GUIDE TO

BODY-WIRE TECHNOLOGY

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1.0 Introduction to Body-Wire Technology

Law enforcement agencies utilize body-wires for officer security and to obtain evidence. Audio quality, transmitted power and price vary with different systems. Typically, the transmission range can be between 30 and more than 3,000 feet depending on the environment and the quality of the equipment. In addition, there are many different frequencies utilized for transmission. Faced with a bewildering array of technical specifications and different technologies, the non-technical user requires a way to relate significant manufacturer specifications to field performance.

This report selects key manufacturer specifications and shows how they can be used to evaluate body-wire performance. Figures of Merit are developed for these specifications to assist in the selection of a body-wire. The Figures of Merit establish markers or criteria that can be used to evaluate equipment performance as a pre-purchase consideration. A comparison is made of three technologically different systems: Narrowband Frequency Modulation (NBFM), Digital and Digital Spread Spectrum. Field tests in different locations were performed to verify the use of the specifications and the associated Figures of Merit. This report demonstrates how field performance of body-wires can be estimated by an understanding of key specifications listed by the manufacturer. The absence of such specifications should be a red flag to the law enforcement user that the equipment may be deficient in important areas.

The purpose of a body-wire system is to transmit audio in the form of a radio signal to be received, understood and/or recorded at a remote location. The person wearing the body-wire can be moving and turning in locations that range from outside to inside a building and from ground level to many stories up. While the transmitter is often mobile, the receiver is generally in one location. In the case of vehicle audio surveillance, both the transmitter and receiver are in motion, but the transmission distance is generally constant.

The transmitter may be required to cover thousands of feet or a few yards. The different environments of the signal propagation path will cause different attenuation levels: the signal will be more attenuated and the range, therefore, reduced if it is required to travel through numerous buildings. Noise conditions, present at the time the audio signal is recorded, will vary from those of an outdoor, urban environment (which has many possible levels of background noise) to that of a quiet, indoor room.

There are trade-offs to be considered in the purchase of a body-wire. In general, superior voice quality is achieved in digital systems at the expense of reduced range and higher transmit power as compared to FM systems. Digital systems provide an inherent level of message privacy and Digital Spread Spectrum systems spread the signal across a wider bandwidth making it less prone to detection. This spread signal is more prone to multipath effects (see Section 1.4) which can severely limit the received audio quality in the absence of a multipath corrector in the receiver. System costs tend to increase as one moves from lower quality FM to Digital and Spread Spectrum technology.

1.1 Body-Wire System Overview

Figure 1.1 shows a diagram of a body-wire consisting of microphone, antenna and transmitter. A microphone changes acoustical energy (sound) into electrical energy. A body-wire that uses analog modulation, such as NBFM, uses the output signal of the microphone to modulate a frequency tone, referred to as a 'carrier', and this transmitted signal is referred to as being 'analog'. A digital system passes the output of the microphone through an analog-to-digital converter, the output of which is a series of 1's and 0's referred to as digital data. This digital data then modulates a carrier tone and the transmitted signal is referred to as being "digital". In Digital Spread Spectrum systems the digital data is further encoded with another sequence of 1's and 0's referred to as a PN or Pseudorandom Noise sequence before modulating the carrier tone. Thus there are Analog, Digital and Digital Spread Spectrum body-wire systems; the difference in technology being the type of signal used to modulate the carrier.

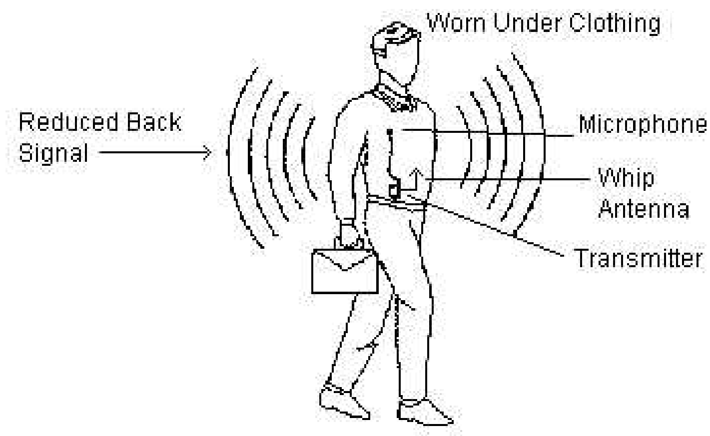


Figure 1.1 A Complete Body-Wire System

1.2 The Decibel as a Unit of Measure

The decibel (dB) is a unit that is used to describe the ratio of two voltages, currents, or power levels and is based on a logarithmic scale. The unit dBm is used to express power in dB relative to one milli-Watt (1 mW). The decibel is used in acoustic measurements because the human ear responds to the sound volume in approximately a logarithmic manner. In measurements of transmission range the decibel is used since transmitted power attenuation has a logarithmic relationship with distance. Since manufacturers use different measurement expressions, this report provides conversion tables to show the relationship between power in milli-Watts and decibels (mW to dBm) and power in micro-Volts converted to dBm (uV to dBm). It should be emphasized that dBm is an absolute power level in mW, i.e. 20 dBm = 100 mW, whereas dB relates to relative power levels, i.e. a power difference. Many body-wire specifications are in dB or dBm.

Decibel Conversion Formula

* Power in dBm to power in mW is calculated from
  Power (dBm) = 10 Log_{10}(power mW).
  For example 100 mW;
  P (dBm) = 10 Log_{10} (100) = 20 dBm.

* Power in dBm to power in Volts in a 50 ohms system is calculated from
  Power (dBm) = 10 Log_{10} (20 x V^2)
  For example 10 uV;
  P (dBm) = 10 Log_{10} (20 x 0.00001^2) = -87 dBm

* Power change in dB is calculated from
  Power change = 10 Log_{10} (Power ratio).
  For example the power increase in a signal from 1mW to 5 mW is;
  P (dB) = 10Log_{10} (5/1) = 7 dB

The dBm conversion chart, Figure 1.2, shows conversion from mW to dBm. For example to convert, 100mW to dBm read 100 from the horizontal scale and then find the corresponding vertical value of 20 dBm. The receiver sensitivity, a manufacturer's specification, is given in micro-Volts (uV) or dBm. The micro-Volt and dBm conversion chart, Figure 1.3, shows conversion from uV to dBm in a 50 ohm system. For example, 0.18uV is –122 dBm

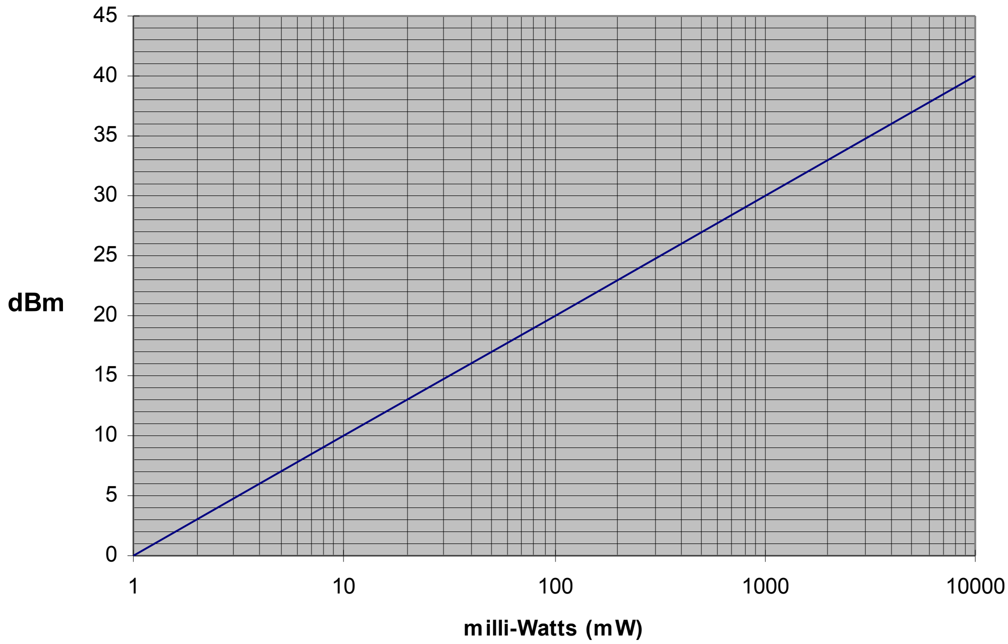


Figure 1.2 Conversion from milli-Watts (mW) to dBm

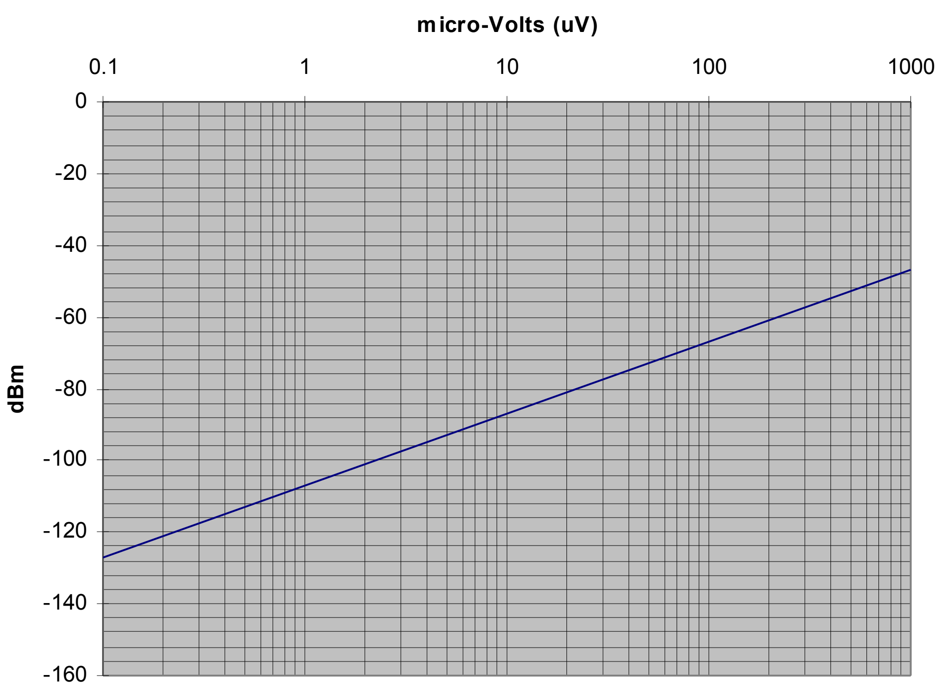


Figure 1.3 Conversion from micro-Volts (uV) to dBm for a 50 ohm system

Table 1 shows relative volume levels for different sounds. The levels in dB are relative to the threshold of hearing that is taken to be 0 dB. For example the audio dynamic range necessary to capture audio from whispers to a shout, must be greater that 72 dB (90-18 dB)

Table 1: Relative Audio Dynamic Range – Sound Pressure Level

Threshold of hearing	0 dB
Quiet Whisper at 5 feet	18 dB
Quiet Office	55 dB
Typical Analog Tape Recorder	57 dB
Average Conversational Speech	70 dB
Shout	90 dB
Typical DAT Recorder	90 dB
Subway	102 dB
Threshold of Painful Sound	130 dB

1.3 Body-Wire Antenna Placement and Type

Antenna considerations are very important for body-wire applications. The type of antenna and placement can have a great effect on body-wire performance. Omni-directional antennas, sometimes called 'whip' or 'stub' antennas, are most commonly furnished with body-wires. These antennas transmit the radio frequency (RF) signal in a circular pattern or, more precisely, a doughnut pattern. These antennas are a good choice for stand alone or 'free space' usage since they are non-directional, give good coverage and avoid having the receiver operator engage in an exercise to pinpoint the strongest signal.

However, using whip antennas on or near the human body can seriously degrade the overall performance. The body can be considered a bag of mineral water and as such, severely attenuates radio energy. An antenna placed on the body will exhibit some loss in the outward (away from the body) and a large loss in the backward (through the body) directions. The attenuation may be sufficient to cause a significant loss of signal power at the receiver. Reference (2) indicates that the human body may absorb up to 80% of the power transmitted by the body-wire when a whip antenna is used. If one fifth of the power is transmitted this corresponds to a 7 dB reduction in power at the receiver ($10 \text{ Log}_{10} (0.2) = 7$ dB). If the power loss is too large there will be insufficient energy for the receiver to product intelligible audio.

There are antennas (patch antennas), which will minimize the effect the body has on the transmission. These antennas are very directional and are supplied as a pair (front and back radiators). These antennas allow maximum transmission (without gain) away from the body and still provide ease of concealment. The gain of an antenna is a measure of its directivity, which is the ability to focus the energy it radiates in a particular direction.

A guide to good body-wire installation dictates that the antenna should be placed as high on the body as possible. It would be a great accomplishment if the antenna could be placed on the top of a “beanie hat” (disguised as a propeller). A more realistic alternative is to locate the antenna on the shoulder. The shoulder mount is a good compromise for a whip antenna since the radiation pattern will be horizontal, which is considered favorable for operations at/near ground level. The “patch antennas”, mentioned above, also benefit from being mounted as “high as possible”. Antenna size and type must be considered. The general rule is that for any given antenna as the frequency goes up the antenna gets smaller. Antenna gain increase is at the expense of increasing directionality and size.

1.4 Effects of Multipath, Absorption Losses, and Motion on Transmission Range

From reference (4), “*Complex interaction between geometry, radio propagation effects and mobility make prediction of coverage and path loss a practically intractable problem. Rudimentary models have been developed but empirical or heuristic methods nearly inevitably fare better. Building materials, physical layout and the motion of people effects coverage.*”

Multi-path effects are due to portions of the signal arriving at the receiver at different times from the main signal, caused by reflections within the environment. In digital systems with large bandwidths, multi-path causes a smearing of the received data bit stream and can result in audio outage. Signals from a transmitter reach the receiver via multiple paths and arrive at slightly different times. The multiple signals are as disruptive to communications as signal interference from other transmitters. True free space propagation without multipath is encountered only in such Line-of-Sight (LOS) systems such as satellite-to-satellite communications where ground reflections are minimal.

In typical urban environments the signal is partially blocked and attenuated due to noise clutter, and absorption by trees, people and other obstacles. Building penetration and absorption losses are very important considerations to urban wireless systems. Depending upon building material and radio frequency, penetration losses of typically 7.6 to 16.4 dB into a building may be encountered. People moving about will create short-term fading.

Multipath propagation in body-wires occurs largely due to reflections from the earth contributing to the received signal. Free space attenuation is 6 dB/octave. From Reference (2), a consideration of free space and ground reflections is typically 12 dB/octave*. As discussed in Reference (2), this agrees with the Federal Communications Commission measurements for UHF and VHF communications. A 6 dB/octave requires a power increase of 4 to provide a doubling of distance with the same received power. 12 dB/octave requires a **16** times increase in power to provide a doubling of distance. For example in an environment where there is a 12 dB/octave requirement in power, to go from 100 meters with a power level of 100 mW at the transmitter to 200 meters with the same received power level requires that the power at the transmitter be increased from 100 mW to 1600 mW or 1.6 W. This corresponds to an increase from 20 dBm (100mW) to 32 dBm (1600mW) or 12 dB change.

*A change "per octave' is the engineering way of saying 'a change every time the unit is doubled'. In this example a 12 dB change would occur when going from 100 feet to 200 feet or when going from 300 feet to 600 feet.

2.0 The Six Main Features of a Body-Wire System

When considering acquiring or using a body wire system the user should be cognizant of six performance features:

1. **Voice Quality of the Received Audio**
2. **Transmission Range**
3. **Battery Lifetime**
4. **Physical Disguise**
5. **Electronic Security**
6. **Cost**

Understanding the role played by these six attributes will prove to be an asset in determining the suitability of a body wire system under consideration. Each of the features 1 through 5 is discussed in this section. The most significant manufacturer specifications for each feature are provided along with the associated Figures of Merit.

2.1 Feature 1: VOICE QUALITY OF THE RECEIVED AUDIO

The human ear has a dynamic range of over 120 dB. Contemporary digital recording techniques can only achieve a dynamic range of about 90 dB. The typical threshold of pain is around 130 dB, with discomfort starting around a sound level of 118 dB. The normal hearing range is considered to be 15 Hz to 20 kHz. The typical hi-fi specification range is 20 Hz to 20 kHz. Typically, however, the average person cannot hear 20 Hz. The typical telephone has a frequency response of 400 Hz to 4 kHz. The human ear does not hear all frequencies at the same intensity. It is less sensitive at both the lower and upper ends of the audio spectrum, and this characteristic varies with both age and gender.

Voice Quality can be assessed primarily from specifications of AUDIO BANDWIDTH and AUDIO DYNAMIC RANGE and, if available, AUDIO SIGNAL TO NOISE RATIO. The complete band of frequencies that extend through the range of human hearing is generally described as being between 20 Hz to 20 KHz. The audible bandwidth and the corruption of the quality of the delivered sound due to noise and distortion are critical factors in determining voice quality at the receiver.

The specifications to be considered in determining Voice Quality are:
Audio Bandwidth, Audio Dynamic Range, Audio Signal to Noise Ratio, Bit Error Rate

Audio Bandwidth

FM systems typically cut off around 6 KHz. The effect of this is that the audio will sound more like a telephone response. Voice identification requires a more complete identification of sounds, which is only achievable with high quality systems. Figure 2.0 shows the spectrum of sound of the spoken letter ‘o’. One would think that the spoken ‘o’ contains little high frequency content, however, the chart clearly shows that there is high frequency content for this speech (above 6 KHz). Typically telephone systems use 400 Hz to 4 KHz audio bandwidth and high quality music Compact Disk (CD) recording can have an Audio Bandwidth of 20 Hz to 20 KHz. There is clearly a difference between the sound quality of a voice on a telephone and on a music CD. Voice intelligibility requires a lower bandwidth than voice identification. The body-wire manufacturer specifies Audio Bandwidth as a low frequency to high frequency range. Audio Bandwidth is sometimes provided with the term Audio Frequency Response.

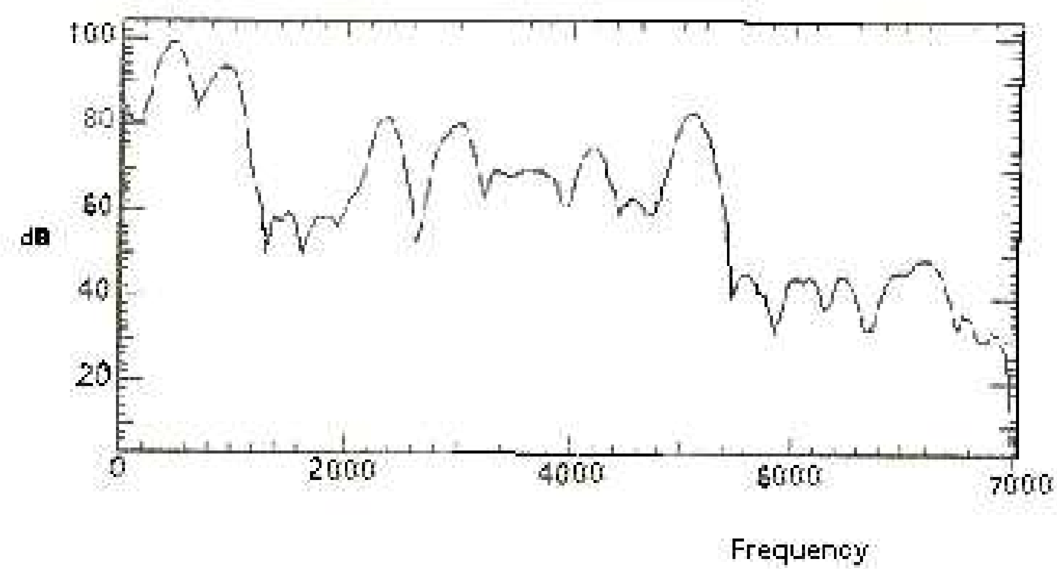


Figure 2.0 shows the spectrum 0.15 seconds into the utterance of the "o" vowel.

Figure of Merit for Audio Bandwidth

Lower Frequency Response	Higher Frequency Response	
>400 Hz	<4 KHz	Telephone quality
>200 Hz	<6 KHz	Adequate
>100 Hz	<8 KHz	Good
>100 Hz	<12 KHz	Very Good
>50 Hz	<16 KHz	Excellent
>50 Hz	>16 KHz	Superb

Audio Dynamic Range (ADR)

ADR is a measure of the systems ability to handle loud and soft sounds. It is the ratio of the loudest undistorted signal that the system can handle compared to its internal noise. ADR indicates how well the system reproduces audio within a range of volume and noise conditions. ADR is basically an indication of how well the system will respond to very low-level sounds and very high-level audio. For example: if a recording was made of a whisper and then of a shout, the system would need to have sufficient ADR to reproduce both the audio signals <u>without</u>

distortion. The ADR should be given in dB for the system (transmitter and receiver). The system audio dynamic range must exceed the rating of the loudest audio to be encountered in order to produce an undistorted response. From Table 1, if whispers and shouting were present then the dynamic range would have to have a range from 18 dB to 90 dB.

Automatic Gain Control (AGC) complicates the matter. AGC is a process by which gain is automatically adjusted as a function of the audio input level or other parameter.

Many radio systems do not have sufficient dynamic range to handle full audio sound levels. Some may be limited to as little as 30-40 dB. In order to accommodate a variety of sound levels, electronic methods are used to position the dynamic range window in the most advantageous place to accurately pick up the most critical audio levels. From Table 1, if whispers and low voice were important, a dynamic range window of 50 dB would be centered on the 45 dB mark. Therefore, audio levels from 20 to 70 dB could be received without distortion, whereas sounds below 20 dB and above 70 dB would be distorted to varying degrees. Well-designed systems can automatically shift this dynamic range window to accommodate louder or quieter sounds. However the AGC shifting may produce undesirable audio artifacts. A carefully crafted AGC will reduce or eliminate artifacts associated with automatic control.

Figure of Merit for ADR

Less than 40 dB	Poor
Around 60 dB	Moderate
Greater than or equal to 80 dB	Excellent

Audio Signal to Noise Ratio (SNR)

In most listening environments a SNR of >80 dB means that the electronic noise from the system cannot be heard if the maximum signal power at the output is greater than 80 dB above noise power. The electronic noise will then be inaudible at normal listening levels and deliver what is perceived to be "clean" and "clear" sound. A SNR of less than 65 dB will realize more audible noise. In some cases, enough noise is realized to provide levels of distortion and annoyance. Manufacturers often fail to provide this specification. From Reference (1) Figure 2.0 shows typical SNR for audio systems.

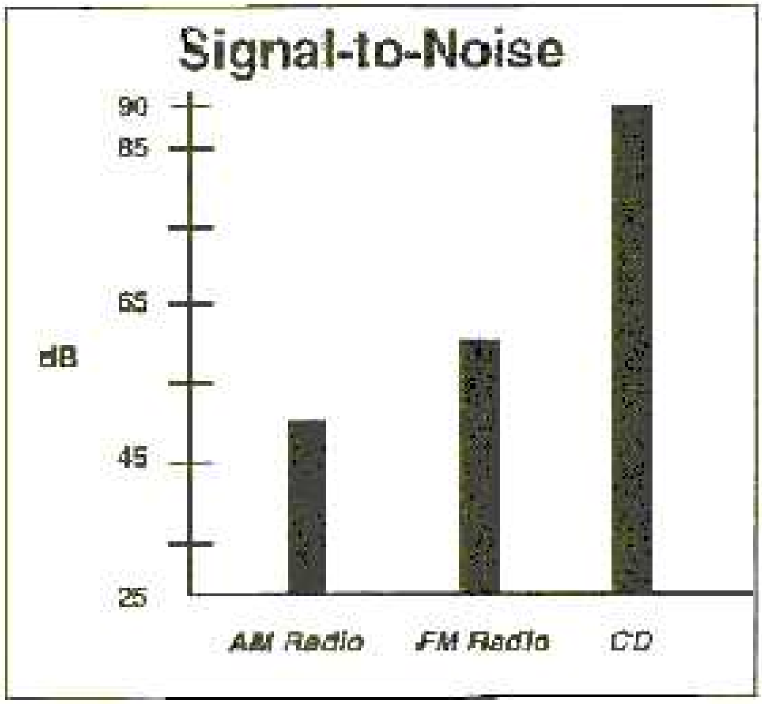


Figure 2.1 Typical SNR for Audio Systems

Figure of Merit for Audio SNR

SNR less than 45 dB	Poor
SNR between 45 dB and 65 dB	Moderate
SNR greater than 80 dB	Excellent

Bit Error Rate (BER)

Bit Error Rate is a specification found only in digital systems and is defined as follows:

Bit Error Rate is the number of bits in the digital stream, which have been received with the wrong value, compared to the total number of bits received.

Each bit in the digital stream of data has a value of 1 or 0. These bits taken together in preset groups (usually 8, 16 or 32 bits) form the 'words' which correspond to the digital representation of the audio wave form being transmitted. If one of these bits, is somehow assigned the wrong value the sound finally put out by the receiver will be distorted. The more bits sent without error, the better the quality of the resultant audio.

Typically, Bit Error Rate is expressed as the frequency of a single erroneous bit. For example, if the system design resulted in one bad bit out of every 100,000 bits sent, then the Bit Error Rate is 1/100,000 or 10^{-5}. A Bit Error Rate of 10^{-6} means that for every 1,000,000 bits sent, one of them will have the wrong value and the audio will be distorted for that instant. Obviously, the more erroneous bits the worse the audio sounds. The better the digital system is designed, the lower the Bit Error Rate. Bit Error Rate has a relationship to the receiver sensitivity. In general, receiver sensitivity is influenced by a change in Bit Error Rate (and vice versa). Thus, a receiver with –100 dBm sensitivity @ BER of 10^{-5} could have a sensitivity of –103 dBm @ BER of 10^{-4}. In other words, the receiver is less sensitive but produces a higher quality audio at the –100 dBm figure, but as the apparent range increases (sensitivity improves to –103 dBm) the audio gets worse.

NOTE: All digital systems have a Bit Error Rate associated with them and this number should be available to the user.

Figures of Merit for Bit Error Rate (BER)

$< 10^{-4}$	Poor
10^{-5}	Good
10^{-6}	Excellent
10^{-7} and up	Excellent ++
10^{-9}	Outstanding

2.2 Feature 2: TRANSMISSION RANGE

Range evaluation is dependent on two manufacturer specifications: Transmitter (TX) power, and Receiver (RX) sensitivity. Path loss represents loss in signal power due to the transmission from body-wire to receiver, and is an environment factor which determines range for a given TX power and RX sensitivity. Path loss cannot be specified by the manufacturer and needs to be accounted for by the user. There are many environmental factors, which will increase path loss over a specific distance. Path loss across 100 meters in an urban environment may be the same as path loss across a much longer distance in an environment without buildings or crowds of people.

For example, one may experience a 50 dB path loss across 40 meters in one environment and 70 dB across 40 meters in another. From specifications of TX output power and RX sensitivity the maximum path loss for received audio that can be accommodated by the system can be calculated. For example, if the body-wire transmitted a maximum of 100mW (20 dBm) and the receiver sensitivity was 0.18uV (-122 dBm) then the Maximum Path Loss (MPL) would be (20 dBm - (-122 dBm)) = 142 dB. For the same distance path loss is greater in urban areas than in open terrain. Estimation of path loss is provided in Appendix C.

Specifications to be considered in determining Transmission Range are

Transmitter Output Power, Receiver Sensitivity, Path Loss

Transmitter Output Power

In general, increasing TX power will increase range for a particular terrain and RX sensitivity specification. The power should be expressed in mW or dBm. Output power is an important factor in useable transmission range of the equipment. (Refer to the dBm conversion chart to change between mW and dBm, Figure 1.2).

There is no Figure of Merit for Transmit output power since each operation will accommodate different equipment with different power ratings

Recommendations:

Below 20 mW	Use with caution - do trial run in the actual environment to be sure the equipment performs as required.
20 mW to 100 mw	Short-range applications but remain cautious in urban environment.
100 mW to 200 mW	Good - general purpose use.
Above 200 mW	Good but size and battery requirements may be a problem.

Receiver Sensitivity

The Receiver sensitivity defines the lowest received power level of the transmitted signal that can be detected by the receiver at its antenna. A signal received at this level should provide audio output at the receiver. Receiver sensitivity should be quoted for a specific SNR. Sensitivity is usually given in dBm. Some radio frequency (FM) systems use a receiver sensitivity notation of micro-Volts (uV) for a specific SINAD instead of SNR; SINAD is signal to noise plus distortion. Figures 1.2 and 1.3 convert mW to dBm and uV to dBm.

Figures of Merit for Receiver Sensitivity

Typically specifications will be lower for narrow bandwidth signals such as FM and higher for wider bandwidth signals such as Digital Spread Spectrum. Note that sensitivity is stated with negative numbers since the power is much below 1 mW (see Section 1.2). Example: -100 dBm sensitivity is better than –98 dBm and –108 dBm is better yet.

FM systems typically -110 dBm or below. A specification of -120dBm or below represents very good sensitivity.

Digital systems typically -90 to –110 dBm. A specification of -103dBm or below represents very good sensitivity.

Path Loss

Path loss is very dependent on physical conditions present in the locale of the transmitter and receiver and on the carrier frequency. Building structures, the number of people between transmitter and receiver, interfering vehicles, metal wall studs, etc. (the local operating conditions) will serve to attenuate the transmitted signal by varying amounts. It is not uncommon to see a requirement of a 8-fold increase in required power to double the range. Engineering studies have shown that in some cases, the attenuation at ground level is so great that output power must be increased 16 times in order to double the range. The expression often stated of four times the power to double the range is mainly applicable for line of sight conditions. Terrain is very important when looking at power outputs of different systems when trying to determine whether the equipment will meet range expectations.

2.3 Feature 3: BATTERY LIFETIME

Minimum and Maximum Operating DC voltage and Current Drain have a direct bearing on the type of battery most suitable for the equipment. The lower the current drain the longer the equipment will run on a battery. Since many battery manufacturers list the battery capacity in mAh (milli-Amp hours) or Ah (Amp hours) it is quite easy to determine how long the equipment will run on a given battery.

To conserve battery power, some room transmitters are voice activated and start transmitting automatically when sounds or conversations begin and turn off when sounds cease. This practice has severe pit falls because an unanticipated sound (dog barking) can keep the system running, reducing battery life.

Example #1

Assume a transmitter requires 6 volts DC and consumes 130-mA current and the operation requires that the transmitter run at least 80 hours. AA alkaline style batteries are typically 1.5 VDC per battery. A typical capacity for AA batteries is 170 hours at a current drain of 130 mA and at the end of that time the battery voltage will be approximately 1 Volt.

Batteries in series (negative terminal to plus terminal in a chain) will add voltage, thus four batteries in a series, @ 1.5 VDC each, will make a battery pack of 6 VDC, while 6 such batteries will make a pack of 9 VDC. For this example, 4 batteries are not recommended. Four batteries will start out at 6 VDC, but when connected will immediately drop voltage. The transmitter will cease to operate at some minimum voltage. In this example, the minimum operating voltage is not known. (Unfortunately, this is a common occurrence since many manufacturers do not list a minimum operating voltage). In order to have an operating voltage "cushion" six batteries should be used. Note that commercial battery containers are available in 2, 4, 6, and eight configurations. Six batteries will provide 9 volts at 130-mA current for an operating time of about 170 hours. In this example because the lack of information about minimum operating voltage, we assume the transmitter must have 6 volts. With this battery pack, at the end of 170 hours the voltage will have dropped to 6 volts (one volt per battery). Note that the initial voltage of 6 AA batteries in a series is 9 VDC; therefore, the <u>maximum allowed voltage</u> must be at least 9 VDC.

Example #2

Using the same assumptions as example #1 but the minimum voltage is known (say 5 VDC) then the battery pack size can be more accurately determined. In this example, four AA batteries would have an initial voltage of 6 VDC and at the end of 170 hours would show 4 VDC. The question to ask is how long does it take four batteries to go from 6 volts to 5 volts? Another way of looking at the problem is - if it takes 170 hours to drop 2 volts (6 volts start to 4 volts at the end), then how long does it take to drop 1 volt (from 6 volts start to 5 volts minimum required.) Using the ratio:

$$\frac{2 \text{ Volts}}{170 \text{ hrs}} = \frac{1 \text{ Volts}}{x \text{ hrs}}$$

$$x = 170/2$$
$$x = 85 \text{ hours}$$

The number of hours to go from 6 volts to 5 volts is 85 hours. The operational requirement was 80 hours and this battery configuration gives 5 hours extra time for this operation and there is a size/space saving of two batteries.

Thus by knowing equipment maximum and minimum voltage required and current consumption, it is possible to make an educated selection of battery types and pack size. It is important also to consider the types of battery if they are to be easily purchased and not ordered as a specialty. To assess Battery Lifetime the most significant technical specification are EQUIPMENT MAXIMUM and MINIMUM OPERATING VOLTAGE and CURRENT CONSUMPTION.

Minimum and Maximum Operating Voltage

The minimum voltage a body-wire needs to operate. Voltages should be given in VDC (Volts, Direct Current). The minimum operating voltage is the minimum voltage that the battery must supply. Generally, if the battery falls below this level the equipment will cease operating. There may also be a maximum (not-to-exceed) voltage. Voltages beyond this figure will probably damage the equipment. The minimum operating voltage is often not given but it is important in determining battery requirements.

Body-wire Current Consumption

The current drain should be given in A (Amps) or mA (milli-Amps). From this figure, battery lifetime can be estimated.

Figure of Merit for Battery Lifetime

The less current is consumed the longer the batteries will last. The lower the voltage the fewer the batteries that are needed. The wider the operating voltage range (max. voltage – min. voltage) the longer the system will operate on a given battery pack.

NOTE: ALWAYS USE NEW BATTERIES. IF THE BATTERIES HAVE BEEN TAKEN OUT OF THEIR STORAGE PACKAGE, DON'T USE THEM FOR FIELD OPERATION.

2.4 Feature 4: PHYSICAL CHARACTERISTICS

Two physical features are important for body-wires: Package size and Antenna type. Dimension should be given for length width and thickness. For body-wire usage the transmitter must be as thin as possible. It is also advantageous to remote the antenna from the transmitter. Being able to move the antenna away from the transmitter, allows greater concealment options.

Figure of Merit for Size (thickness)

Less than 1/8 inch thick	Superb
1/4 inch to 1/8 inch thick	Excellent
1/4 inch to 3/8 inch thick	Good
3/8 inch to 1/2 inch	Adequate
Over 1/2 inch	Not good

2.5 Feature 5: ELECTRONIC SECURITY

Narrowband scanners can easily detect Narrowband FM (NBFM) systems since most detectors are of the narrowband sweep type. The fact that the signal is digitized is significant for Electronic Security since it reduces the probability of interception. Digital Spread Spectrum systems are the most secure.

Detection is defined as the ability of an outside person to discover the presence of the body-wire signal. This can be done with frequency counters, spectrum analyzers or scanning receivers.

NOTE: Effective use of a spectrum analyzer requires an experienced operator.

Figure of Merit for Low Probability of Detection are:

	Scanning Receiver	Frequency Counter	Spectrum Analyzer
FM	Poor	Poor	Poor
Digital	Good	Small Benefit	Small Benefit
Spread Spectrum	Excellent	Small Benefit	Benefit

Interception is defined as the ability of an outside person to acquire the body-wire signal and obtain understandable audio. A tunable receiver is necessary for this purpose and should be one that can select various detection modes, such as single sideband, double sideband etc.

Figure of Merit for Low Probability of Interception are:

FM	Poor
Digital	Very Good
Spread Spectrum	Excellent

3.0 FIELD TESTS

3.1 Description of System Under Field Test

Three body-wire systems were evaluated. One used analog FM modulation and could be operated with receivers that could tune to the 173 MHz operating frequency. The second represented digital modulation and the third was digital modulation with spread spectrum. The measured spectral content of the transmitted signal for the three systems is shown in Figures 3.1 A, B & C.

Narrowband Frequency Modulation

The FM body-wire selected for field test was supplied with out a receiver, however; it could use a standard receiver such as the ICOM R7000. The body-wire is small and easily concealed. It has a built in electric microphone and a captive fixed wire antenna. External power leads are equipped with 9V battery snaps.

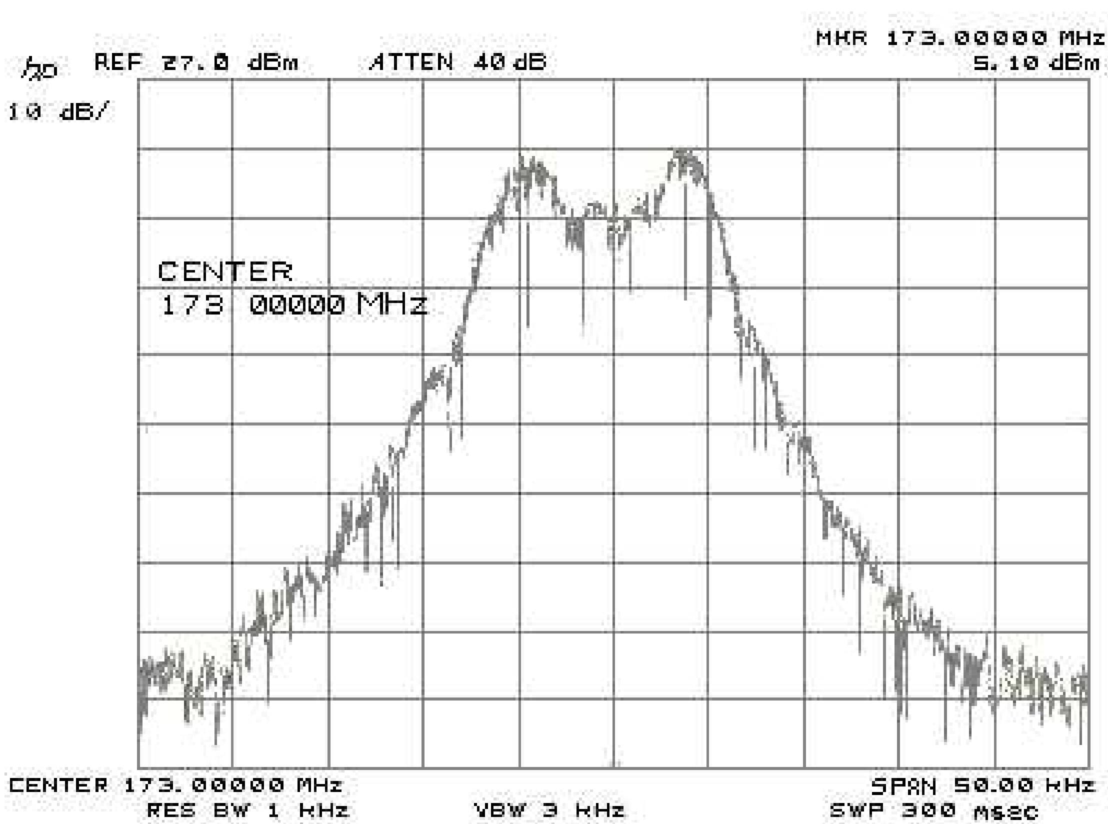


Figure 3.1A Spectrum of NBFM System

Digital BPSK Modulation

This digital system is a digital wireless stereo unit consisting of two external miniature electric microphones, and a RF transmitter operating in the 900 MHz band. A required companion receiver delivers audio signals. Antenna diversity, using two antennas at the receiver, is used to combat multi-path conditions. The body-wire can be operated from a standard 9V battery.

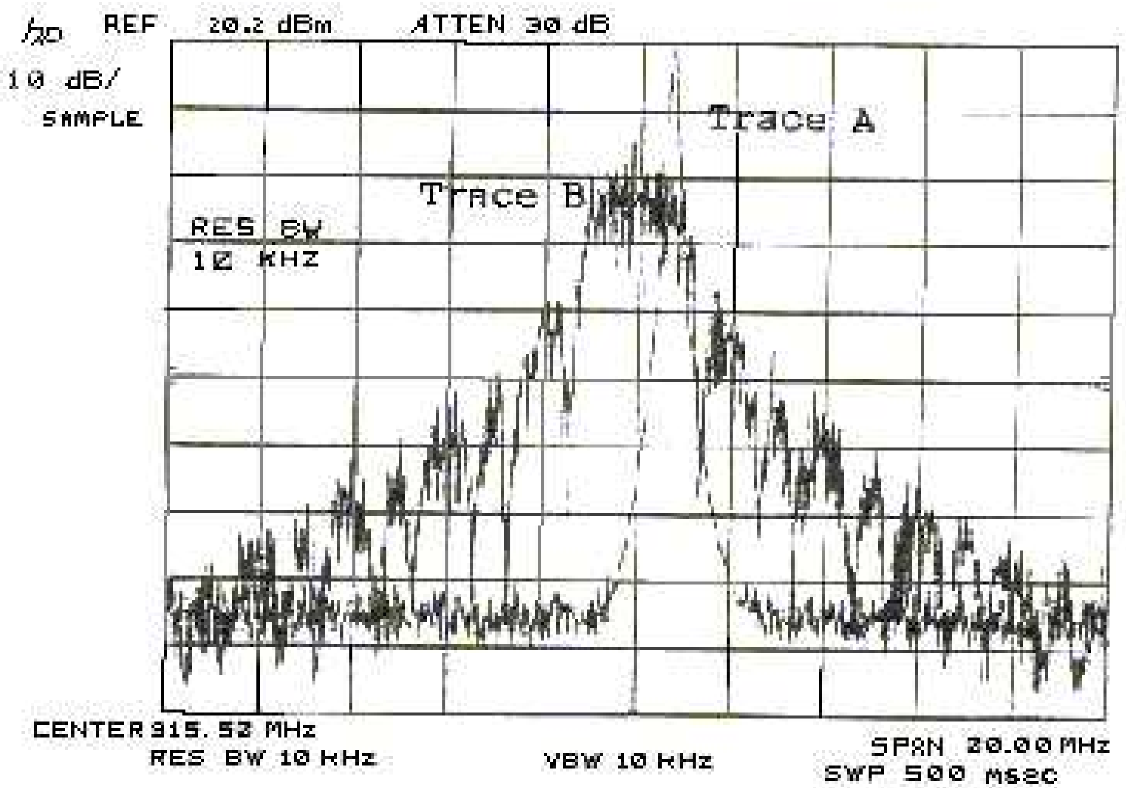


Figure 3.1B Spectrum of BPSK Digital System

Trace A is an unmodulated signal (no digital information).
Trace B is the modulated signal with digital information.

Digital BPSK with Spread Spectrum

This stereo system uses Direct Sequence Spread Spectrum and has remote control of TX power so the receiver can turn off the transmitter. The required receiver has a transmitting antenna for the output power control of the body-wire. The body-wire can be operated from a standard 9V battery.

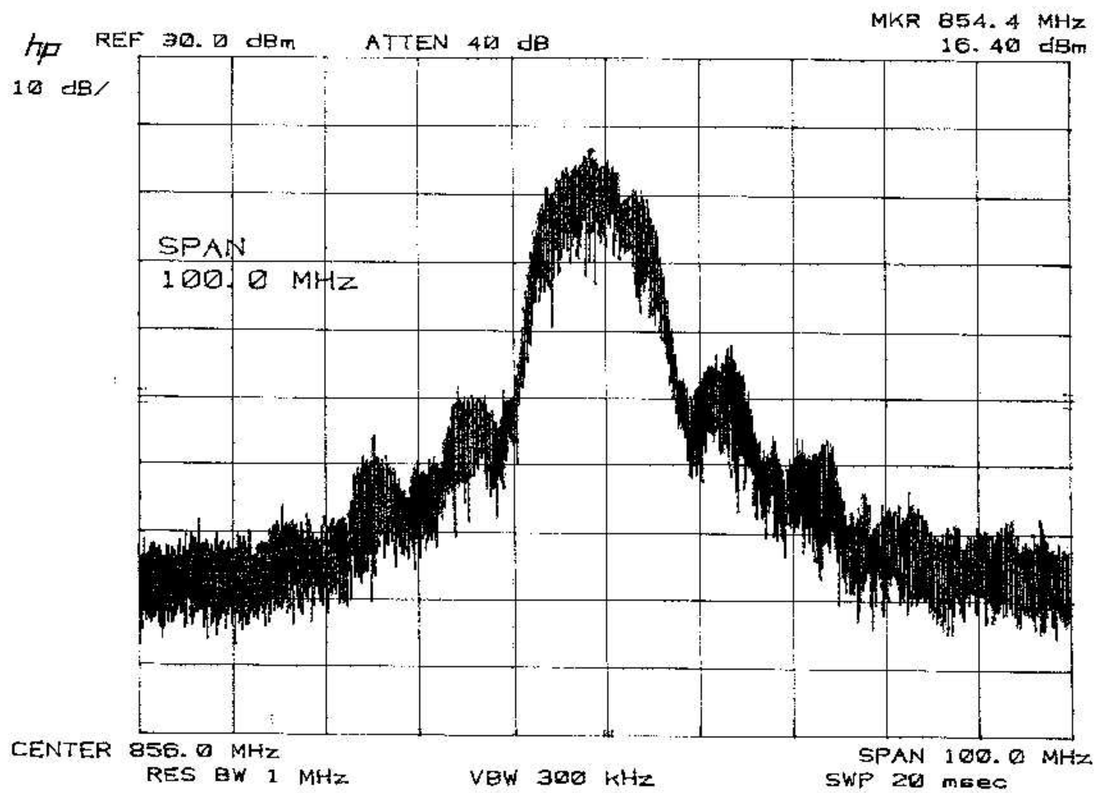


Figure 3.1C Spectrum of Spread Spectrum System

Table 2: Systems Specifications

	Specification	ANALOG NBFM	DIGITAL	DIGITAL SPREAD SPECTRUM
1.	TX output Power	140 mW 21.5 dBm	750 mW max 28.6 dBm	300 mW max 24. dBm max
2.	TX Operating V Max Min	9V (M) >10 V(M) 5 (M)	6 VDC 16 VDC 4.8 VDC	6 V 6.5 V 4.5 V
3.	TX Current Drain	71 mA/9V(M) 37 mA /5V(M)	Varies with VDC 120 mA – 360 mA	160 – 350 mA
4.	Audio Bandwidth	7 KHz (M)	40 Hz – 16 KHz	15Hz – 7 KHz
5.	Audio Dynamic Range	NK	>90 dB	>70 dB
6.	Receiver Sensitivity	-117 dBm	-97 dBm	-105 dBm
7.	Antenna Type	¼ wave Flex	¼ wave whip	¼ wave whip
8.	Size	1"x 3"x 0.25"	2.02"x 2.04"x 0.54"	3.2"x 2.1"x0.76"
9.	Carrier Frequency	173 MHz	923.7 MHz	850 MHz
10.	Modulation type	NBFM	BPSK	BPSK + DSS
11.	TX Bandwidth	7 KHz	2 MHz	16 MHz
12.	Quantization	NA	16 bit	8 bit
13.	Sampling Rate	NA	32 KHz	NK
14	Audio SNR	NK	>80 dB	NK

*NA: not applicable
*M: measured
*NK: not known
*NBFM: Narrowband Frequency Modulation
*BPSK: Binary Phase Shift Keying
*DSS: Direct Sequence Spread Spectrum

3.2 Relationship to the Derived Figures of Merit

The systems under test have been listed according to their placement within the Figures of Merit.

Signal-to-Noise Ratio (Figures not available for DSS & FM)

SNR less than 45 dB	Poor	
SNR between 45 dB and 65 dB	Moderate	
SNR greater than 80 dB	Excellent	***Digital***

Audio Bandwidth

Lower Frequency Response	Higher Frequency Response		
>400 Hz	<4 KHz	Telephone quality	
>200 Hz	<6 KHz	Adequate	
>100 Hz	<8 KHz	Good	***NBFM & DSS***
>100 Hz	<12 KHz	Very Good	
>50 Hz	<16 KHz	Excellent	***Digital***
>50 Hz	>16 KHz	Superb	

Audio Dynamic Range

Less than 40 dB	Poor	***Estimated NBFM***
Around 60 dB	Moderate	***DSS***
Greater than or equal to 80 dB	Excellent	***Digital***

Transmit Output Power

Finding:

100 mW to 200 mW Good-general purpose use ***All***

Receiver Sensitivity

FM systems typically–110 dBm or below ***FM - Good***

A specification of –120 dBm or below represents, very good sensitivity.

Digital from: -90 to –110 dBm. A specification of -103 dBm or below represents, very good sensitivity ***Digital & DSS - Good***

Size (thickness)

Less than 1/8 inch thick	Superb	
1/4 inch to 1/8 inch thick	Excellent	
1/4 inch to 3/8 inch thick	Good	***FM***
3/8 inch to 1/2 inch	Adequate	***Digital (.04"over ½")***
Over 1/2 inch	Not good	***DSS***

Battery Lifetime

The less current is consumed the longer the batteries will last. The lower the voltage the fewer the batteries that are needed. The wider the operating voltage range the longer the system will operate on a given battery pack

Good	***FM***
Good	***Digital***
Poor (limited voltage range)	***DSS***

3.3 Systems Comparison After Figure of Merit Evaluation and Field Trials

	Feature	NBFM	Digital	Digital & Spread Spectrum
1.	Voice Quality	LOW	VERY HIGH	MODERATE
2.	Transmission Range	HIGH	MODERATE	LOW
3.	Battery Lifetime	MODERATE	MODERATE	LOW
4.	Physical Disguise	HIGH	MODERATE	LOW
5.	Electronic Security	LOW	MODERATE	HIGH
6.	Cost	NO INFORMATION AVAILABLE		

3.4 FIELD TEST PERFORMANCE

Body-wire systems used in surveillance are subject to several environmental factors:

- Multipath time delay spread of the received signal due to reflections from buildings, vehicles etc.
- Doppler frequency shifts in the transmitted frequency due to the motion of receiver or transmitter. This can occur when the officer is walking or the receiver is positioned in a moving vehicle.
- Ground attenuation of the transmitted signal due to the body-wire being only a few feet from the ground.
- Power absorption by building material, vegetation and human bodies.

Field Test locations were chosen in order to identity the strengths and weakness of each system associated with the different environmental factors.

Location 1: Simulates mainly multipath time delay spread and ground attenuation, also some attenuation and reflection from walls and building material.

Location 2: Simulates primarily the effects of ground attenuation and body absorption. Traffic between the stationary transmitter and receiver contributes to Doppler effects and causes bursts of multi-path time delay associated with portions of the signal being absorbed and reflected from the vehicles.

Location 3: Simulates all effects: multipath time delay spread, ground attenuation, Doppler frequency shift, and absorption by buildings, human bodies and vegetation.

LOCATION 1

Location 1 is inside an office building along the main corridor as shown in Appendix A. The entire office complex, which consists of 5 separate offices side by side, has 16 inch metal studs in each section of dry wall. Both body-wire and receiver were placed on stands about 2 feet in height. The receiver was placed on a stand at the end of the corridor at the back of the building as shown in Appendix A. The transmitter was placed at distance "D" from the receiver along the corridor. Both the whip antenna on the body-wire and the receive antenna were in the vertical position. Importantly, the average background noise was that of a quiet office. Estimated ADR for voice in presence of quiet office noise was 40 dB. A portable radio was used as the voice source at the body-wire. A variable external attenuator was placed at the receiver after the antenna to reduce signal levels until audio was lost. The distance "D" and value of the attenuation was recorded.

Test Results Location 1

In the NBFM system the presence of static caused problems after 18 meters. At 40 meters the static was the limiting factor reducing audio quality. Since the manufacturer of the NBFM system did not furnish a figure for Audio Dynamic Range (ADR), the ADR was determined through the use of calculations and measurements. A system with minimal ADR would give satisfactory performance only in very quite environments. It should be noted that the limit to discernible audio in the NBFM system was commensurate with an estimated ADR of 40 dB.

The first measurement at 18 meters occurred at a location at the beginning of secure metal doors facing into the corridor. These doors have a combined length of approximately 8 meters in length. With the spread spectrum signal, measurements at 22 meters and 26 meters, within the vicinity of these doors, exhibited considerable attenuation. The spread spectrum system lost audio at 40 meters. (Note that in Location 3 the test audio was recovered beyond 40 feet.)

The digital system performed well and did not lose audio anywhere in location 1, multipath problems were not evident and audio remained clear.

The measurements shows, that the spread spectrum unit is the most effected by multipath and ground attenuation, severely affecting its range. It has limited use in this environment.

LOCATION 2

Outdoor, Line-of-Sight along a wide-open road, that had commercial trucks and cars moving in the vicinity of the body-wire and the receiver. The lane was in the flight path and only four miles from Baltimore Washington International Airport. The body-wire was held in the hand of the experimenter at about 4 feet above the ground and about 6 inches from the body. The receiver was placed on top of a parked station wagon and run from the 12 V car battery supply. Performance tests were made with an experimenter slowly walking away from the receiver and then towards it along the same side of the road as the receiver. Distance "D" between body-wire and receiver corresponding to when audio was lost or not discernible was recorded with and without cars and trucks, and airplanes directly overhead. Distance "D" was determined with the body-wire not moving. Effects of noise from cars, trucks and airplanes were noted. Antennas were vertically polarized.

Estimated Audio Dynamic Range (ADR) for voice in presence of airplane overhead	=90 dB
Estimated ADR for voice in presence of commercial trucks	=70 dB
Estimated ADR for voice in presence of cars	=50 dB

Test Results in Location 2

Digital gave the best results for this environment. The superior ADR of the Digital system was demonstrated in it being the only system with ability to have understandable audio in the presence of airplanes and trucks.

The effects of multipath made the spread spectrum system unusable in a practical sense, in this location since audio was lost in presence of trucks and some cars passing across the transmission path. In this environment, the spread spectrum system is most affected by ground attenuation severely limiting its range. The range for the spread spectrum system in the absence of passing vehicles is only 500 feet, indicated a high path loss, probably due to the adverse impact of multipath caused by the wide bandwidth of the system. A possible remedy is a more complex receiver at the expense of higher cost. The particular body-wire tested had shortened time use due to the operating voltage range limitations of the transmitter.

The NBFM system has some limitations in this location due to marginal ADR, resulting in degraded audio output when the background is noisy. Poor audio was noted when vehicle noise was present. Since vehicular noise is a common condition for surveillance applications, this NBFM system would not be recommended for use in similar locations.

NBFM

Clear audio could be heard at 3,000 feet with the experimenter's back to the receiver, in the absence of significant background noise. However, when trucks passed or when airplane passed overhead at this distance, voice audio was distorted. Whenever the background noise included truck passage or airplane noise the NBFM system was unusable. This situation was consistent even when the body-wire was within fifty feet of the receiver. The performance of the NBFM system was consistent and produced acceptable audio throughout the test as long as the background noise was low. It is understood that airplane noise is a particularly difficult case, however, vehicular noise is common in surveillance applications and it is reasonable to expect the body-wire to perform adequately in that environment.

Spread Spectrum

When the experimenter faced the receiver at 500 feet audio was barely heard, but audio was lost when traffic was present. Beyond 500 feet, even with the absence of traffic, audio could not be discerned, indicating that the spread spectrum system is severely affected by ground attenuation. This was verified when the experimenter stopped at 600 feet without an audio signal, the body-wire was then raised from about 4 feet to 8 feet, at which point audio was received. In both cases the body-wire antenna was vertically polarized, as was the antenna at the receiver. At a distance of 600 feet with the body-wire 8 feet above ground but only the transmit antenna horizontally polarized no audio could be heard. (Note: Antenna positioning did not have a similar effect with either the digital or FM systems.) The loss of audio when commercial trucks passed between body-wire and receiver was noted as close as 60 feet even when the experimenter faced the receiver.

It was also noted that after about 30 minutes the battery pack in the receiver needed to be replaced. The battery pack had a full charge at the start of the experiment.

Digital

When the experimenter faced the receiver at 3,000 feet (923 meters) there was good audio even with a truck parked in the signal path. Also when an airplane passed overhead, there was clear audio signal. Line-of-sight range for the digital system is considered to be beyond 3,000 feet. When the experimenter turned his back to the receiver (RF signal attenuated by the body) at 3,000 feet and stood still, without trucks and other loud environmental noise, voice was still of good quality. At 2,500 feet with the experimenter's back to the receiver there was a little crackle when trucks passed between the body-wire and receiver. At 2,000 feet with the experimenters back to the receiver, the trucks and airplane noise did not corrupt the voice quality. 2,000 feet was considered the limit for consistent good audio with the experimenters back to the receiver. The difference in range between 3,000 feet and 2,000 feet is due to power absorption by the body estimated to be about 7 dB with the body-wire held about 6 inches from body.

LOCATION 3

Location three was outdoors, in a typical office complex area, with a route across a road and alongside a commercial building with trees and parked cars. The receiver was placed inside the same office building used in Location 1. The experimenter walked from inside the building to outside following the path shown in Appendix B. Cars and other obstructions were situated between the body-wire and the receiver commercial vehicles, trucks and cars moved across the transmission path, parallel to it and within the areas of the parking lots. The body-wire was held in the hand at about 4 feet above the ground and about 6 inches from the body. Performance tests were made with an experimenter walking away from the receiver and towards it. The path walked is shown in Appendix B. The designation UPL and LPL stand for Upper Parking Lot and Lower Parking Lot. The references to the grassy knoll and ornamental bush are shown in Appendix B.

The required ADR was not so great as in Location 2 since this location was not in the airport flight path and faster moving vehicles and trucks were further away.

Estimated ADR for voice in presence of commercial trucks	less than 70 dB
Estimated ADR for voice in presence of cars	less than 50 dB

Test Results Location 3

NBFM

The experimenter walked the entire path to 870 feet and back to the starting point inside the building without losing audio. Moving cars and trucks creating audio noise were approximately 100 feet away, unlike location 2 where the distance was only a few feet between passing vehicles and body-wire. The FM system showed immunity to the effects of cars and trucks passing across the signal path and to walking alongside the building and also to the effects of multipath, Doppler from the experimenter movement, ground attenuation and absorption by buildings and vegetation. This audio environment required a lower ADR than in Location 2 and at all distance the NBFM system had sufficient audio SNR to accommodate the ADR for vehicles passing some distance away.

Spread Spectrum

Outward from Office: At foyer (40 feet) and edge of parking lot (60 feet) had some audio drop out. There was some audio loss at Grassy knoll (110 feet) and at the ornamental bush (350 feet) for a few seconds, and alongside the building, audio was missed for a few seconds. At the upper parking lot (420 feet) audio was lost completely. The oriental bush (350 feet) was considered to be the range limit with the stationary experimenters back to the receiver. Returning to the office audio was clear when the experimenter faced the receiver at distance of 400 feet. Audio was lost at the Grassy knoll and at roadside when any truck passed. The Spread Spectrum system was of marginal use in this environment. Audio was spotty when the experimenter was in motion. Good audio at the distances noted was attained when the experimenter was stationary.

Digital

Outward from office: Audio had a little crackle like noise near curb and grassy knoll (110 feet) also some near upper parking lot (420 feet). Some audio outage was experienced at around 700 feet and at 830 feet audio was lost with experimenters back to the receiver, i.e., the RF signal passed through the experimenter's body. At 870 feet walking back to office (i.e. without body obstruction) audio was good and did not lose audio with cars moving between transmitter and receiver. Walked entire return path from 870 feet with good audio.

The range of 830 feet with back to receiver was considered the limit in this environment. It should be noted that good audio was received at 870 feet when the RF signal did not have to pass through the human body. This is a good example of the need for good antenna placement to avoid body loss.

Summary

The FM system showed good immunity to multipath and to Doppler effects brought about by the experimenter's motion. The transmitted signal was sufficient to reach the receiver from the end of the measurement area, at 870 feet even with the experimenter's back to the receiver (i.e. RF signal passing through the experimenter's body).

The Digital system had some audio outages at around 700 feet when the experimenter's back was to the receiver. Some audio crackle was heard at the grassy knoll indicating a Doppler problem effect due to the experimenter's motion. On the return path the signal was present from the edge of the measurement area (870 feet) to the office and, audio was not degraded in presence of moving vehicles.

The spread spectrum system was only useful for very short-range operation in this environment, and failed to produce good audio, when the experimenter was in motion

3.5 Conclusion After Field Test

DIGITAL

The Digital system was usable in all three locations unlike the NBFM or Spread Spectrum systems. The Digital system performed well in terms of audio quality and ADR. Along a long open road with vehicular traffic it performed better than the NBFM in terms of the range that the audio could be clearly discerned in the presence of substantial background noise. This capability is due to its 90 dB Audio Dynamic Range.

The Digital had some Doppler outages due to the effects of the experimenter walking briskly near the side of an office complex.

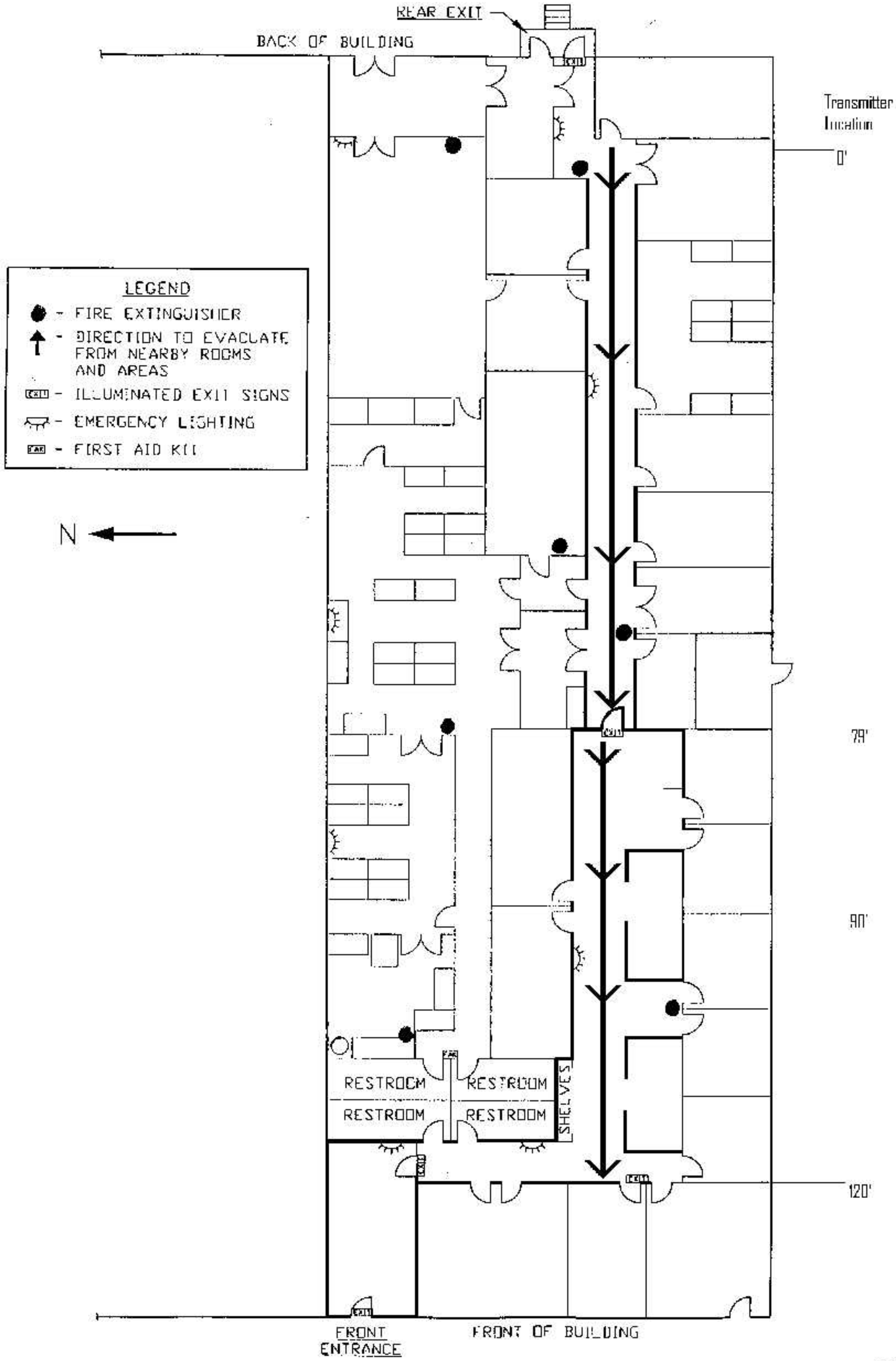
SPREAD SPECTRUM

The Spread Spectrum system has limited use and should not be used in locations with high background noise and its range is limited by ground attenuation. It is very susceptible to multipath effects and experiences more path loss than the digital system. Its ADR is not as good as the digital, voice cannot be distinguished in high noise environments unlike the Digital system whose ADR accommodates this noise level. Due to its reduced operating voltage range the Spread Spectrum system has very limited use as a body-wire transmitter. It is best suited for indoor use with a DC adapter (as supplied by the manufacturer). However; it showed spotty range when tested in Location 1, an indoor environment, with audio lost at 40 meters, however, the audio was reacquired further away along a different transmission path (Location 3). The spread spectrum system is not a good choice as a surveillance tool due to its susceptibility to multipath effects resulting in limited operational range. It would prove useful, however, if security from interception / detection was a paramount concern, but only if the transmitter and receiver were stationary (avoiding multipath) and the range was short.

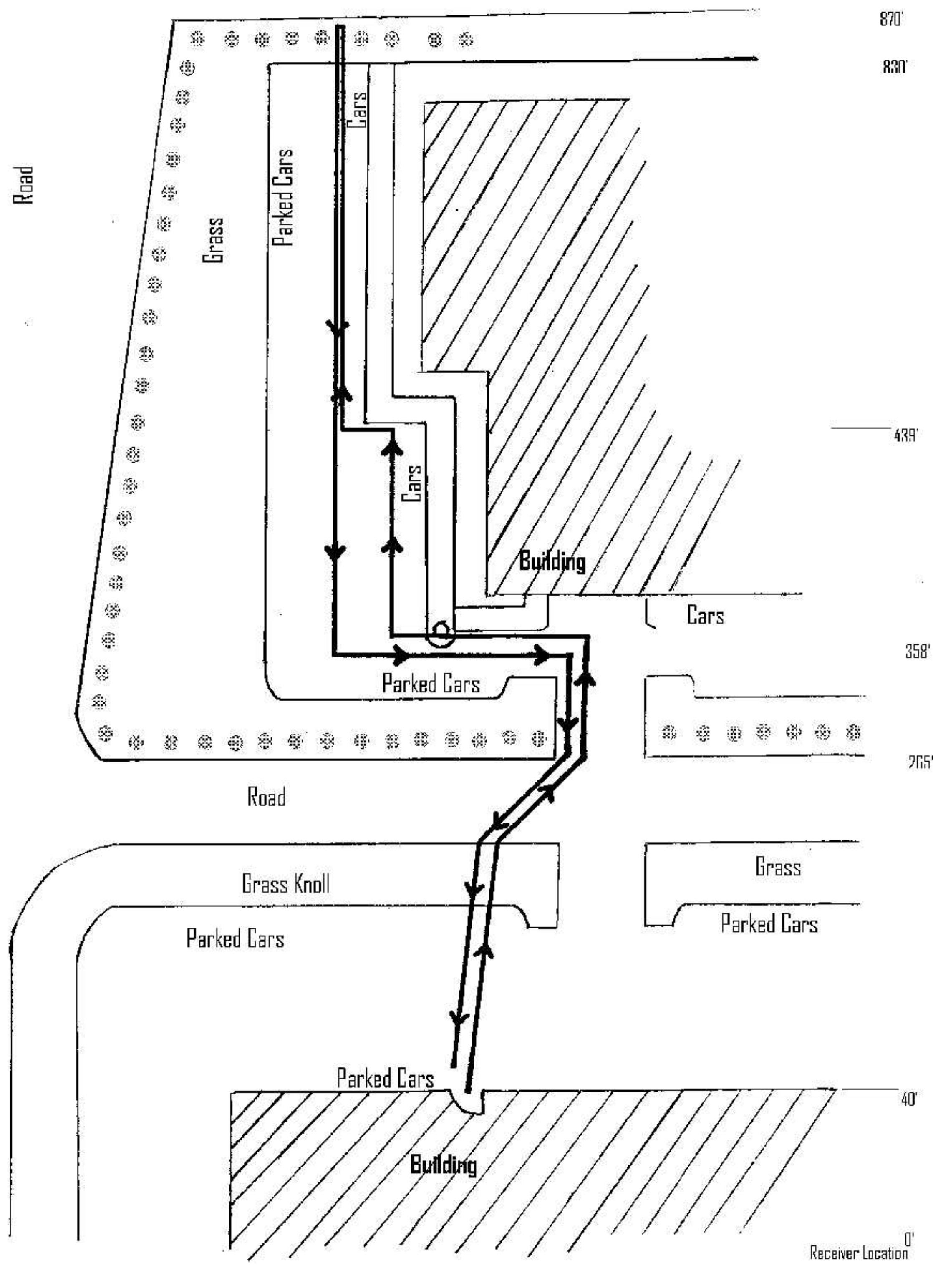
NBFM

The NBFM has limited ADR and moderate to low voice quality. The NBFM system has an ADR estimated to be 40 – 45 dB. The NBFM system should not be used in an adverse audio environment where an ADR of greater than about 45 dB is required. If it is used under these conditions then the voice audio will be distorted and unintelligible. In a built up environment such as Location 3 where the background audio noise was reasonably low, the NBFM performed well but without the voice clarity of the digital system. The NBFM system did not demonstrate significant multipath effects but was affected by range limiting static noise in the Location 1. Range advantages must be correlated with Audio Dynamic Range requirements when comparing systems, especially Digital and NBFM. In order to estimate range, the receiver sensitivity specification used for reception of voice needs to be adjusted to account for the required ADR of the field environment. Therefore, in spite of the fact that a NBFM system can have a very good receiver sensitivity figure, the ultimate usefulness may suffer. The body-wire system must accommodate a certain level of background audio and not obliterate the voice. This means that a wide dynamic range is required. If the system does not have the necessary Audio Dynamic Range then the effect is the same as having an insufficient RF signal. In fact, the received signal level may have to be increased in order to compensate for low Audio Dynamic Range. A good receiver sensitivity may be negated in poor audio environments if the transmitted power is insufficient to overcome poor ADR, resulting in poor audio quality.

APPENDIX A Office Layout used in Location 1 and 3 Field Trials



APPENDIX B Office Complex used in Location 3 Field Trials



Appendix C

Determination of Path Loss Through Use of Standardized Methods

Background

Law enforcement users of body-wires and radio frequency surveillance equipment are faced with the prospect of placing equipment in environments that differ substantially from day to day. The typical law enforcement scenario is to install equipment for one or two hours in a location where there can be no pre-setup measurements or scientific surveys to establish the local radio environment. If an operation were to take place in an established office or restaurant, any attempt to conduct proper scientific measurements would likely alert the subjects of the investigation. Contrast this to the situation where a news team moves into a location to do the "late night news". They have the luxury of operating from a well equipped van with extendable radio antennas, well placed large visible directional antennas and a nice hand held microphone for clear audio.

It would be helpful if there was a method to use manufacturers equipment specifications to establish radio frequency path loss, thereby giving law enforcement the means to select the proper equipment in advance for a given location. Ideally, a standardized procedure could be used whereby the user could estimate environment parameters; combine them with equipment specifications then apply a standard chart or method to produce a reasonable approximation of path loss. With path loss information in hand, the suitability of the prospective equipment could be determined.

There have been attempts to quantify the parameters which contribute to path loss and detailed analysis have been performed to specify the attenuation characteristics of building materials, trees, water vapor, etc. All these efforts have proven unsuccessful for law enforcement use, not because of lack of understanding the problem or poor analysis – instead it is the inability to model the great variety of factors, which contribute to path loss attenuation. A standardized chart to estimate path loss by adding attenuation values is fine if one knows, in advance, what materials lay in the radio frequency signal path. If a signal is going to pass through a building walls, it is almost impossible to know what the building composition is (brick plus concrete block plus insulation plus metal studs plus…etc), let alone what the type of materials are involved (dense brick, light weight concrete or cinder block, metal backed insulation or paper… etc.). Basically, the effort has fallen down because of the complexity involved factoring in the details of the radio frequency environments, effects of multipath and ADR limitations for the different technologies.

The desire for a review of this law enforcement application was given impetus from the fact that a standardized approach is in use by the commercial communications industry. It was reasoned that if the communications world had advanced the state-of-art for this type of estimation, then there might be an application for law enforcement.

<u>Estimation of Path Loss</u>

From Reference (2), a common path-loss model is the log-distance path loss model, which estimates path loss as a function of the transmitter and receiver separation:

$$Lp\ (d) = Lp\ (d_o) + 10\ n \log (d/d_o)$$

Where, d_o is a close-in reference distance before multipath occurs often taken as 1 meter, and Lp (d_o) is the path loss in dB at this reference distance. Values of "n" depend on different environments and values are from 2 to 3 for transmission through factories and 4 to 6 for transmission through general buildings.

In order to determine whether a particular system can be used in a specific location, Path Loss associated with the environment needs to be determined.

A receiver can pick up its intended signal if the energy received at its antenna is greater than its sensitivity. For example, if the energy from a 100 mW (20 dB) transmitter is reduced to –110 dB when it arrives at the receiver, the receiver will be able to use that signal only if the receiver sensitivity is better than –110 dB (say –115 dB). The amount of energy lost as the signal passes from the transmitter to the receiver, 130 dB loss in this example, is path loss. The maximum path loss that the body-wire system can accommodate is determined from the subtraction of the receiver sensitivity specification from the TX power. Figures C1 and C2 enable an estimation of path loss for particular frequencies and environments, corresponding to n = 3 and n = 4 in the above equation. Figure C1 shows the Path Loss at 9 dB/Octave (n = 3) for different carrier frequencies and distances between the body-wire and receiver. Figure C2 shows Path Loss for n = 4. For 9 dB/octave at 100 MHz, the LOS attenuation at 100 meters is 72 dB and at 1000 meters it is 102 dB using Figure C1.

Examples:

1 What is the Path Loss for a body-wire system operating at 1000 MHz at 100 meters, and at 1000 meters with a loss of 9 dB/octave?

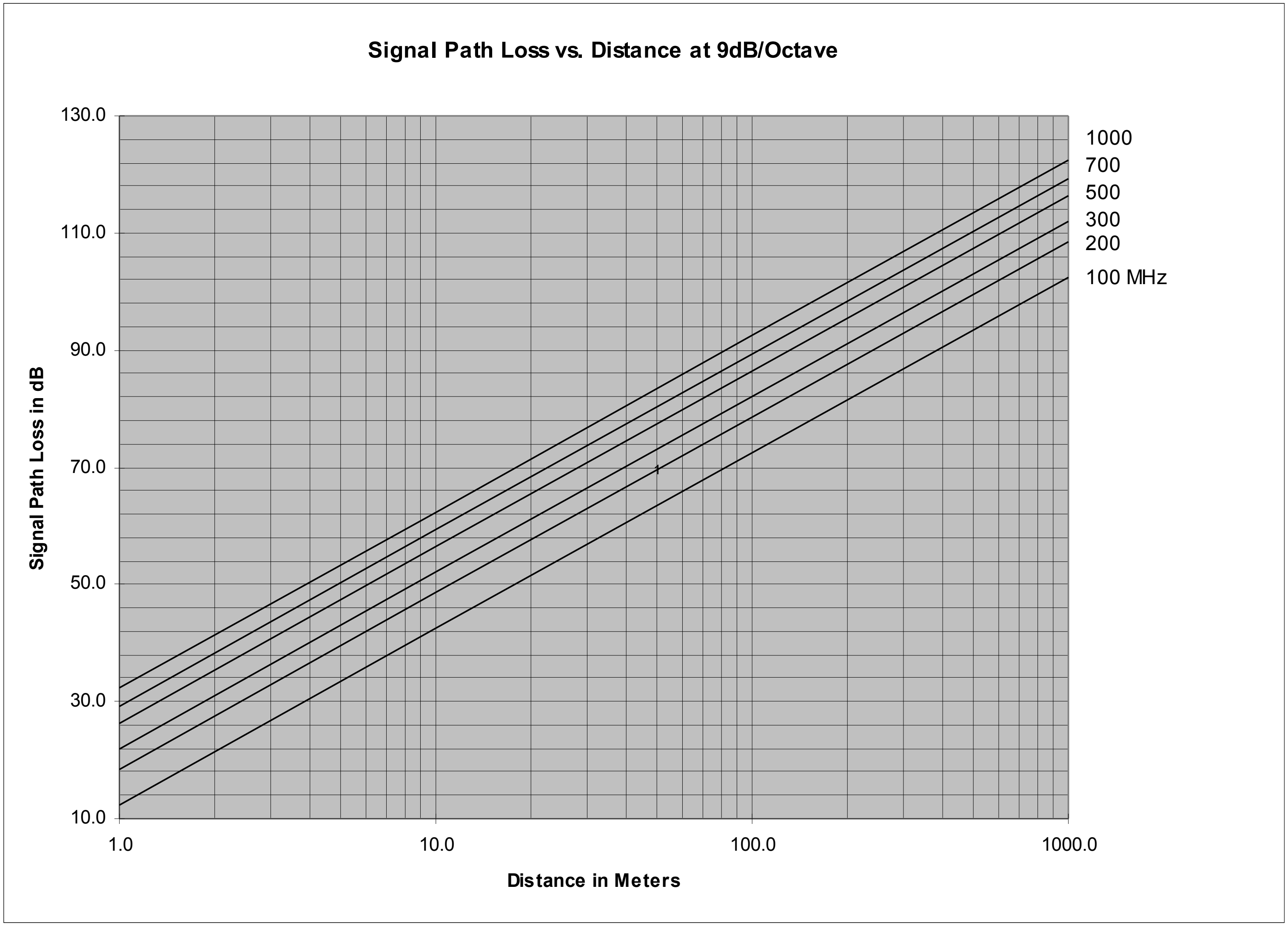
From Figure C1 the attenuation at 100 meters is 72 dB and at 1000 meters it is 102 dB.

2 What is the Path Loss for a 1000 MHz signal traveling a distance of 10 meters at 12 dB/octave and 100 meters at 9 dB/octave?

First use Figure C2 for 12 dB/octave attenuation at 10 meters using the transmitter frequency (in this example, 100 MHz). The chart shows 52 dB meters. Then go to the 9 dB/octave attenuation chart, Figure C1, and find the difference between 10 and 100 meters on the horizontal scale and read 30 dB for additional attenuation. Therefore the attention would be estimated as 52 dB + 30 dB = 82 dB. This should be less than the Acceptable Attenuation for the system. Acceptable Attenuation is defined as the difference in power between the transmission from the body-wire and the receiver sensitivity specification. For example the digital system has Acceptable

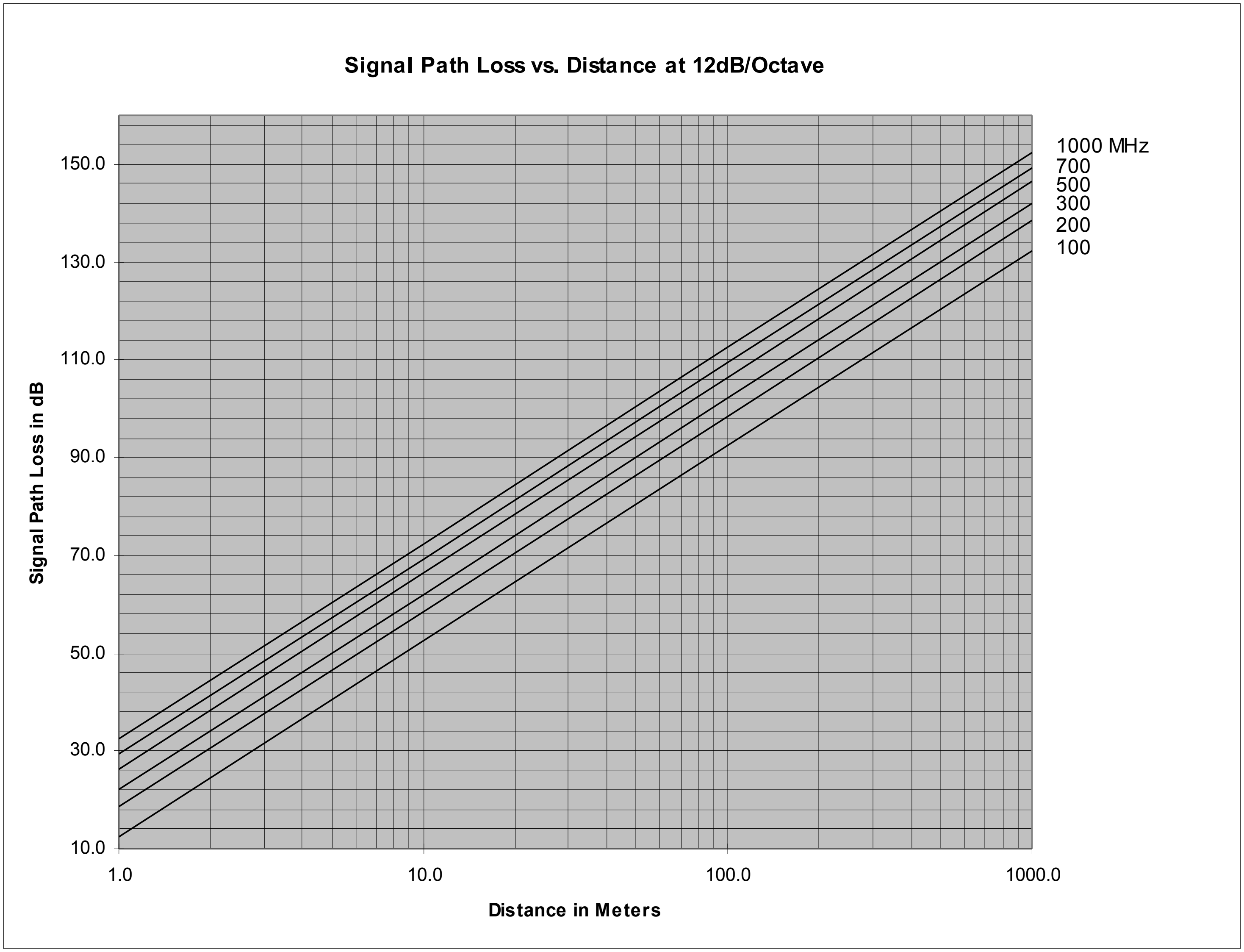
Attenuation of 115 dB meters (20 dBm – (-95 dBm) = 115 dBm). This represents the attenuation that can be accommodated due to the environment and still produce a discernable audio signal at the receiver. If the actual Path Loss is greater than the acceptable attenuation then there is no audio signal at the receiver.

FIGURE C1



Signal Path Loss vs. Distance at 9dB/Octave
Signal Path Loss in dB
130.0
110.0
90.0
70.0
50.0
30.0
10.0
1.0
10.0
100.0
1000.0
Distance in Meters
1000
700
500
300
200
100 MHz

FIGURE C2


Signal Path Loss vs. Distance at 12dB/Octave
Signal Path Loss in dB
150.0
130.0
110.0
90.0
70.0
50.0
30.0
10.0
1.0
10.0
100.0
1000.0
Distance in Meters
1000 MHz
700
500
300
200
100

Field Test Results

The systems under test had the following transmitted frequency, transmitted power level and receiver sensitivity.

System	Frequency	Tx Power	Receiver Sensitivity
NBFM:	173 MHz	140 mW (21.5 dBm)	-117 dBm @ SINAD =12 dB.
Digital:	923.7 MHz	100 mW (20 dBm)	-95 dBm @BER = 10^{-6}.
Spread Spectrum:	850 MHz	100 mW (20 dBm)	-105 dB @BER unspecified.

Field Test Results, Location 1

The Measured Path Loss (**MPL**) was determined from the difference between Acceptable Attenuation and the External Attenuation (ExtA) needed to lose discernible voice at a Distance (**D**) between the body-wire and the receiver. (External Attenuation was added via an adjustable attenuator inserted between the receiver radio frequency input and the receiver antenna.) Estimated Path Loss (**EPL**) was determined from Figure C2 (12 dB/octave)

System	AA	D	MPL	EPL
NBFM	138 dB	18 meters	<73	69
		40 meters	103	81
Digital	115 dB	18 meters	70	84
		40 meters	97	96
Spread Spectrum	125 dB	18 meters	74	84
		22 meters	86	85
		26 meters	93	90
		40 meters	no audio	96

The test results show poor correlation between the Path Loss Chart and Measured Path Loss for the NBFM system. This was considered to be due in part to the adjustment required to the minimum SNR at the receiver (defining RX sensitivity), in order to accommodate the required audio dynamic range for the test. The Digital and Spread Spectrum system measured values were closer to the figures obtained from the chart.

Field Test Results Location 2

Estimated Path Loss **(EPL)** was provided by Figure C1 (9 dB/octave)

	AA	D	EPL
Digital System	115	615 meters (2000 feet)	115
NBFM	138	914 meters (3000 feet)	108

The Spread Spectrum System was effectively unusable in this location. Outdoor Line-of-Sight along a wide-open road, that had commercial trucks and cars moving in the vicinity of the body-wire and the receiver. The lane was in the flight path and only four miles from Baltimore Washington International Airport. The body-wire was held in the hand of the experimenter at about 4 feet above the ground and about 6 inches from the body. The receiver was placed on top of a parked station wagon and run from the 12 V car battery supply. Performance tests were made with an experimenter slowly walking away from the receiver and then towards it along the same side of the road as the receiver. Distance "D" between body-wire and receiver corresponding to when audio was lost or not discernible was recorded with and without cars and trucks, and with airplanes directly overhead. Distance "D" was determined with the body-wire not moving. Effects of noise from cars, trucks and airplanes were noted. Antennas were vertically polarized.

Estimated Audio Dynamic Range (ADR) for voice in presence of airplane overhead = 90 dB

Estimated ADR for voice in presence of commercial trucks = 70 dB

Estimated ADR for voice in presence of cars = 50 dB

The Path Loss Charts give a reasonable estimate of operational adequacy for the NBFM and Digital systems if ADR is taken into account. The 9 dB/octave chart showed a Path Loss of 108 dB for the 173 MHz NBFM systems. The system produced audio at 3000 feet. The same chart showed the digital system at 900 MHz had a path loss of 115 dB at 2000 feet and acceptable attenuation was also 115 dB, which meant that range performance should be limited to approximately 2000 feet. This conforms to the test result.

Chart Utilization with the Spread Spectrum system gave very poor results. The acceptable attenuation of the spread spectrum system is 125 dB. Using this figure Path Loss, the 9 dB/octave chart for the 850 MHz Spread Spectrum system gives a distance of over 3000 feet before 125 dB path loss is accrued. However, the test results came nowhere near their distance. The poor performance of the Spread Spectrum system could not be anticipated from the charts.

Field Test results Location 3

Location three was outdoors, in a typical office complex area, with a route across a road and alongside a commercial building with trees and parked cars. Cars and other obstructions were situated between the body-wire and the receiver. The receiver was placed inside the same office building used in Location 1. A map of the route walked is shown in Appendix B. The designation UPL and LPL stand for Upper Parking Lot and Lower Parking Lot.

Location 3 is a mix of high (office buildings) and low (outdoor) attenuation areas. In fact, part of Location 3 was included in Location 1 (the office space). Therefore, Chart #2 (12 dB/octave) should be applied to the first 40 feet and Chart #1 (9 dB/octave) used for the remainder of the signal distance. The chart results are as follows:

Path Loss	Figure C1, 790 feet (243 meters)	Figure C2, 40 feet (12 meters)	Chart Total	Acceptable Attenuation
NBFM	39	64	103	138
Digital	39	77	116	115
Spread Spectrum	39	78	117	125

Field trials showed that 830 feet was the operating range limit of the Digital system, this is in agreement with the chart. The NBFM system performed beyond this distance also consistent with the charts. The Spread Spectrum system failed to produce good audio at distances beyond 60 feet especially when the experimenter was in motion.

Conclusion on Using a Standardized Chart Method to Calculate Path Loss

The use of a standardized method to calculate Path Loss would not appear to be an exact science, at least concerning the approach used in this experiment. Unfortunately, the variance of the factors contributing to signal attenuation is greater than and can be accommodated by one or two charts. Additionally signal attenuation from differing transmission methods does not appear to be sufficiently uniform to put them under a common method of estimation. The effects of the environment on spread spectrum signals are not the same as those on a narrow bandwidth signal - to the extent that it is not feasible to devise a signal approach to Path Loss calculations, which will fit all transmission schemes and conditions.

There may be other ways of approaching the problem; Separate methodologies for each transmission method, separate methods based on bandwidth of protocol (digital or analog). Accommodating the nearly infinite combination of attenuating materials and conditions remains particularly daunting.