vegetation. Indoors, the wave interacts with the building's walls, floors, and furnishings. Because of clutter, propagation loss cannot be accurately predicted with ideal free-space and plane-earth loss.

From a physical perspective, these interactions can be explained by electromagnetic transmission, reflection, and diffraction phenomena. From a radio engineering perspective, they are characterized by shadowing and multipath fading. Shadowing attenuates mean radio signal power and is caused by obstructions in the radio wave path. It is characterized by l_p, which like free-space and plane-earth loss, depends on the distance between antennas.

Multipath enhances and diminishes instantaneous radio signal power and is caused by scattering off nearby objects in the vicinity of the antennas. The effects of multipath are readily noticed with small changes in position [B-2]. The instantaneous power fluctuations created by multipath have no effect on mean radio signal power or path loss. When measuring path loss, the fluctuations are removed by averaging instantaneous power measurements (in watts) over a small area.

As mentioned previously, path loss due to shadowing is dependent on distance. However, even at the same distance, path loss has been found to vary with large changes in position—a phenomenon called path loss variability, or shadow fading. This occurs because large changes in position also mean a change in the characteristics of the obstructions in the radio wave path and a corresponding effect on path loss. Because of its variability, path loss is considered a non-stationary random process

$$l_p = m_p x_p \,, \tag{B-12}$$

where m_p is the mean path loss and x_p is the random variable that characterizes path loss variability. The corresponding expression in decibels is

$$L_p = M_p + X_p \ (dB) \,. \tag{B-13}$$

The mean has two components. The first component is a reference distance and accounts for the part of the path, out to a distance d_0, which experiences free-space loss. However, after that distance, losses can increase with a path loss exponent, n, which only needs to be greater than 0.

$$m_p = \left(\frac{4\pi d_0}{\lambda}\right)^2 \left(\frac{d}{d_0}\right)^n \tag{B-14}$$

The variable X_p is often characterized as a zero-mean, Gaussian or normally distributed random variable with standard deviation, σ [B-3]. It is important to note that both n and σ are environmentally dependent. As an example, we do not expect office buildings, warehouses, suburban areas, and urban areas to have the same n and σ.

The complete expression for path loss is

$$l_p = \left(\frac{4\pi d_0}{\lambda}\right)^2 \left(\frac{d}{d_0}\right)^n x_p, \tag{B-15}$$

which in decibels is

$$L_p = 20\log\left(\frac{4\pi d_o}{\lambda}\right) + 10\, n \log\left(\frac{d}{d_o}\right) + X_p \;\; (dB) \quad . \tag{B-16}$$

B.3 Propagation Into Buildings

For propagation into buildings, the path loss is extended to include building attenuation. Like path loss above, building attenuation varies with large changes in position and is considered a non-stationary random process characterized by

$$l_{BLD} = m_{BLD} x_{BLD}, \tag{B-17}$$

where m_{BLD} is the mean building attenuation and x_{BLD} is the building attenuation variability.

The total path loss is

$$l_p = m_{OUT} x_{OUT} m_{BLD} x_{BLD}, \tag{B-18}$$

where m_{OUT} and x_{OUT} are the mean and variability of the path loss outside the building, respectively. Let $x_p = x_{OUT} x_{BLD}$ or $X_p = X_{OUT} + X_{BLD}$. Assuming building attenuation variability is independent of outside variability, zero-mean, and Gaussian distributed in decibels, the standard deviation of X_p is

$$\sigma = \sqrt{\sigma_{OUT}{}^2 + \sigma_{BLD}{}^2} \quad (dB). \tag{B-19}$$

The complete expression is

$$l_p = \left(\frac{4\pi d_0}{\lambda}\right)^2 \left(\frac{d}{d_0}\right)^n m_{BLD} x_p, \tag{B-20}$$

which in decibels is

$$L_p = 20\log\left(\frac{4\pi d_o}{\lambda}\right) + 10\,n\log\left(\frac{d}{d_o}\right) + M_{BLD} + X_p \quad (dB) \quad . \tag{B-21}$$

B.4 Propagation Inside Buildings

A number of methods are used to increase the accuracy and precision of indoor path loss predictions. For example, if antennas will be installed on each floor of a multistory building, then *n* and σ should be derived from measurements performed on the same floor instead of with measurements that may have included paths between floors.

Another more site-specific approach is to replace M_p terms with free-space loss over the entire distance, and the sum of the losses of the walls the signal is known to pass though along the direct path, i.e.,

$$L_p = 20log\left(\frac{4\pi d}{\lambda}\right) + \sum_i A_i + X_p \quad (dB) \tag{B-22}$$

where A_i is the attenuation of the i-th wall [B-4].

Examples of differences between these approaches are shown in Table B-1 [B-4]. These measurements were taken at 900 MHz in a five-floor, two-wing, office building divided by 5 ft. (1.5 m) tall plastic office partitions. The first row represents parameters derived from measurements between any two points in the entire building. The second row restricts measurements to those acquired on the same floor. The third row predicts the mean path loss by summing wall attenuation, as in (B-22), assuming 1.39 dB loss through the office partitions and 2.38 dB loss through masonry block walls. Clearly, the use of wall attenuation decreases σ.

Table B-1. Path loss parameters for office building furnished with 5 ft. (1.5 m) tall office partitions

Measurement Area	*n*	σ
Entire building	3.54	12.8
Same floor	3.27	11.2
Summing wall attenuation	2.0	4.1

B.5 Availability

Because of path loss variability, radio link designers using path loss models can only quantify the chances that the power will exceed a required value. This is referred to as availability. Availability is defined as

$$A = Pr\left\{P_r \geq P_{req}\right\}, \tag{B-23}$$

where $Pr\{\}$ represents the probability of its argument, P_r is the received power in dB and P_{req} is the required value.

Beginning with the link budget equation

$$P_r = P_t + G_t + G_r - L_p\,(dBm), \tag{B-24}$$

we can rewrite the expression for availability as

$$A = Pr\left\{L_p \le P_t + G_t + G_t - P_{req}\right\} \tag{B-25}$$

or

$$A = 1 - Pr\left\{L_p > P_t + G_t + G_r - P_{req}\right\}. \tag{B-26}$$

As mentioned earlier, L_p is Gaussian distributed with mean M_p and standard deviation σ so

$$A = 1 - Q\left\{\frac{\left(P_t + G_t + G_r - P_{req}\right) - M_p}{\sigma}\right\}, \tag{B-27}$$

where $Q\{\}$ is the Q function[3]

Thus, for a link to meet its performance objective, the condition

$$P_t + G_t + G_r - M_p = P_{req} + \sigma t\ (dBm) \tag{B-28}$$

must be met, where t is the availability factor defined by

$$t = Q^{-1}\{1 - A\} \tag{B-29}$$

and the product σt is the shadow-fading margin.

Land mobile radio evaluates availability in two ways. The expression

$$Pr\{P_r(R) \ge P_{req}\} \tag{B-30}$$

is referred to as contour availability. This is the availability at a specific location on the circumference of a circle with radius *R*. The transmitter is at the center of the circle. The expression

---

[3] $Q\left\{\frac{a-m_x}{\sigma_x}\right\} = Pr\{X > a\} = \int_{\frac{a-m_x}{\sigma_x}}^{\infty} e^{\frac{-y_2}{2}}\, dy$ and its inverse is $Q^{-1}\{Pr\{X > a\}\} = \frac{a-m_x}{\sigma_x}$, where m_x and σ_x are the mean and standard deviation of the random variable X.

$$\frac{1}{\pi R^2} \iint_{\theta=0\ r=0}^{2\pi\ R} Pr\{P_r(r) \geq P_{req}\}\, dr d\theta \tag{B-31}$$

is referred to as covered area availability. This is the average availability over the circular area. Contour and covered area availabilities can be related to one another through the path loss model σ and n parameters [B-5].

For public safety, 97 percent covered area availability is often required for outdoor applications and 90 percent is required indoors, except in critical areas such as exit stairs where 95 percent or more is required. Table B-2 lists t for the most common percent availabilities.

Table B-2. Parameter t for the most common percent availabilities, %A

%A	**84.13**	**90.0**	**95.0**	**97.0**	**97.7**
t	1.0	1.28	1.64	1.88	2.0

B.6 Site-specific Propagation Models

Site-specific models calculate the power at any point in a building from detailed information such as floor layout and building material electrical properties. Site-specific models can be very helpful for positioning antennas inside the building. Ray tracing and dominant-path are two commonly used site-specific models.

Ray tracing sums continuous-wave signals launched over the antenna beamwidth [B-6]. It is based on physical principles and depends on knowing the exact locations and electrical characteristics of the building's walls, floors, and ceilings. The signals or "rays" arrive delayed and attenuated due to interactions with the building's walls and floors. Furnishings are generally not considered. Enhanced versions include effects of diffraction. The rays can be summed with or without phase information. If they are summed with phase, the results include multipath fading effects. Although ray tracing is computationally burdensome for in-building propagation analysis, it is not prohibitively so with current computer technology. Comparison of ray tracing results to measurements within a building showed a 1.6 dB mean error with a 6.8 dB standard deviation.

The dominant path method reduces computational burden by dramatically reducing the number of rays or paths used to predict field strength [B-7], [B-8]. This approach is based on empirical evidence, which shows that most energy arriving at a location comes from a small number of paths. The dominant path is obtained using an algorithm that selects the path with the least attenuation from a tree diagram depicting the spatial relationships between rooms within the building. Field strength is then predicted by feeding a number of characteristics of the dominant path into a neural network algorithm that has been previously trained with measured data from similar buildings. Accuracy of the dominant path method is increased if the neural network is also trained with measurements from the specific building. Comparison of the dominant path method to measurements within a building showed a 7.7 dB mean error with an 8.0 dB standard deviation when no measurements from the building were used in training. This mean error was reduced to 0.2 dB and the standard deviation to 3.5 dB when measurements from the building were used in training.

B.7 Multipath Fading

Although multipath fading has no effect on path loss, this is not to say it has no effect on radio performance. In fact, the low instantaneous signal powers caused by multipath fading do momentarily diminish audio quality. One way to compensate for multipath fading is to add a multipath fading margin to the SNR required for a radio operating in AWGN.

Determination of the margin depends on knowing the statistical distribution of the instantaneous power fluctuations. Worst-case multipath fading is typically characterized by Rayleigh distributed amplitudes. This is a reasonable assumption when the radios operate in a narrow bandwidth, with omnidirectional antennas, and in or around nearby objects that scatter the radio signal into a number of rays. In addition, this assumption is well supported by measurements in outdoor [B-9] as well as indoor [B-10], [B-11] environments.

B.8 References

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APPENDIX C: CALCULATIONS

This Appendix contains calculations that compare how well a portable radio operates in a building without and with an IBRES as in Section 2.6, demonstrate how automatic gain control (AGC) can cause gain reduction as in Section 3.2, and demonstrate how noise transmitted by BDA can degrade the performance of another systems repeater as in Section 3.3.

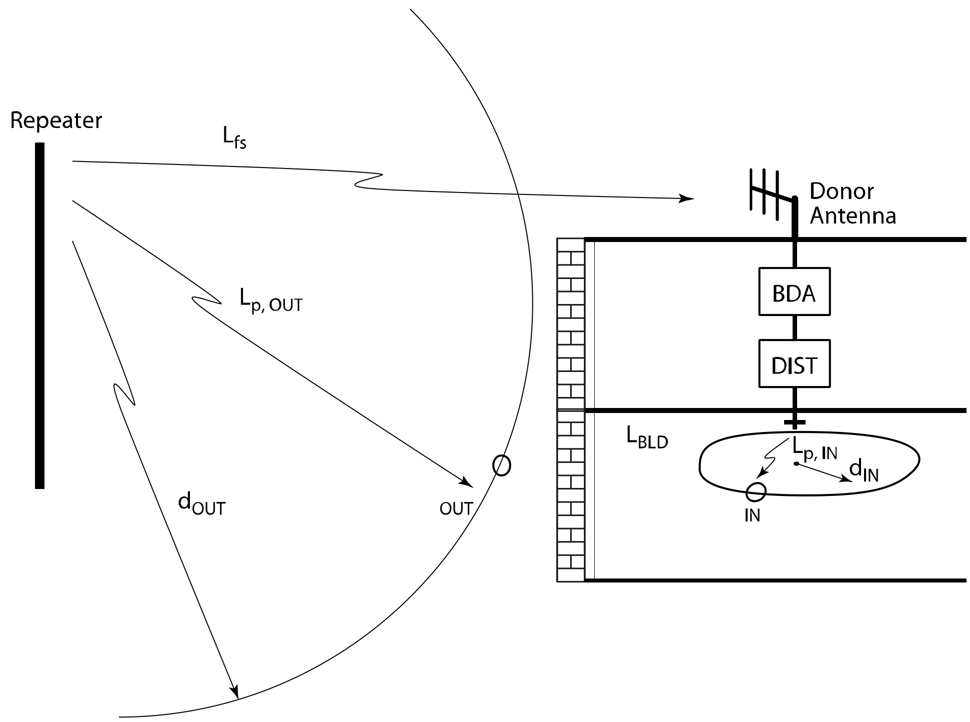

Figure C-1. Schematic representation of scenario used for calculations in this Appendix.

Figure C-1 depicts the scenario used in this Appendix which is composed of a repeater and a building located on the edge of the repeater coverage area. The repeater has a circular coverage area with radius d_{OUT}. The path loss from the repeater to the edge of the coverage area is $L_{p,OUT}$. For calculations without the IBRES, building attenuation is L_{BLD}. The portable radio is assumed to be on the first floor. The exact location on the first floor is not important.

For calculations with the IBRES, the building has a donor antenna, BDA, distribution network, and indoor antenna. The path loss from the repeater to the donor antenna is L_{fs}. The indoor antenna has a circular coverage area with radius d_{IN}. The portable radio is assumed to be at the edge of the indoor antenna coverage area. The path loss from the indoor antenna to the edge of its coverage area where the portable radio is operated is $L_{p,IN}$.

Outdoor, building, and indoor propagation parameters are derived from measurements. In all cases propagation loss is composed of a mean and variable, shadow fading component as described in Appendix B

$$L = M + X \ (dB), \qquad \text{(C-1)}$$

where M is the mean and X is the variable component characterized by σ.

The outdoor propagation parameters are derived from measurements of a 900 MHz cellular system [C-2] where M is computed from n = 3.0 and d_0 = 1 km, and σ is 8.9 dB. The building attenuation parameters are derived from measurements of urban high-rise buildings on the first floor [C-3] where M is 18 dB and σ is 8 dB. The indoor propagation parameters are derived from measurements of an office environment at 914 MHz [C-7] where M is computed from n = 3.3 and d_0 = 1 m, and σ is 11.2 dB.

The calculations assume an analog frequency modulated (FM) public safety portable radio operated in the 800 MHz National Public Safety Advisory Committee (NPSAC) band in a 12.5 kHz channel. The portable radio has a quarter-wave whip antenna and is mounted on the hip. The repeater is equipped with a stacked dipole antenna and a tower top amplifier.

Transmitter powers and receiver noise figures are referred to the antenna terminals. Received powers are reported in terms of the power received by an unobstructed dipole antenna. Variable names are consistent within the Appendix. Unless otherwise stated, upper case variables are the decibel equivalents of their corresponding lower-case variables and logarithms are base 10.

C.1 Required Power

This section calculates the amount of power, P_{req}, required to achieve our desired delivered audio quality (DAQ) performance level. It is a worst-case estimate in that it assumes high antenna loss associated with a hip-mounted portable radio with a quarter-wave whip antenna. The carrier to noise ratio (CNR) is that needed to achieve the desired performance level in a Rayleigh fading channel. Shadow fading is not taken into account.

This worst-case estimate is expressed in terms of the power received by an unobstructed vertically-polarized, half-wave dipole antenna by

$$p_{req} = \frac{p_t g_t g_d}{l_p}, \tag{C-2}$$

where p_t is the transmitted power, g_t is the transmitter antenna gain, g_d is the dipole antenna gain, and l_p is the path loss. Dipole antennas are commonly used for conformance tests.

The CNR after reception by the antenna and detection filtering is

$$\psi = \frac{p_{req}}{l_a n}, \tag{C-3}$$

where l_a is the antenna loss relative to g_d and n is the noise power in the detection filter bandwidth. The loss includes body absorption, depolarization and antenna pattern irregularities. The noise power is

$$n = kT_0 b_{eq} f_{port}\,, \tag{C-4}$$

where k is Boltzman's constant, T_0 is the ambient temperature in Kelvin, b_{eq} is the detection filter equivalent noise bandwidth, and f_{port} is the noise factor.

Solving for p_{req} we find that

$$p_{req} = kT_0 b_{eq} f_{port} \psi l_a \tag{C-5}$$

or in decibels

$$P_{req} = kT_0 + B_{eq} + F_{port} + \Psi + L_a \ (dBm)\,. \tag{C-6}$$

Table C-1 shows that -87.7 dBm is needed when measured with the dipole antenna.

Table C-1. Required power when measured with a dipole antenna

	Value	**(C-6)**	**Notes**
kT_0	-174.0 dBm/Hz	-174.0	
B_{eq}	38.9 dB-Hz	38.9	7.8 kHz ENBW
F_{port}	6.0 dB	6.0	
Ψ	26.0 dB	26.0	DAQ 3.4, Rayleigh fading
L_a	15.4 dB	15.4	Relative to dipole antenna
P_{req}		-87.7 dBm	Dipole antenna

The factors B_{eq}, ψ, and L_a were derived from [C-1]. The factor B_{eq} is from Table 5, "Intermediate Frequency Filter Specifications for Simulating Receiver." The factor ψ is from Table A-1, "Projected Channel Protection Criteria (CPC) Requirements for Different Delivered Audio Qualities (DAQ)." The target DAQ, commonly used for public safety radio design, is from Table 2, "Delivered Audio Quality." The factor L_a is from Table D-5, "Median Portable Antenna Loss Outside and Inside Vehicle."

In some municipalities radio power measurements are made with the handheld portable radio. In general the loss of a portable radio with an unobstructed quarter-wave whip antenna is 5 dB compared to the dipole antenna. The corresponding received signal strength is -92.7 dBm.

C.2 Link Budgets

C.2.1 Portable Radio Operated Outside Building

The portable radio operating outside a building requires

$$P_{req,OUT} = P_{req} + \sigma_{OUT} t \ (dBm), \quad \text{(C-7)}$$

where σ_{OUT} is the standard deviation of the outdoor path loss variability in dB, t is the contour availability factor, and $\sigma_{OUT} t$ is the outdoor shadow-fading margin. As shown in Table C-2, $P_{req,OUT}$ is -73.0 dBm assuming σ_{OUT} is 8.9 dB, the contour availability corresponding to 97 percent covered availability is 95 percent, t is 1.65, and the shadow fade margin is 14.7 dB.

Table C-2. Minimum power for portable radio operated outside building

	Value	(C-7)	Notes
P_{req}	-87.7 dBm	-87.7	Dipole antenna
$\sigma_{OUT} t$	14.7 dB	14.7	
$P_{req,OUT}$		-73.0 dBm	Dipole antenna

C.2.2 Portable Radio Operated Inside Building Without an IBRES

A portable radio operating inside a building without an IBRES requires

$$P_{req,IN} = P_{req} + \sigma t \ (dBm), \quad \text{(C-8)}$$

where

$$\sigma = \sqrt{\sigma_{OUT}^2 + \sigma_{BLD}^2} \ (dB) \quad \text{(C-9)}$$

and σ_{BLD} is the building path-loss variability standard deviation.

The power received in the building is

$$P_r = P_{req,OUT} - M_{BLD} \ (dBm), \quad \text{(C-10)}$$

where M_{BLD} is the mean building attenuation.

As shown in Table C-3 and Table C-4, $P_r < P_{req,IN}$. Consequently, the link does not meet the performance level objective. The calculations assume σ_{BLD} is 8 dB, M_{BLD} is 18 dB, the contour availability corresponding to 90 percent covered availability is 83 percent, t is 0.96, and the shadow fade margin is 13.7 dB.

Table C-3. Power required by a portable radio operated inside building without an IBRES

	Value	**(C-8)**	**Notes**
P_{req}	-87.7 dBm	-87.7	Dipole antenna
σt	13.7 dB	13.7	
$P_{req,IN}$		-74.0 dBm	Dipole antenna

Table C-4. Power provided to the portable radio operated inside building without an IBRES

	Value	**(C-10)**	**Notes**
$P_{req,OUT}$	-73.00 dBm	-73.00	Dipole antenna
M_{BLD}	18.0 dB	-18.0	
P_r		-91.0 dBm	Dipole antenna

C.2.3 Portable Radio Operated Inside Building With an IBRES

A portable radio operating inside a building with an IBRES requires

$$P_{req,IN} = P_{req} + \sigma_{IN} t \ (dBm). \quad \text{(C-11)}$$

The power received in the building is

$$P_r = P_{req,OUT} + G_C + G_{IBRES} - M_{p,IN} (dBm) \quad \text{(C-12)}$$

where G_c is the clutter gain, G_{IBRES} is the IBRES gain, and $M_{p,IN}$ is the mean indoor path loss.

Clutter gain is

$$G_C = M_{p,OUT} - L_{fs} (dB) \quad \text{(C-13)}$$

The mean outdoor path loss is

$$M_{p,out} = P_{t,REP} + G_{REP} + G_d - P_{req,OUT} \ (dB) \quad \text{(C-14)}$$

where $P_{t,REP}$ is the repeater power, G_{REP} is the repeater antenna gain, and G_d is the dipole gain. Using the values in Table C-5, $M_{p,out}$ is 123.3 dB. This path loss corresponds to a distance of 12.4 km when the path loss exponent, n, is 3 and the reference distance, d_0, is 1 km . The L_{fs} at this distance is 112.4 dB. Consequently G_c is 10.9 dB. This estimate is considerably more conservative than one that uses a flat-earth reference [C-4].

Table C-5. Mean outdoor path loss

	Value	(C-14)	Notes
$P_{t,REP}$	43.0 dBm	43.0	20 watts at antenna terminals
G_{REP}	5.15 dBi	5.15	40 degree elevation beamwidth, omnidirectional antenna
G_d	2.15 dBi	2.15	
$P_{req,OUT}$	-73.0 dBm	73.0	Dipole
$M_{p,out}$		123.3 dB	

The IBRES gain is composed of three elements, i.e.

$$G_{IBRES} = G_\alpha + G_{BDA} - L_\beta \ (dB), \tag{C-15}$$

where G_α is the IBRES gain before the BDA due primarily to the donor antenna, and L_β is the IBRES loss after the BDA primarily due to the distribution network. Locations of these IBRES model parameters are depicted in Figure C-2.

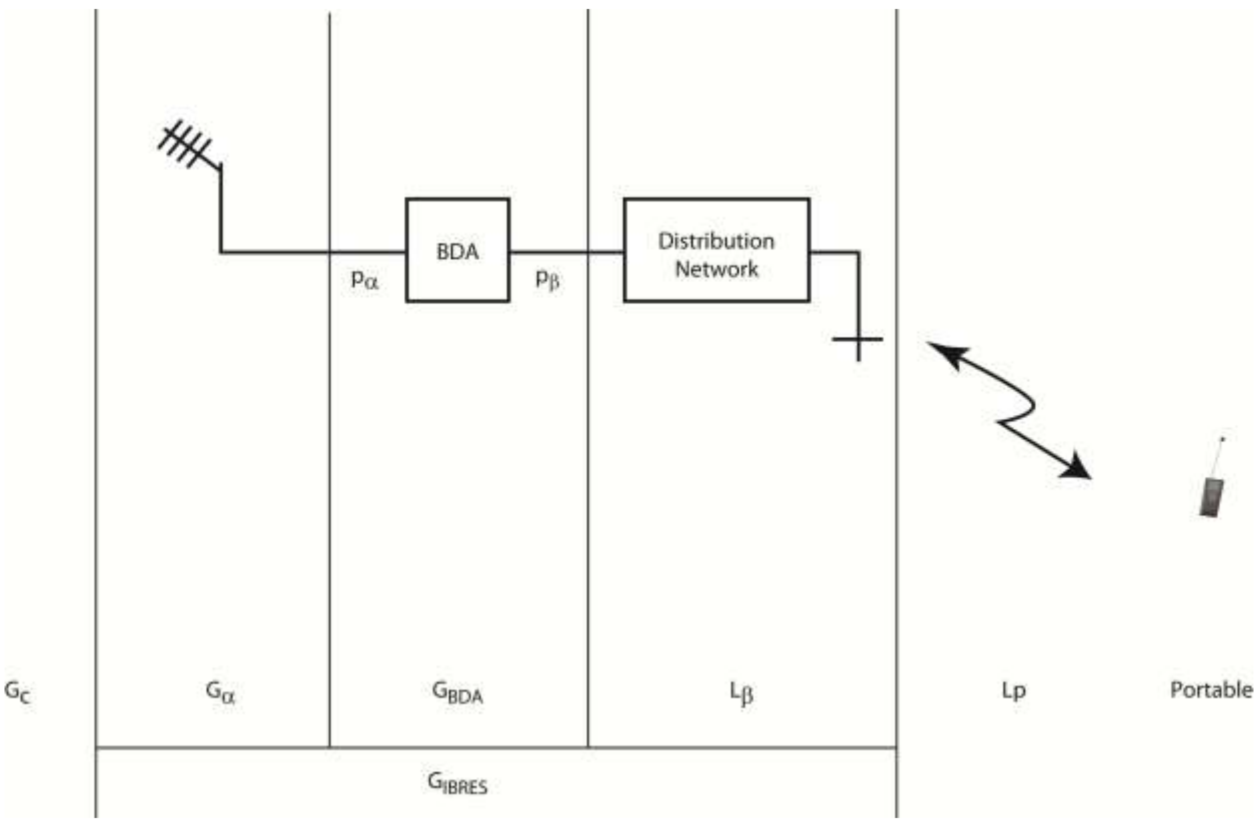

Figure C-2. IBRES model parameters

The BDA gain, G_{BDA}, can vary from $G_{BDA,max} - L_{mgc}$ to $G_{BDA,max}$ where L_{mgc} is the manual gain control attenuation. The effective BDA gain, Γ, is the amount of gain in dB after both manual and automatic gain control has been applied and can vary from $G_{BDA} - L_{agc}$ to G_{BDA} where L_{agc} is the automatic gain control attenuation. The gain factor corresponding to Γ is γ. The maximum amount of power the BDA can supply is $P_{BDA,max}$ dB.

The optimal BDA gain is that needed for $P_r = P_{req,IN}$ when the power outside is $P_{req,OUT}$. Combining (C-12) and (C-15) and solving for G_{BDA}

$$G_{BDA,opt} = P_{req,IN} + L_\beta + M_{p,IN} - P_{req,OUT} - G_c - G_\alpha \ (dB) \qquad \text{(C-16)}$$

Gain is computed for the IBRES in our example, which consists of a Yagi donor antenna, BDA, and coaxial distribution network similar to the one shown in Figure 16. The Yagi donor antenna is connected to a BDA through 25 feet of cable. The $G_{BDA,max}$ is 80 dB, $L_{mgc,max}$ is 30 dB, $L_{agc,max}$ is 30 dB, and $P_{BDA,max}$ is 30 dBm.

The distribution network, shown in Figure C-3, is designed with guidance from [C-5] and [C-6]. The network is composed of coaxial cable and directional couplers. The cable has losses of 2 dB per 100 feet. Directional coupler loss is shown in the figure. Starting with the antenna closest to the vertical cable, the signal is attenuated 17.0, 17.8, and 16.8 dB by the distribution network. We will use the highest attenuation in our calculations.

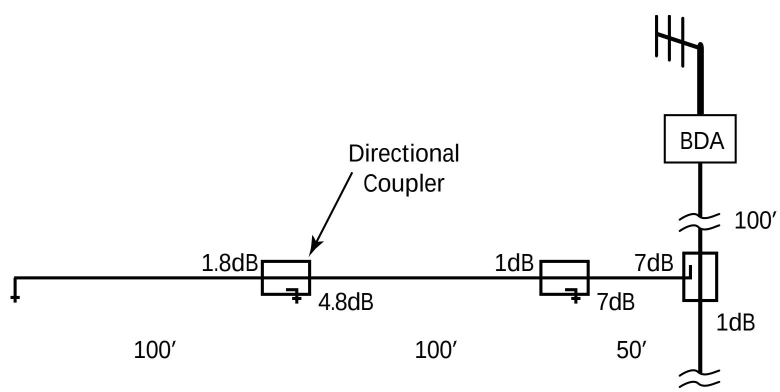

Figure C-3. Distribution network used in this example

Mean indoor path loss, $M_{p,IN}$ $M_{p,IN}$, at the edge of the 62.5 foot radius coverage area is 72.8 dB when the path loss exponent, n, is 3.3 and the reference distance, d_0, is 1 m.

The $G_{BDA,opt}$ and G_{IBRES} are given in Table C-6 and Table C-7. As shown in Table C-8 $P_{req,IN}$ is -78.2 dBm assuming σ_{IN} is 11.2 dB, the contour availability corresponding to 90 percent covered area availability is 80 percent, t is 0.85, and the shadow fade margin is 9.5 dB. As shown in Table C-9, $P_r = P_{req,IN}$ and the IBRES meets its performance level objective.

Table C-6. Optimum BDA Gain

	Value	(C-16)	Notes
$P_{req,IN}$	-78.2 dBm	-78.2	
Distribution network loss	17.8 dB		
Indoor antenna gain	3.0 dB		
L_β	14.8 dB	14.8	
$M_{p,IN}$	72.8 dB	72.8	
$P_{req,OUT}$	-73.0 dBm	73.0	
G_C	10.9 dB	-10.9	
Donor antenna gain	11.1 dB		
Rooftop cable loss	0.5 dB		
G_α	10.6 dB	-10.6	
$G_{BDA,opt}$		60.9 dB	

Table C-7. IBRES Gain

	Value	(C-15)	Notes
G_α	10.6 dB	10.6	
G_{BDA}	60.9 dB	60.9	
L_β	14.8 dB	-14.8	
G_{IBRES}		56.7 dB	downlink

Table C-8. Power required by a portable radio operated inside building with an IBRES

	Value	(C-11)	Notes
P_{req}	-87.7 dBm	-87.7	Dipole antenna
$\sigma_{IN}t$	9.5 dB	9.5	
$P_{req,IN}$		-78.2 dBm	Dipole antenna

Table C-9. Power provided to the portable radio operated inside building with an IBRES

	Value	(C-12)	Notes
$P_{req,OUT}$	-73.0 dBm	-73.0	Dipole antenna
G_C	10.9 dB	10.9	
G_{IBRES}	56.7 dB	56.7	downlink
$M_{p,IN}$	72.8 dB	-72.8	
P_r		-78.2 dBm	Dipole antenna

The corresponding uplink link budget needed later in repeater desensitization calculations is

$$P_{r,REP} = P_{t,PORT} + G_{PORT} - \sigma_{IN} t - M_{p,IN} + G_{IBRES} - L_{fs} + G_{REP}\ (dBm) \qquad \text{(C-17)}$$

where $P_{r,REP}$ is the power received by the repeater antenna, $P_{t,PORT}$ is the power transmitted by the portable radio, G_{PORT} is the portable antenna gain, and G_{REP} is the repeater antenna gain. Tables C-9 and C-10 show how this link budget can be satisfied. The repeater is assumed to have a tower top amplifier and a system noise figure equivalent to the portable noise figure. Consequently, the optimal BDA gain is that needed to achieve -103.1 dBm at the output of the repeater antenna. G_{BDA} is 69.1 dB in the uplink, making G_{IBRES} 64.9 dB.

Table C-10. Power required by repeater

	Value		**Notes**
kT_o	-174.0 dBm/Hz	-174.0	
B_{eq}	38.9 dB-Hz	38.9	7.8 kHz ENBW
F_{REP}	6.0 dB	6.0	
Ψ	26.0 dB	26.0	DAQ 3.4, Rayleigh fading
$P_{r,REP}$		-103.1 dBm	

Table C-11. Power received by repeater antenna

	Value	**(C-17)**	**Notes**
$P_{t,PORT}$	34.8 dBm	34.8	3 watts
G_{PORT}	-13.25 dBi	-13.25	Hip-mounted, quarter-wave whip
$\sigma_{IN} t$	9.5 dB	-9.5	
$M_{p,IN}$	72.8 dB	-72.8	62.5 feet coverage radius
G_{IBRES}	64.9 dB	64.9	uplink
L_{fs}	112.4 dB	-112.4	12.4 km
G_{REP}	5.15 dBi	5.15	Omnidirectional, 40 degree vertical beamwidth
$P_{r,REP}$		-103.1 dBm	

C.3 Effects of AGC

Class B BDA ACG reduces gain when activated. The reduction in gain can potentially cause the received signal power to fall below what is required. In this section, we show two examples of how this might occur in the IBRES downlink. These examples are highly idealized in that they assume that channels can be evenly powered and always in use.

Channel powers outside the building at street level and inside the building are P_{OUT} and P_{IN}, respectively. The relationship between these powers is

$$P_{IN} = P_{OUT} + G_c + G_\alpha + \Gamma - L_\beta - M_{p,IN} \ (dBm) \qquad \text{(C-18)}$$

where G_c is the clutter gain, $G_\alpha$is the IBRES gain before the BDA, Γ is the BDA gain after both manual and automatic gain control have been applied, L_β is the IBRES loss after the BDA, and $M_{p,IN}$ is the mean indoor path loss.

In the first example, we show how increasing the number of channels can cause the received signal to fall below $P_{req,IN}$ when AGC is activated. Assume there are n equal power channels that have outdoor powers equal to $P_{req,OUT}$.
The power at the input to the BDA is

$$P_\alpha = P_{req,OUT} + G_c + G_\alpha + N \ (dBm) \qquad \text{(C-19)}$$

where $N = 10\log(n)$.

If $P_\alpha + G_{BDA,min} \leq P_{BDA,max}$ then the AGC is not activated

$$\Gamma = G_{BDA,opt} \ (dB) \qquad \text{(C-20)}$$

and

$$P_{IN} = P_{req,OUT} + G_c + G_\alpha + G_{BDA,opt} - L_\beta - M_{p,IN} \ (dBm) \ . \qquad \text{(C-21)}$$

If $P_\alpha + G_{BDA} > P_{BDA,max}$ then the AGC is activated

$$\Gamma = P_{BDA,max} - P_\alpha \ (dB) \qquad \text{(C-22)}$$

and

$$P_{IN} = P_{BDA,max} - L_\beta - M_{p,IN} - N \ (dBm) \ . \qquad \text{(C-23)}$$

The maximum number of channels the BDA can provide $P_{req,IN}$ is

$$n_c = 10^{(P_{BDA,max} - P_{req,IN} - L_\beta - M_{p,IN})/10}. \qquad \text{(C-24)}$$

For the example in C.2.3 where

$P_{BDA,max}$	30 dBm
$P_{req,OUT}$	-73.0 dB
$P_{req,IN}$	-78.2 dB
G_c	10.9 dB
G_α	10.6 dB
$G_{BDA,opt}$	60.9 dB
L_β	14.8 dB
$M_{p,IN}$	72.8 dB

n_c is 114.8. If n is 32 then P_α= -36.45 dBm, $P_\alpha + G_{BDA,min} \leq P_{BDA,max}$, the AGC is not activated, Γ = 60.9 dB, and P_{IN}= -78.2 dBm. If n is 128 then P_α= -30.4 dBm, $P_\alpha + G_{BDA,min} > P_{BDA,max}$, the AGC is activated, Γ = 60.4 dB, and P_{IN}= -78.7 dBm which is less than $P_{req,IN}$. Table C-11 summarizes these results for a range of n.

Table C-12. Gain and indoor channel power for various numbers of channels with equal input power.

n	**Γ (dB)**	**P_r (dBm)**	**AGC state**
1	60.9	-78.2	Off
2	60.9	-78.2	Off
4	60.9	-78.2	Off
8	60.9	-78.2	Off
16	60.9	-78.2	Off
32	60.9	-78.2	Off
64	60.9	-78.2	Off
114	60.9	-78.2	Off
128	60.4	-78.7	Activated

In the second example we show how one strong channel can drive the remaining channels below $P_{req,IN}$ when n is less than n_c. Suppose $n-1$ channels operate outside the building at $P_{req,OUT}$ as in the previous example, but the n-th channel power is allowed to vary. Also, assume that the $n-1$ channels operate inside the building at $P_{req,IN}$, AGC attenuation is not activated, and Γ= $G_{BDA,opt}$.

The power of the n-th channel inside the building is

$$P_{n,IN} = 10\log\left(p_{BDA,max} - p_{req,IN}(n-1)l_\beta m_{p,IN}\right) - L_\beta - M_{p,IN}\ (dBm) \qquad \text{(C-25)}$$

and the corresponding power outside the building is

$$P_{n,OUT} = P_{n,IN} + L_{\beta} + M_{p,IN} - G_{BDA,opt} - G_{\alpha} - G_c\ (dBm). \quad \text{(C-26)}$$

Any additional power would activate the AGC, decrease BDA gain, and cause the other n-1 channels to fall below $P_{req,IN}$. Table C-13 shows the maximum n-th channel power allowed without activating the AGC. These results were calculated with the same parameters used in the previous example. They show a strong channel can drive the other equally powered channels below $P_{req,IN}$ with fewer than n_c channels.

Table C-13. Maximum $n-$th channel power allowed without activating the AGC.

n	$P_{n,OUT}$ **(dBm)**	$P_{n,IN}$ **(dBm)**
2	-52.4	-57.6
4	-52.5	-57.7
8	-52.6	-57.8
16	-53.0	-58.2
32	-53.7	-58.9
64	-55.8	-61.0
114	-70.4	-75.6

C.4 Distance Needed to Prevent Repeater Receiver Desensitization

This calculation determines the distance needed to separate another system's antenna from the IBRES donor antenna to protect the other system's receiver from noise desensitization. The estimate is worst-case because the propagation path from the donor antenna to the other system's antenna is assumed to be line of sight.

We start with the equation for calculating free-space loss between the other system's antenna and the IBRES donor antenna

$$l = \frac{p_t}{p_i} = \frac{1}{g_t g_r}\left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{(C-27)}$$

where p_t is the transmitted IBRES noise power in the channel bandwidth at the BDA output, p_i is the interfering noise power in the same bandwidth received by the other system, g_t is the donor antenna gain, g_r is the other system's antenna gain, d is the distance between the two antennas, and λ is the wavelength.

Rearranging terms,

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{p_t}{p_i} g_t g_r} \quad \text{(C-28)}$$

or

$$d = 10^{\frac{20\log(\lambda/4\pi) + G_t + G_r + P_t - P_i}{20}} . \qquad \text{(C-29)}$$

In decibels

$$P_t = kT_0 + B + F_{BDA} + G_{BDA} \ (dBm), \qquad \text{(C-30)}$$

where kT_0 is the thermal noise floor, F_{BDA} is the BDA noise figure, G_{BDA} is the BDA gain, and B is the channel bandwidth.
P_i is computed from

$$P_i = N + INR \ (dBm), \qquad \text{(C-31)}$$

where

$$N = kT_0 + B + F_{os} \quad (dBm), \qquad \text{(C-32)}$$

$$INR = 10\log\left(\frac{snr}{sinr} - 1\right)(dB), \qquad \text{(C-33)}$$

and F_{os} is the other system noise figure.

We have chosen an $SINR$ of 23 dB which would correspond to a 3.0 DAQ for the 12.5 kHz analog portable radio we are analyzing. The DAQ degradation from 3.4 at 26 dB to 3.0 at 23 dB would be noticeable to the user. At a DAQ of 3.4, repetitions are rarely needed. However, at a DAQ of 3.0, occasional repetitions are necessary.

For our example, P_t is -61.5dBm as shown in the table below. SNR is 26 dB, $SINR$ is 23 dB, INR is 0 dB, and P_i is -129.1 dBm, as is also shown in the table below. Finally, G_t is 11.15 dBi, G_r is 5.15 dBi, and the distance is 1447.2 ft. (441.0 m).

Table C-14. Noise power at the BDA output.

	Value	**(C-30)**	**Notes**
kT_0	-174.0 dB/Hz	-174.0	
B	38.9 dB-Hz	38.9	7.8 kHz ENBW
F_{BDA}	5.0 dB	5.0	
G_{BDA}	69.12 dB	69.12	
	0.5 dB	-0.5	Cable loss
P_t		-61.5 dBm	

Table C-15. Other system receiver noise power.

	Value	(C-31) and (C-32)	Notes
kT_0	-174.0 dBm/Hz	-174.0	
B	38.9 dB-Hz	38.9	7.8 kHz ENBW
F_{os}	6.0 dB	6.0	
INR	0 dB	0	
P_i		-129.1 dBm	

C.5 References

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[C-6] Bird Technologies, How to properly design an In-building DAS, Part: 1, http://www.bird-technologies.com/resources/white_papers/How-to-Properly-Design-an_In-Building-Distributed-Antenna-System_Pt.2.pdf

[C-7] S.Y. Seidel and T.S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multi-floored buildings," IEEE Trans. on Veh. Tech., Vol. 40, No. 2, Feb. 1992, pp. 207–217.

APPENDIX D: BDA MEASUREMENTS

BDA gain, output power, feedback, and noise measurements are described in this Appendix. Unless otherwise stated, uppercase variable names are in decibels.

The measurement test fixture is shown in Figure D-1. Principle components of the test fixture are a continuous wave (CW) signal generator, BDA, and spectrum analyzer (SA). These components are connected together by various cable assemblies.

The cable assembly connecting the signal generator to the BDA input, A to B, includes a power combiner and has loss L_{AB}. The cable assembly connecting the spectrum analyzer to the BDA output, C to D, includes a 20 dB directional coupler and has loss L_{CD}. The cable assembly comprising the feedback loop path, C to B, includes a 20 dB directional coupler, variable attenuator, and power combiner. The variable attenuation, L_{VA}, can be adjusted from 0 to 132 dB in 1 dB steps. The feedback loop has loss L_{CB} when L_{VA} is set to 0 dB.

Specifications for the BDA are listed in Table D-1. The BDA amplifies both uplink and downlink signals. It does not matter which link is used for these measurements. The BDA has manual gain control (MGC) and automatic gain control (AGC). The BDA did not have a specialized oscillation detection and mitigation function. AGC prevents the signal from exceeding the BDA's FCC-certified maximum power output. For these measurements, MGC was set to its minimum 0 dB value and AGC was turned off unless otherwise noted.

Spectrum analyzer settings are given in Table D-2. Reference level and attenuation are given with the spectrum measurement descriptions. The SA is tuned to the middle of the BDA bandwidth. The span is set wider than the BDA bandwidth. Video averaging is used to obtain a reliable noise power estimate.

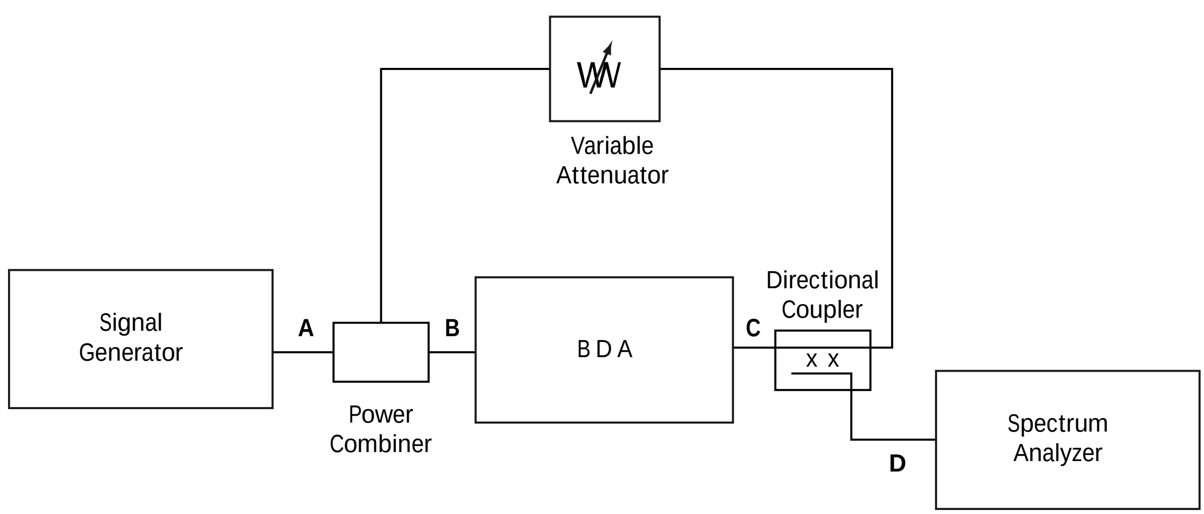

Figure D-1. Measurement test fixture used to perform BDA measurements.

Table D-1. BDA Specifications supplied by manufacturer.

Parameter	Specification	Notes
Frequency range (MHz)	806-824 uplink 851-869 downlink	
Power output (dBm)	24 +/- 1	
Gain (dB)	60	Minimum gain at minimum attenuation
Gain flatness (dB)	+/- 1.5	Maximum deviation from mean gain
Manual gain control (dB)	15	
Automatic gain control (dB)	30	Activated at maximum output
Noise figure (dB)	6	At maximum gain
VSWR In/Out	1.5:1	Maximum
3rd order intermodulation distortion (dBc)	50	Typical. Two 20 dBm tones.
3rd order intercept point (dBm)	45	Typical. Two 20 dBm tones.

Table D-2. Spectrum analyzer settings.

Setting	Value
Frequency	860 MHz
Span	30 MHz
Resolution bandwidth	300 kHz
Video bandwidth	300 kHz
Video averaging	On
Detection	sample
Sweep time	50 ms
Points per trace	601
1 dB compression point	-5 dBm

A number of measurements were made with this test fixture. Measurement details are provided below.

First, the cable assembly losses L_{AB}, L_{CB}, and L_{CD} were measured. The cabling assemblies were temporarily detached from the measurement fixture. The power supplied by the CW signal generator, P_1, was measured by connecting a cable directly to the spectrum analyzer. Next, the power through the cable assembly, P_2, was measured by disconnecting the cable from the SA and reestablishing the circuit through the cable assembly. The cable assembly loss is

$$L = P_1 - P_2 . \quad \text{(D-1)}$$

Second, the BDA gain, G_{BDA}, was measured. The variable attenuator was set to maximum attenuation to eliminate feedback. Using the same methodology as measuring the cable assembly loss above

$$G_{BDA} = \left(P_2 + L_{CD}\right) - \left(P_1 - L_{AB}\right). \quad \text{(D-2)}$$

Third, the maximum BDA output power, P_{max}, was measured. The variable attenuator was set to maximum attenuation to eliminate feedback. The power out of the CW signal generator was increased from a level where the BDA maximum output power light was off until it turned on, $P_{2,max}$. The maximum output power is

$$P_{max} = P_{2,max} + L_{CD} \quad \text{(D-3)}$$

Results for these tests are summarized in Table D-3.

Table D-3. Results for cable assembly loss, BDA gain, and maximum power output measurements.

L_{AB}	5.5 dB
L_{CB}	10.8 dB
L_{CD}	21.6 dB
G_{BDA}	64.3 dB
P_{max}	22.5 dBm

Fourth, the BDA output spectrum was measured. For this measurement, the signal generator was turned off. Feedback between the output of the BDA and its input causes two conditions: oscillation and distortion. These conditions are caused by an inadequate feedback loop margin (FLM) defined by

$$FLM = L_{FL} - G_{BDA}, \quad \text{(D-4)}$$

where

$$L_{FL} = L_{VA} + L_{CB}. \quad \text{(D-5)}$$

Table D-3, Figure D-2, Figure D-3, Figure D-4, and Figure D-5 show results of laboratory BDA output spectrum measurements with various amounts of FLM. Measurements for Figures D-2 and D-3 used -10 dBm reference level and 0 dB attenuation SA settings. Measurements for Figures D-4 and D-5 are much higher power and used a 10 dBm reference level and 20 dB of attenuation SA settings and an additional 3 dB attenuator at the SA input. Power was corrected for Figures D-2 and D-3 with

$$P = P_2 + L_{CD}. \quad \text{(D-6)}$$

Power was corrected for Figures D-4 and D-5 by

$$P = P_2 + L_{CD} + 3.0. \quad \text{(D-7)}$$

Table D-4. BDA Spectrum measurement results with AGC turned off.

L_{VA} (dB)	L_{CB} (dB)	L_{FL} (dB)	G_{BDA} (dB)	*FLM* (dB)	Spectral Characteristic
53.0	10.8	63.8	64.3	-0.5	Oscillation
54.0	10.8	64.8	64.3	0.5	Distortion
69.0	10.8	79.8	64.3	15.5	Distortion
99.0	10.8	109.8	64.3	45.5	Filtered noise

Figure D-2 shows the spectrum when the FLM is 45.5 dB. The BDA bandwidth is filled with amplified noise across the BDA bandwidth. Table D-5 shows how the power of this noise is calculated.

Table D-5. Noise power for 45.5 dB FLM trace in Figure D-2.

	Value	Calculation
kT_0	-174.0 dBm/Hz	-174.0 dBm/Hz
Noise figure	6.0 dB	6.0
BDA gain	64.3 dB	64.3
Resolution bandwidth	54.7 dB	54.7
Error due to envelope detection, logarithmic amplification, and Gaussian filter response	-2.5 dB	-2.5
Noise power		-51.5 dBm/300 KHz

Figure D-3 shows the spectrum when the FLM is 15.5 and 0.5 dB. The noise at the BDA input is distorted in a way that produces ripple in the spectra. Distortion occurs when the FLM is positive but not large enough stop the signal at the BDA input from interfering with itself. The ripple peaks are spaced approximately 5 MHz apart. The 15.5 dB FLM peaks have much less power than those in the 0.5 dB FLM case; 15 dB is often recommended as a minimal amount of FLM. The shift in frequency between curves is most likely due to the different paths through the variable attenuator.

Figure D-4 shows the spectrum when the FLM is -0.5 dB. This spectrum has a spike, the power of which exceeds 1 watt. The ripple observed in the distorted measurements is also present. The measurement noise floor has risen due to the increased SA attenuation.

All the previous measurements were conducted with AGC off. We repeated the spectrum measurements with AGC on to see what effect the AGC has. The AGC had no effect in the distorted and undistorted cases shown in Figure D-2 and Figure D-3. Figure D-5 is the exact same oscillating BDA measurement as in Figure D-4 except that the AGC is turned on. The figure shows that the AGC only limits the maximum power. It does not stop oscillation.

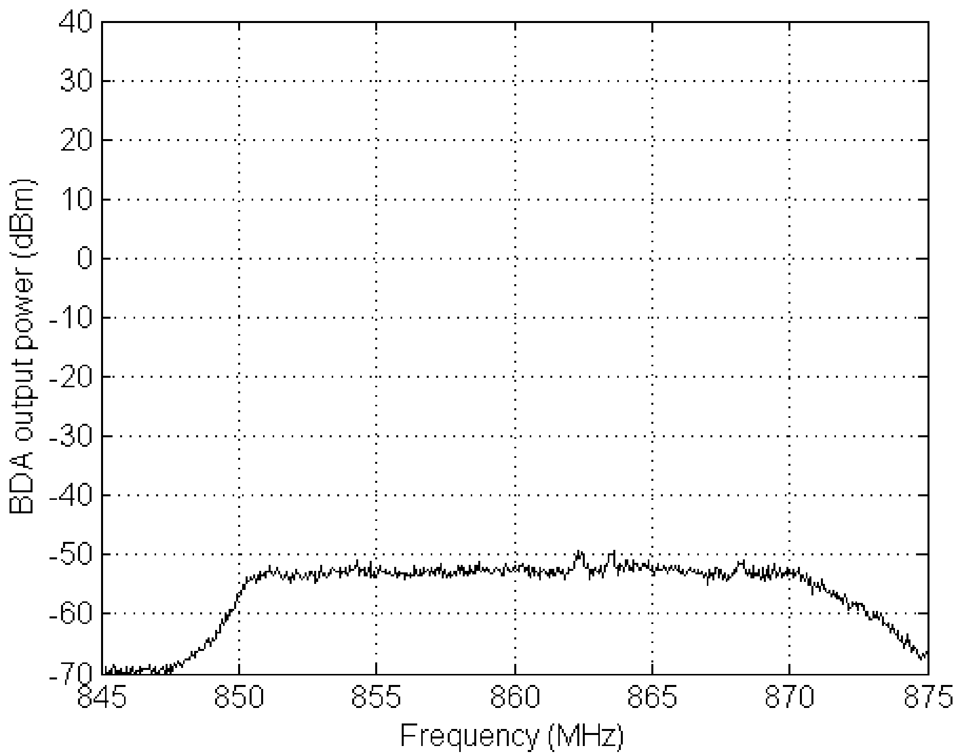

Figure D-2. BDA output spectrum with 45.5 dB FLM showing amplified noise, but no feedback.

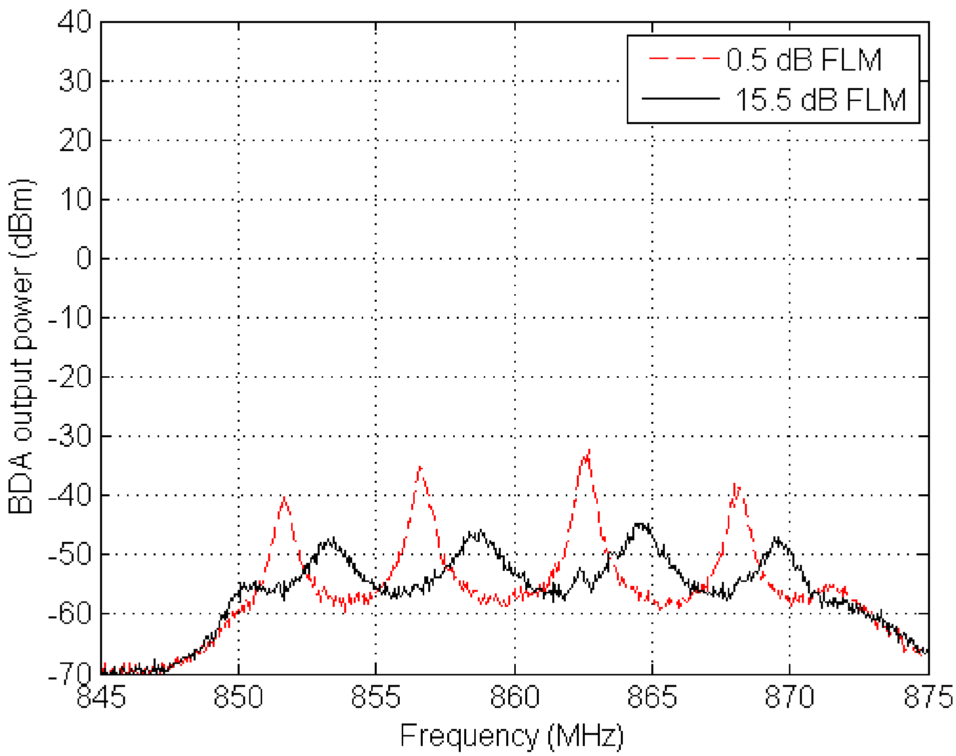

Figure D-3. BDA output spectrum with 15.5 and 0.5 dB FLM showing distortion.

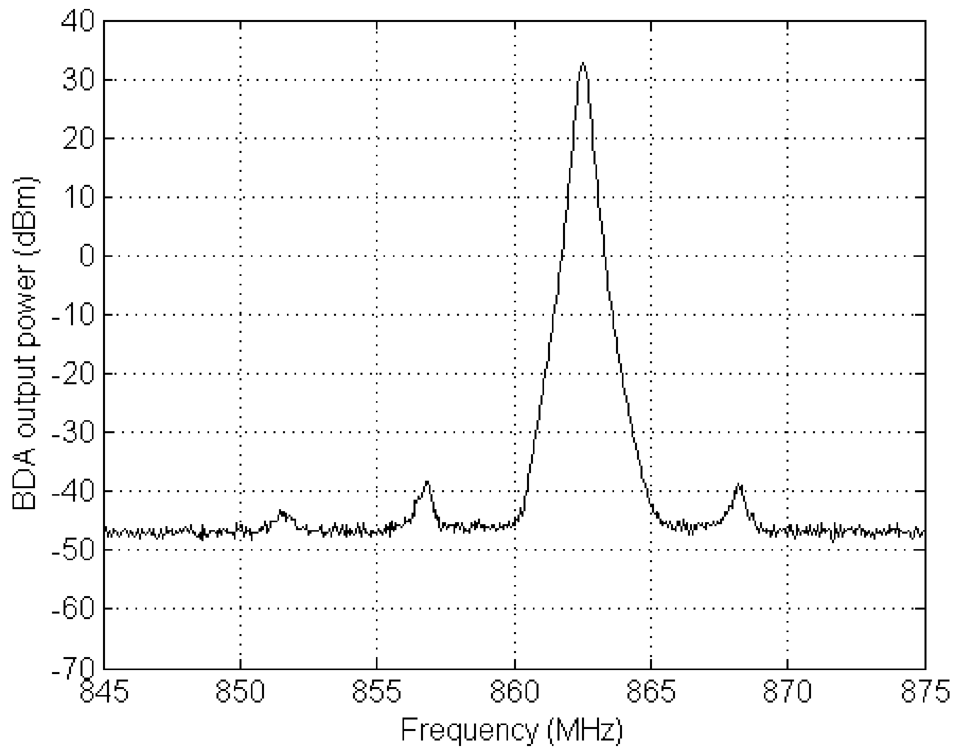

Figure D-4. BDA output spectrum with -0.5 dB FLM showing oscillation.

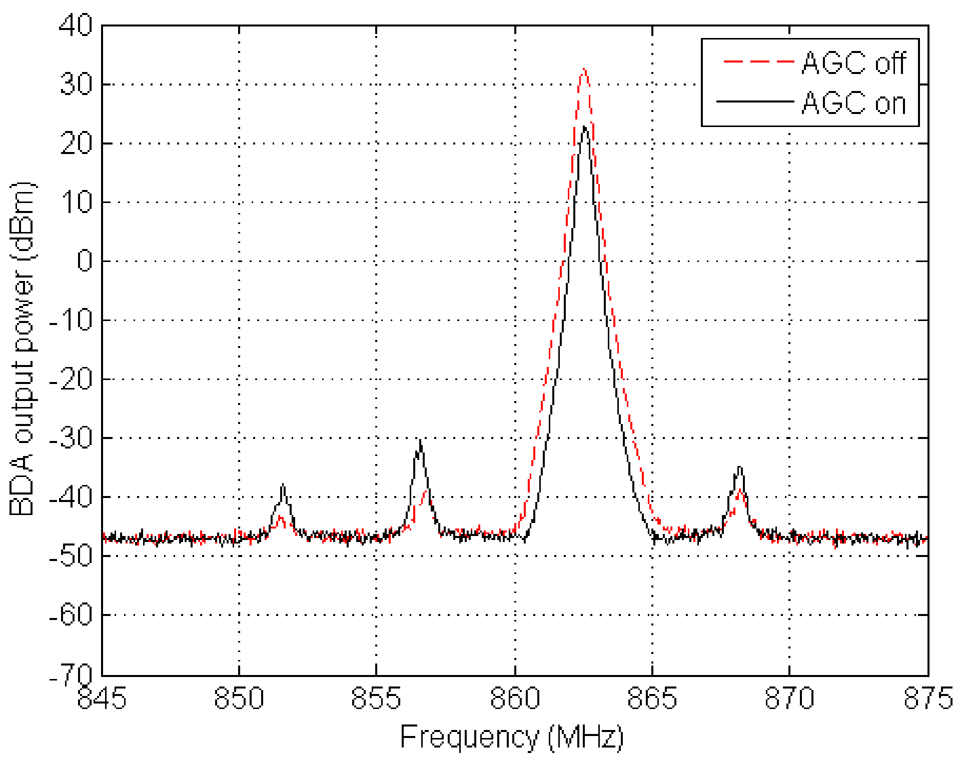

Figure D-5. BDA output spectrum with -0.5 dB FLM showing oscillation regardless of AGC setting.

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Reliable public safety communications between system repeaters outside of a building and portable radios inside of a building is often not possible due to building attenuation. To circumvent this problem, increasing numbers of municipalities are requiring building owners to provide in-building radio enhancement systems (IBRES). The report is intended to be used by public safety communications professionals who are tasked with assisting building owners fulfill this requirement. The main body describes IBRES technology, problems endemic to it, solutions to these problems, and its future challenges. Appendices provide detailed tables, theory, calculations, and measurements that support assertions made in the main body.

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bi-directional amplifiers; building attenuation; distributed antenna system; in-building radio enhancement system; land mobile radio; link budget; public safety radio; radio-wave propagation

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