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(NASA-CR-168063) MOBILE RADIO ALTERNATIVE SYSTEMS STUDY TERRESTRIAL SYSTEMS CONCEPTS (General Electric Co.) 76 p HC A05/MF A01 CSCL 17B
N84-10403
Unclas
G3/32 36100

MOBILE RADIO ALTERNATIVE SYSTEMS STUDY

Volume II

TERRESTRIAL SYSTEMS CONCEPTS

JUNE 1983

PREPARED FOR

NASA-LEWIS RESEARCH CENTER
CLEVELAND, OHIO

CONTRACT NAS3-22244

General Electric Company
Corporate Research and Development
Schenectady, New York

Norman Cromwell
Howard L. Lester
Roy E. Anderson

PREFACE

The Mobile Radio Alternatives Systems Study addressed the needs for mobile communications in the non-urban areas of the United States between the present and the year 2000, and considered two ways of fulfilling the needs: by terrestrial systems only and by a combination of terrestrial and satellite systems. Results of the study are presented in three volumes.

Volume I defines the functions and services that will be needed, and presents estimates of the mobile radio traffic that will be generated and the geographical distribution of the traffic.

Volume II describes and analyzes the performance and cost of terrestrial systems concepts for meeting the needs described in Volume I.

Volume III describes and analyzes the performance and cost of satellite-aided mobile radio systems concepts designed to serve that portion of the needs that may not be fulfilled by terrestrial systems. The volume includes a discussion of regulatory and institutional aspects of satellite land mobile communications.

A companion report, "Non-Urban Mobile Radio Demand Forecast," Final Report, June 25, 1982, was prepared by ECOsystems International Incorporated under a subcontract to the study. The report is available from the National Technical Information Service, Springfield, Virginia, 22161.

ACKNOWLEDGMENTS

Many persons participated in the Mobile Radio Alternatives Systems Study, or contributed directly to its performance. The efforts of the following persons are deeply appreciated:

General Electric Corporate Research and Development:

Roy E. Anderson
Howard L. Lester
William T. Tucker
Carolyn B. Morgan
Richard L. Frey
Richard J. Herbs

General Electric Space Division

John D. Kiesling
Charles C. Allen

General Electric Mobile Communications Division

Norman S. Cromwell
Ronald C. Sisson
John A. Mallen
Thomas R. Lusk

ECOsystems International

Peter A. Castruccio
James Cooper

Loats Associates

Harry Loats
Donald G. Lloyd

Comsat General Corporation

Frederick L. Hofmann

Telocator of America

Thomas Lamoureaux

United States Independent Telephone Association

Charles Demek

The staff at NASA-Lewis Research Center provided invaluable guidance and support throughout the study. Their friendly and cooperative participation is deeply appreciated. Staff members most closely associated with the project are:

Steven M. Stevenson
Jack A. Salzman
Bruce Leroy

TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

INTRODUCTION AND SUMMARY

The NASA-sponsored Mobile Radio Alternative Systems Study, Contract NAS3-23244, included the following tasks:

1. Define traffic demand for mobile radio services in the non-urban areas of the United States from the present to the year 2000.
2. Describe concepts for terrestrial systems that could meet the demand.
3. Describe concepts for systems that use satellites in non-urban areas and terrestrial systems in urban areas (hybrid systems).
4. Identify the regulatory and institutional aspects of the hybrid systems.

This report describes the results of the second task, the terrestrial systems concepts.

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Section 1

PROCEDURES AND RESULTS

Terrestrial mobile radio systems concepts were generated and analyzed to determine how well they could fulfill the requirements for mobile radio services in non-urban areas of the United States up to the year 2000. The study assumed that terrestrial installations will serve the SMSA counties of the nation, but that terrestrial and satellite systems are both candidates for serving the less densely populated counties. An attempt was made to configure terrestrial systems that would meet the requirements defined in Volume I of this report. The systems concepts and analyses are limited to the non-SMSA counties of the United States. The non-SMSA area of the contiguous states is 2,386,391 square miles, or 80.5% of the land area. The non-SMSA population is 57 million persons, or approximately 25 percent of the total.

The results of the terrestrial systems study are presented as follows:

- Present day mobile communications technologies, systems, and equipments are described including strengths and limitations. The material is presented as background for evaluating the concepts generated in the study.
- Average propagation ranges are calculated for terrestrial installations in each of seven physiographic areas of the contiguous states. The calculations are used to determine the number of installations required for ubiquitous coverage of all the non-SMSA counties. Consideration is limited to 800 MHz radios with cellular compatible characteristics.
- Four system concepts are defined and analyzed to determine how well terrestrial systems can fulfill the requirements at acceptable costs. The first system provides urban cellular-quality communications everywhere in the non-SMSA counties of the contiguous states. The second system provides ubiquitous coverage but without handover between cells. There are no means to place a call to a vehicle unless the caller knows in which cell the vehicle is located. The third system uses higher power cell site transmitters than the urban cellular systems, and remote receivers, spaced throughout the service area, to increase the service area of the cell. The remote receivers are connected to the cell site by telephone lines or microwave links. The fourth system uses the higher power cell site transmitters and power amplifiers on the vehicle transmitters to achieve the greater service area in the cell without the need for the remote receivers.

All of the systems operate in the 800 MHz band. There are two reasons for the choice. First, the allocation of channels and the techniques for using the lower frequency mobile bands do not provide a sufficient number of channels to accommodate the large demand. Second, compatiblity with urban cellular systems is necessary to fulfill some of the requirements.

The 800 MHz band is the band of choice for the urban cellular systems because propagation range can be limited to short distances. A channel can be reused several times within the limited geographical area of a city. Range can be much shorter than the line-of-sight distance to the horizon.

The 800 MHz band is not the band of choice for non-urban systems because the propagation range is short and the signals are severely blocked by terrain features, structures, and foliage. The number of installations to serve an area is greater if the installations operate in the 800 MHz band than if they operate in a lower frequency band.

Signal propagation range at 800 MHz is strongly affected by terrain roughness. A map supplied by the U.S. Coast and Geodetic Survey outlines seven physiographic areas of the contiguous states. Sample topographic maps, believed to be representative of each physiographic area, were selected, and terrain roughness estimates were made and used to calculate propagation range in accordance with the accepted procedures of the mobile radio industry. Average service area of a terrestrial installation was determined for each physiographic area for a typical base station height. The number of installations required for each area was calculated. The total number of installations for the contingous states is 40,098 or 33, 130 for the non-SMSA counties.

The first of the four system concepts provides full cellular capablility throughout the contiguous states. The 40,098 cells are arranged in 24 cell clusters, each cluster controlled by a Mobile Telephone Switching Office (MTSO). Equipment and installation costs were estimated for an average cluster, and the cost multiplied by the number of clusters. Total cost was $15.74 billion. The cost is so high that no further analysis of the system was made.

The second system eliminates the MTSOs. Each cell operates independently without handover between cells. Frequent redialing during calls is necessary as a vehicle moves from one cell into another. There is no means to place a call to a vehicle unless the caller knows which cell the vehicle is in. The cost of individual cells was based on a population density of 20 persons per square mile, an assumption that one percent of the population would be subscribers, and an average cell radius of six miles as determined by the propagation analysis. Total cost for the system was calculated to be $9.7 billion. Monthly recurring costs for the system are $177 million, and the base user cost, without profit, $502 per month.

The third system relaxes the cell site specifications. It uses higher transmitter power and greater freedom to choose transmitter sites than is permitted in urban cellular systems. An average 15 mile service range is assumed, based on experience with the General Electric G MARC5 800 MHz trunking system. There are many shadowed areas that do not have service, but careful siting of the transmitter and receiver towers can optimise the coverage. Remote receivers throughout the service area enable the 4 watt mobile transmitters to be heard. The number of transmitter installations is reduced from the number required in the first two systems. Costs were determined for individual installations based on a population density of 20 persons per square mile and one percent of the population as subscribers. Implementation costs are $377,000 for the minimum capacity cell that serves 141 persons in its 675 square mile service area. Monthly recurring costs are $11,500 and the cost per subscriber is $142 per month.

The fourth system is like the third except that no remote receivers are used. Talkback from the mobile units is made possible by the addition of a 35 watt power amplifier to the cellular mobile radio. Implementation costs are $307,000 for the minimum capacity cell, monthly recurring costs are $9,250, and cost per subscriber is $106 per month plus $10 per month for the power amplifier.

The market penetration of 1% of the population is based on an average user charge of $100 per month. The elements that make up the charge comprise a base user charge of $30 per month and local calls charged at $0.27 per minute. Long distance charges are additional. Implementation costs and recurring costs must be recovered through the base user charge. The monthly subscriber costs stated above do not include profit, and therefore the base user charges must be higher than the stated costs.

It is obvious that none of the systems can serve a population density as low as 20 persons per square mile and return a profit to its investors. The fourth system was further analyzed to estimate the population density that would support the investment. At a population density of approximately 100 persons per square mile the base user cost per subscriber is $30 per month. Subscriber monthly costs do not scale linearly with population density because system capacity must be increased to accommodate the larger number of susbscibers.

The third and fourth systems are like the present Improved Mobile Telephone System (IMTS) except that they operate in the 800 MHz band instead of the 150 or 450 MHz bands. More channels are available in the higher frequency band so that capacity is increased and call blocking is reduced. An important advantage is compatiblity with urban cellular systems so that the cellular mobile equipments can be used, except that the fourth system requires the addition of a power amplifier.

Structures and terrain features cause sharper shadowing of the signals at 800 MHz than they do at 150 or 450 MHz. Foliage attenuation is greater at the higher frequency. Equivalent service is more costly at 800 MHz than at the lower frequencies.

The study of terrestrial systems did not uncover any ways to reduce the cost of terrestrial systems or improve performance so that a ubiquitous mobile radio service with a national architecture could be implemented and operated at a profit.

The normal development of terrestrial mobile radio systems will continue to serve specific needs of local areas as in the past. "Nationwide service" in terrestrial systems will be limited to compatiblity between local areas. There is no economic incentive to provide service in thinly populated areas except for the specific needs of local entities who implement and operate their own facilities. There is no presently economically competitive terrestrial system approach that will provide nationwide services for users with needs such as those described as "New Services" in Volume I of this report.

Section 2

PRESENT DAY LAND MOBILE RADIO SERVICE

An understanding of present land-mobile service and its growth trends is useful as a background for evaluating new systems that could meet all the requirements of the next two decades. This section provides information regarding present land-mobile users, types of systems, and technology.

2.1 GENERAL DESCRIPTION

In the space of a few decades radio communication with moving vehicles and persons has advanced from the status of an interesting novelty to an indispensable service for business and government. Starting from modest beginnings, land-mobile technology has developed into a widespread and sophisticated network of systems that provide effective umbrellas of communications to vehicles and ambulatory personnel over wide areas. Much of the phenomenal growth is due to the development of narrow bandwidth frequency modulation (FM) technology in the late 1930's. That technology made possible relative freedom from noise interference and "capture," whereby the stronger of two signals suppresses interference from the weaker. Thus FM overcame some of the propagation distrubances and led to the widespread application of land-mobile service. There are currently about ten million* mobile radios in use in the United States, and far from being at saturation, the requirements for service expand at a 6%/year rate. User demand for faster rates of communication transfer and more sophisticated services have pushed the application of state-of-the-art data communication techniques.

2.2 USERS OF LAND-MOBILE COMMUNICATIONS

The high quality and wide availability of land-mobile communications has attracted users in virtually every private and public operation involving the use of remote, moving personnel reporting to a central control.

The following partial listing of users shows the diversity of such operations:

PUBLIC SERVICE	BUSINESS AND INDUSTRIAL	OTHER
Police	Oil and Gas	Federal Government
City	Forest Products	Operations
County	Business Radio	Tactical Law Enforcement
State	Motor Carrier	Telephone Advanced
Fire Department	Citizens	Mobile Telephone
Conservation	Radio Common Carriers	Cellular Mobile
Highway	Marine Telephone	Auto Emergency
Emergency	Taxi	
Ind. Emergency	Industrial—Operations	
Medical Service	Industrial—Processes	
Local Government		
Parks		
Conservation		
Schools		
Utilities		
Gas		
Electric		
Water		
Transit		
Bus		
Railroad		

* Not including citizens' band or amateur radios.

The primary motivation for use of land-mobile communications varies with the class of user, as shown in Table 2-1. "P" is the primary motivation; the check mark indicates an added benefit.

2.3 TYPES OF OPERATION

Land mobile operations can be broadly divided into two categories: those related to direct control of personnel and operations, largely "dispatch" systems, and those for individual-to-individual conversations, such as "mobile telephone." Between dispatch systems and mobile telephone systems there are major differences in operating technique and utilization of radio frequencies.

2.3.1 Dispatch Systems

A dispatch system user employs "Push-to-Talk" or "PTT" operation, and, where possible, a single radio frequency to talk vehicle-to-vehicle, between vehicle and a base location, or person-to-all of these. If a single radio frequency is used, conversation is limited in range by a number of factors:

FACTORS AFFECTING RANGE

Frequency	Water in soil
Transmitter Power	Buildings, etc.
Antenna height: base	Rural/urban
Antenna height: mobile	Receiver sensitivity
Terrain	Site Noise
Type of soil	Antenna system gain/loss

The direct vehicle-to-vehicle system using a single radio frequency is called "simplex," and must use PTT operation because only one user can occupy the single frequency at a time.

In many applications the talk range in a simplex system is insufficient to provide the required level of service, and a "mobile relay" type of system is employed, where it can be licensed under FCC regulations. In Figure 2-1 vehicle "X" will have difficulty communicating directly to vehicle "Y" (the degree of the difficulty depending largely on the distance and the terrain), but by transmitting and receiving through a tower in sight of both vehicles, high-quality communications can be maintained over much larger distances.

Range is extended farther if the tower is located on a terrain peak, but a too-favorable antenna location can exacerbate problems of interference with and from other systems. The mobile relay system requires twice as many frequencies as a direct vehicle-to-vehicle system, and is generally used only when it can be fully justified. The mobile relay system is usually a "half duplex" system with separate frequencies for transmit and receive. PTT operation is employed in the half duplex system because the vehicle radios are not equipped for telephone or "duplex" operation for reasons of cost.

Table 2-1

RADIO DISPATCH BENEFITS VS. USERS

	RESPONSE TIME	SCHEDULING/ FLEXIBILITY	PERSONNEL/ CUSTOMER SAFETY	ASSIGNMENT/ ACCURACY	DATA BASE ACCESS	INCREASE PROFIT
POLICE	P		P	✓	✓	
FIRE	P		P	✓	✓	
TRANSIT		✓	✓			P
UTILITIES	P	✓	✓	✓	✓	P
BUSINESS		✓				P

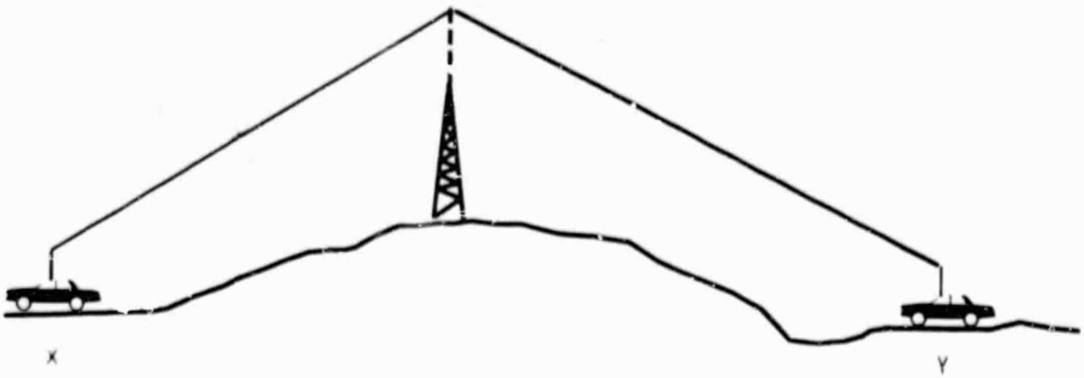


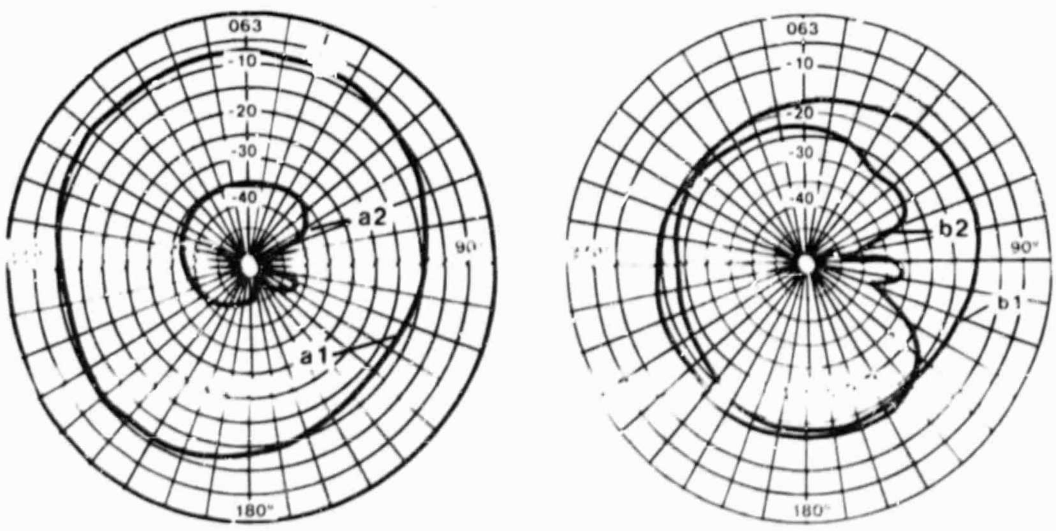
Figure 2-1. Use of relay antenna to increase range.

When using hand-held radios the talk range is less than from a vehicle because of the lower power of the hand-held radio and its inefficient antenna/ground plane system. When the radio is worn on the body, for example, at the hip, there are additional severe losses, as shown in Figure 2-2.

Two system techniques are used to ameliorate these deficiencies:

a. Additional fixed receivers can be placed throughout the system service area, located to provide an acceptably short distance between the hand-held radio and the fixed receiver (Figure 2-3).

   The signals from these "remote" receivers are connected to a centrally located "voting selector," which constantly monitors the various signals, selects the one having



a. 1/4 λ TELESCOPING
a1. HAND HELD EXTENDED
a2. RETRACTED AT HIP

a. 1/4 λ INSULATED SPRING
b1. HAND HELD
b2. AT HIP

Figure 2-2. Effect on radiation pattern of wearing personal radio belt on belt.

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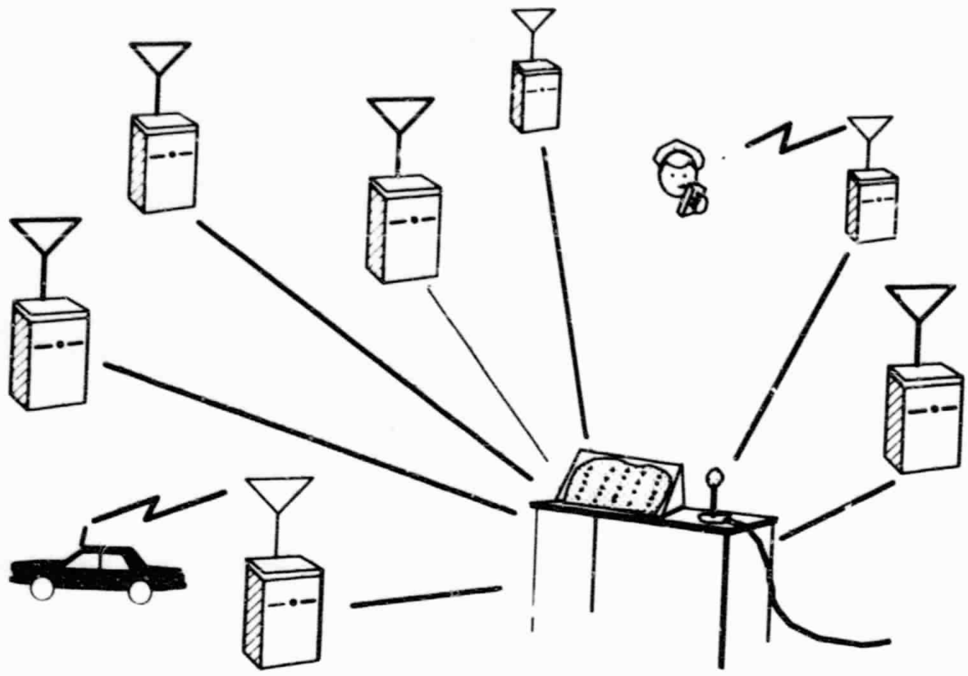

Figure 2-3. Remote receiver voting system.

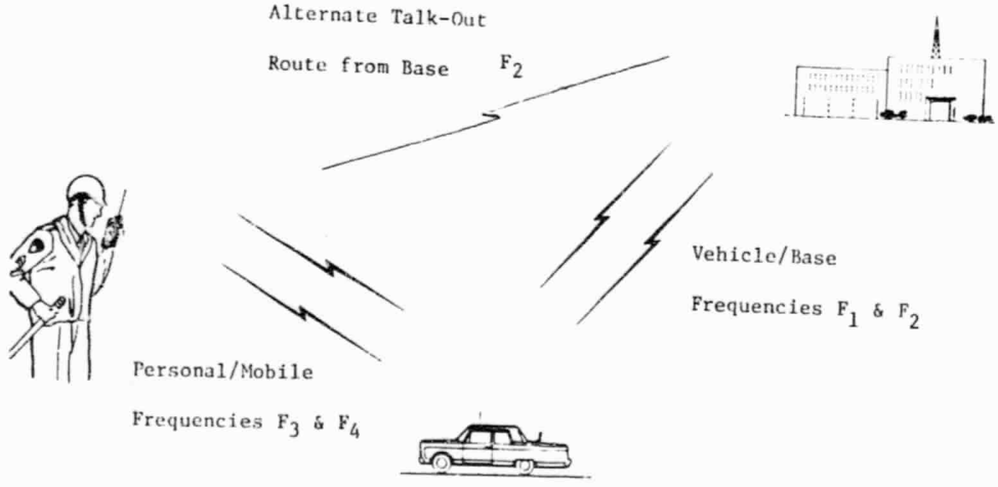

Figure 2-4. Vehicular repeater system.

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the best signal-to-noise quality, and delivers that signal at its output. The same technique is used to improve the voice quality and extend the range of vehicle systems operating in adverse terrain or over distances beyond the range of the vehicle transmitter.

b. When the hand-held radio is operated by a user having a vehicle nearby, such as a police motor patrol officer, the higher power and better antenna system in the vehicle can be utilized by talking through a "vehicular-repeater." This repeater operates much like the mobile relay system described earlier, Figure 2-1. The hand-held radio/vehicular repeater configuration is normally used in a mobile relay system, and can require up to four radio frequencies for its operation. See Figures 2-4 and 2-5.

A small percentage of land-mobile systems use voice-operated or "VOX" control of the vehicle and base transmitters. In a PTT system, it is necessary that the operator depress a hand- or foot-operated switch to energize the transmitter each time he speaks, and hold the switch for the duration of each transmission. When this is not convenient, circuitry can be employed to energize the operator's transmitter when he speaks, and release it when the operator is silent.

When there is no compelling reason to use VOX, PTT operation is generally preferred.

A great variety of system and equipment options are available to the dispatch system user. Selective calling, frequency scanning, call message in the vehicle and many others improve the user's communications and operations.

In designing a land-mobile dispatch system the designer calls upon various system configurations and an almost endless variety of equipment combinations to provide the user with the desired performance. Constraints limiting the designer's freedom in meeting the requirements are cost and FCC licensing rules, which regulate the type of operation, tower height and location, antenna gain, transmitter power, channel frequency, type of emission (modulation), and signal quality (in mobile telephone systems).

2.3.2 Mobile Telep ne Service

Mobile telephone service can be provided to vehicles (and to a lesser extent hand-held radios) by several means. Any dispatch system user can be connected to private or public telephone facilities by means of a manual interconnect at the base station. In most cases, since the vast majority of dispatch systems operate in the simplex or half-duplex mode, the operation is PTT, and requires cooperation of the land-telephone user for successful communications. This is not true mobile telephone service, however. Full telephone service to a vehicle is provided by Bell Telephone and other telephone companies, by Radio Common Carriers (RCC), and by Special Mobile Radio Service (SMRS) operators. This is full-duplex operation, with dial calling and operator-assisted calls to and from the vehicle. There are currently two basic types of mobile radio telephone systems in operation:

1. Previously Developed Systems

   a. IMTS (Improved Mobile Telephone Service)

   b. SMART (Secode Modular Automatic Telephone System)

   c. ACS (Automatic Connect System)

   They are the only services generally available at the time of this writing, and will be referred to as "present systems" or "IMTS systems." These services operate in the "high-band" (152-158 MHz) and "UHF" (454-460 MHz) bands of the land-mobile spectrum

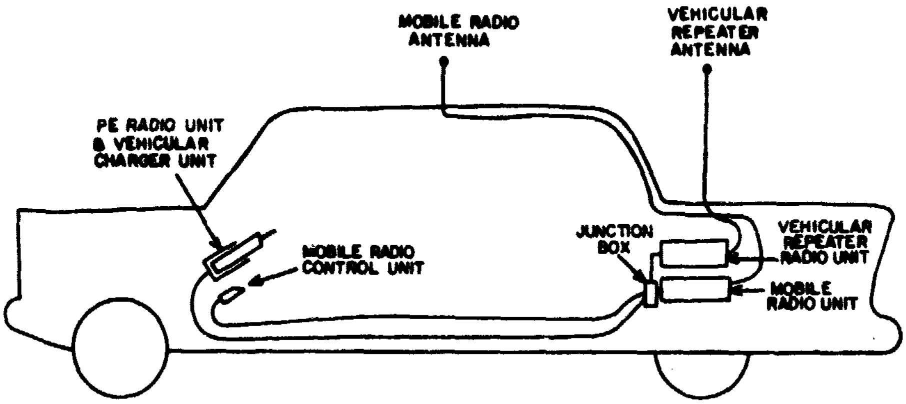

Figure 2-5. Vehicular repeater equipment.

and provide good quality service in cities and along some main highway routes. A single call ties up a radio channel over the entire service area. The systems' ability to handle a large call load within an area is severely limited because few channels are allocated to the service. Furthermore, the user must stay within the service area of the system on which he has placed his call, or must place a new call when he leaves the coverage area of the original system and enters a new one. System operation is duplex, like the home telephone, and the equipment is expensive in comparison to radio transceivers for dispatch service. Another cost is a monthly fee charged for the right to use the base facilties.

The "connect" time, the time required for the system to complete call signaling and prepare for conversation, is long in mobile telephone systems, because of the length of the signaling format and the narrow band-width of the radio channel. Times of 10-15 seconds are typical (assuming a channel trunk is available), which makes the service generally unsuitable for dispatch operations.

2. Cellular Telephone Service

"Cellular" systems are now being licensed and will soon be used more widely than the present systems. Cellular telephone systems, such as AMPS (Advanced Mobile Telephone Service) have been designed to provide a quality of service at least as high as that provided by IMTS systems, but with the advantage of a much higher degree of availability. Cellular systems operate in the 800 MHz spectrum where 666 channels are allocated to provide availability rates approaching land telephone systems. The cellular radio equipment has a wider radio passband width than conventional land mobile equipment, allowing higher-speed and more reliable signaling, thereby reducing connect time from 10-14 seconds typical of IMTS to 1-2 seconds. Voice quality and signaling reliability are enhanced by the use of a diversity receiving system at the base station, which reduces the effect of multipath distortion and makes the vehicle radio's effective talk power greater than in a non-diversity system; this makes the vehicle range essentially the same as the base station range.

Cellular telephone service is now planned for implementation in many SMSA's. It is expected that it will expand to other metropolitan areas, and along arterials connecting some metropolitan areas.

2.4 TYPES OF LAND MOBILE COMMUNICATIONS

Until recent years the land-mobile network was used almost exclusively for voice communications. Increasingly, however, in the interest of improving dispatch operations and securing a degree of communication privacy, various voice code messages have been utilized, the best known of which is the police "10-" code system.

As pressures have built to conserve radio-channel time, simplify operations, and improve user discipline, certain voice transmissions have been enhanced, or replaced, by short data messages. The most widely used of these is the automatic identification (ID) message, which identifies the portable, vehicle, and/or base station transmitter by a short tone or digital message at the beginning of each transmission. Readily added to this is an additional short message actuated by a push-button on the vehicle or portable radio to indicate an emergency, status of the operator, or any of a small number of pre-set messages (Figure 2-6).

Subsequently, it became possible to have a limited-function computer terminal called a Mobile Data Terminal (MDT) in the vehicle, and to receive and transmit text as well as ID and status messages via the land-mobile system. The MDT (Figure 2-7) can transmit or receive 240 characters of text and I.D. in two seconds with a high degree of reliability; this represents exceptionally efficient use of the radio channel as compared to an equivalent voice message.

Also, the MDT can access, or be accessed by, a base computer directly from the mobile without base operator intervention (Figure 2-8).

Data devices for land-mobile use employ various types of modulation, including FSK, PSK, DPSK, and APSK; data rates from 75 bits/sec. to 4800 bits/sec.; and various data coding schemes. There are no industry standards on data formats, nor standardizing control by regulatory agencies, except for the FCC requirement that post-limiter low-pass filters be used in land-mobile data transmission systems to assure that modulation products outside the allowed 3000 Hz passband are sufficiently attenuated. Another FCC constraint is a limit of two seconds for data transmission on a land-mobile radio channel; data is still secondary to voice except in certain special services.

In summary, the use of data communications is popular with some users for one or more of the following reasons:

Faster Information Transfer

	ID Message	Status Message	MDT Message
Data	400 msec	700 msec	2 sec
Voice	3 sec	15 sec	2-5 minutes (including message logging)

Improved Reliability

Tolerant of Signal Quality

Eliminates Voice Ambiguities

Automatic Logging

Caller, Message. Time, Acknowledgment

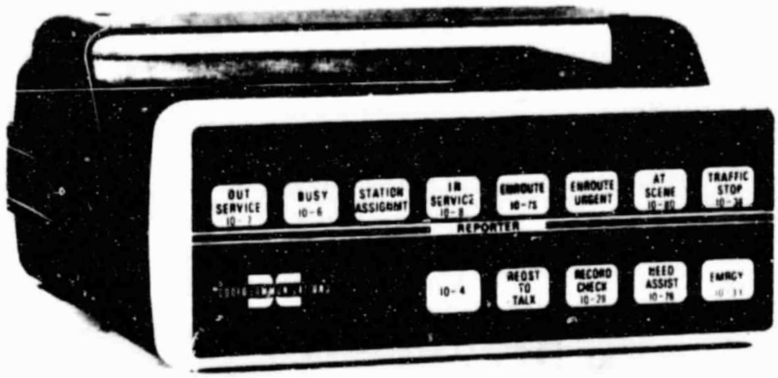

Figure 2-6. Mobile status box.

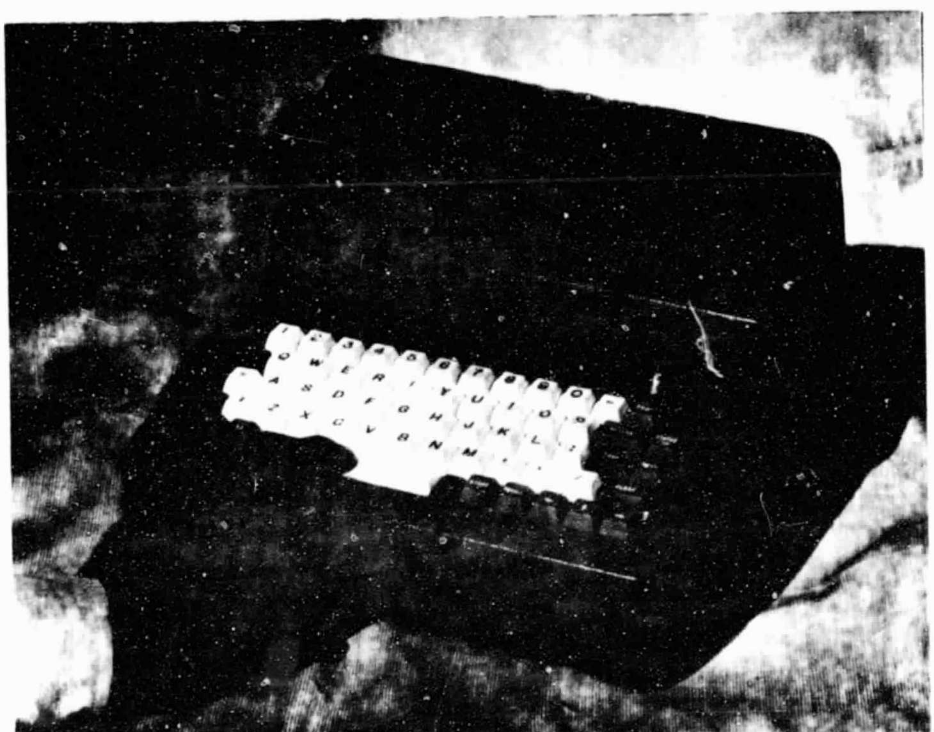

Figure 2-7. Mobile data terminal (MDT).

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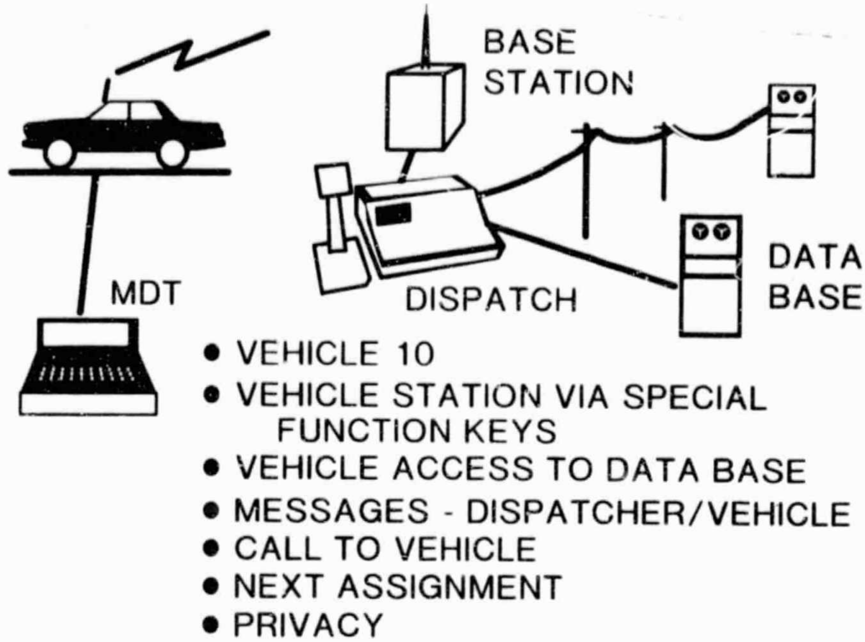

Figure 2-8. Mobile data terminal system.

2.5 LAND-MOBILE RADIO TECHNOLOGY

2.5.1 Frequency Bands of Operation

Land-mobile systems presently operate in the frequency bands shown as "L.M." in Figure 2-9, as allocated by the FCC.

The FCC regulates use of the land mobile spectrum by system rules which are specific to various user groups. The complex rules are designed to allow as much freedom as possible to the user while making efficient use of the radio spectrum and minimizing the possibility of interference with other users.

In general, the land-mobile bands can be divided by characteristics, as follows:

Low Band (25-50 MHz)	High noise susceptibility
	Long propagation, up to 100 miles Long-range skip problems whereby signals from hundreds or thousands of miles distance may cause inteference.
High Band (150-173 MHz)	Lower noise susceptibility
	Medium propagation, up to 70 miles Some long range skip problems
UHF Band (450-512 MHz)	Low noise susceptibility
	Short propagation, up to 50 miles*
800 MHz (806-902 MHz)	Very low noise susceptibility
	Very short propagation, up to 35 miles* (800 MHz cellular system generally limit propagation to 1-10 miles)

*Average under ideal conditions from 300 ft. tower, subject to wide variations due to terrain and environment. See chart in Figure 2-10.

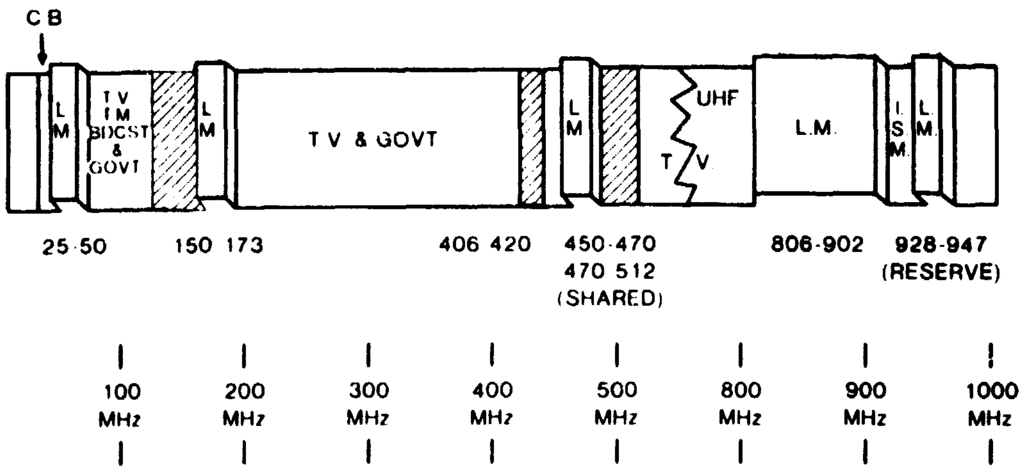

Figure 2-9. Land-mobile radio spectrum (United States).

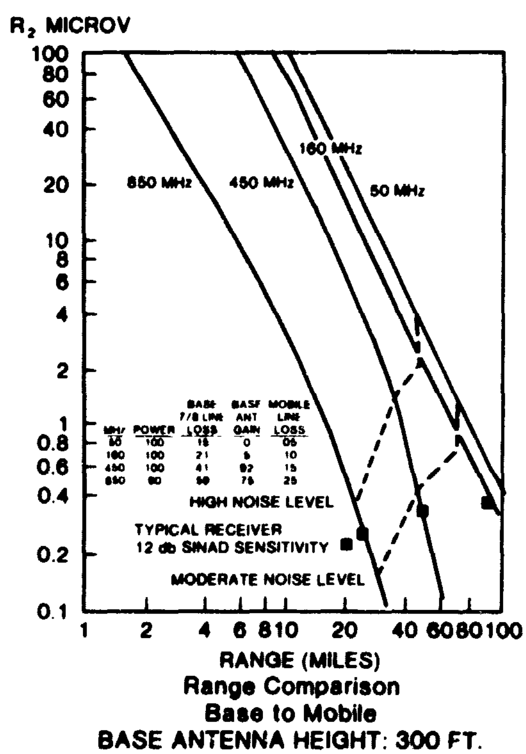

Figure 2-10. Range comparison, base to mobile.

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Comparison of average ranges of land-mobile systems in typical configurations and noise environments are shown in Figure 2-10.

2.5.2 Propagation

a. General

Radio signal propagation is one of the most significant factors in developing a comparison of expanded land-mobile and space-satellite systems. It is also a critical factor limiting the growth and utility of land-mobile service.

As in all radio systems, almost all of the transmitted power in land-mobile systems is wasted, because of the inverse-square law that applies to radio frequency radiation from an antenna.

Even under ideal conditions the signals at mobile receiving antenna are small, but at the frequencies used in land-mobile radio the situation is exacerbated by additional signal impairment factors

Because two-way radio is largely line-of-sight, the curvature of the earth limits coverage. Beyond the horizon, radio signals continue on into space, out of reach of other antennas. Radio direct-wave propagation is slightly greater than optical line-of-sight due to diffraction effects (see Figure 2-11.) In the UHF (470-512 MHz) and 800 MHz land-mobile bands the attenuation is very rapid beyond the optical horizon, even on an idealized earth surface.

In actual practice a terrain over which land-mobile signals are transmitted is not smooth earth. Hills, mountains, and man-made obstacles exist which cause radio signals to be absorbed, reflected, and diffracted (Figure 2-12). Diffraction causes radio waves passing over the edge of a solid body to be bent slightly, providing some propagation beyond the "shadow area." Since lower frequencies are diffracted more than higher frequencies, the higher mobile radio bands have deeper shadow areas behind obstructions, but diffraction and reflection from other terrain and man-made features will often provide something more than a zero signal level in the shadow area.

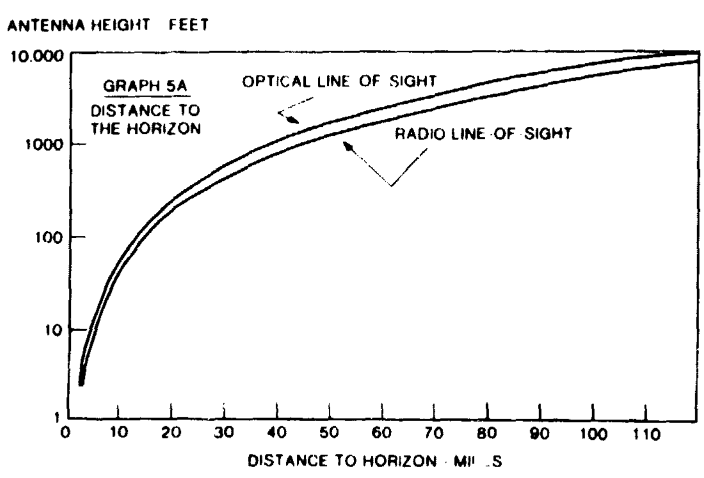

Figure 2-11. Optical vs. radio line-of-sight.

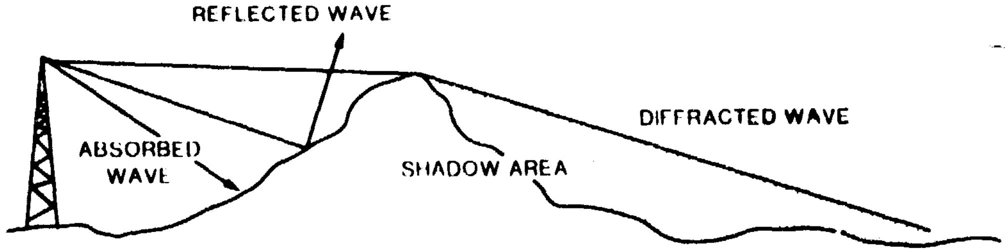

Figure 2-12. Obstructions cause radio waves to be absorbed, reflected, and diffracted.

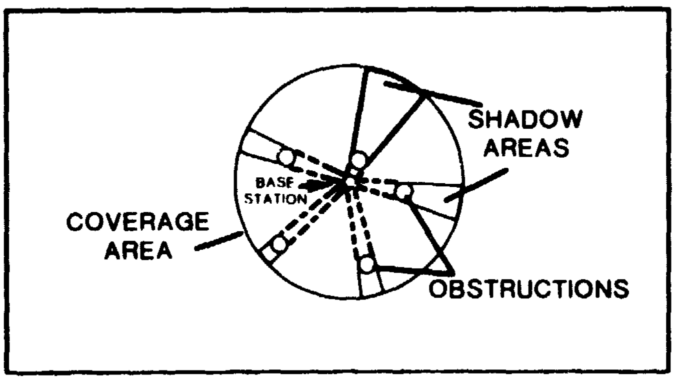

Figure 2-13. Obstructions closest to the base station produce the largest shadow areas.

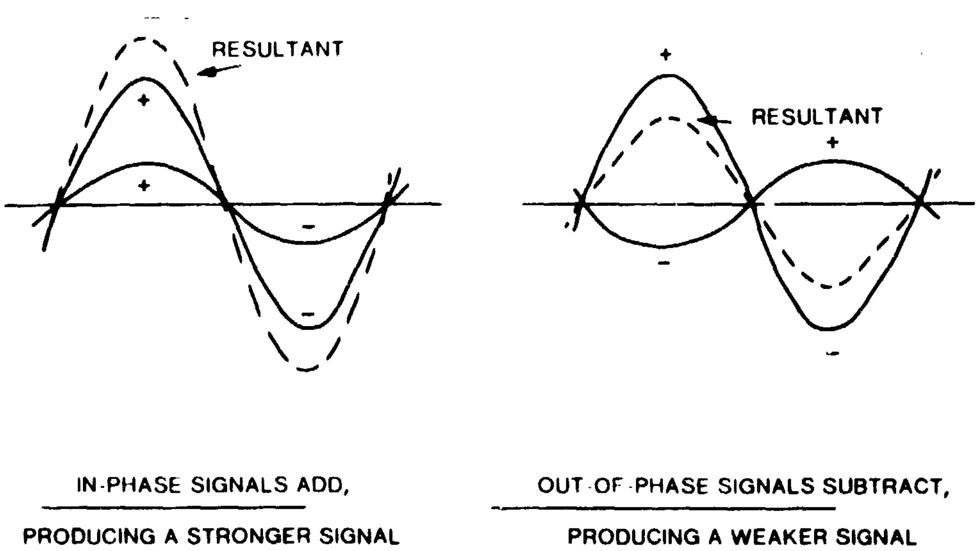

Figure 2-14. Comparison of in-phase and out-of-phase signals.

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The farther away obstacles are from the transmitting antenna the smaller their shadow areas are (Figure 2-13). As mentioned above, diffraction helps to fill in behind obstructions, but the signal strength is not as strong as it would be if the obstructions were not present. Most two-way radio systems can tolerate a considerable number of dead spots, because they constitute a small percentage of the total coverage area, and coverage in practical systems is expressed in terms of 90% or 95% coverage; infrequently, a user may request as high as 99% coverage, but 100% coverage is not achievable in practical use.

The greatest uncertainty in signal levels, particularly at large distances from the transmitting antenna, is caused by the arrival of the r.f. energy by multiple paths. The signal at the input of a receiver is a composite of many signals which follow many different paths to reach the receiving antenna. That signal which travels directly from the transmitting antenna to the receiving antenna is usually the strongest component. Next there is the ground-reflected wave, the wave reflected by the earth on its way to the receiving antenna. Finally, there may be signals reflected by vehicles, hills, buildings and other structures. Since each signal follows a different route with a different length, some arrive earlier or later than others. Some signals arrive in phase so that their positive and negative peaks coincide (Figure 2-14).

In-phase signals add to each other to provide a stronger signal for the receiver. Signals that arrive out of phase, however, partially cancel each other, resulting in a weaker composite signal. Severe distortion results due to the random phases of arriving signals. As a mobile travels through its coverage area the signal into the receiver constantly changes in strength as the many individual reflected signals change in phase and strength. The effect of concern to the system designer is the cancellation of signals, since it commonly reaches values of 20-40 dB. The multipath distortion is of great significance in systems involving transfer of data, since the phase and amplitude distortions can wreak havoc with accurate reproduction of a digital stream. Most land-mobile data techniques have been designed with this propagation effect in mind; that is, with redundancy and error correction.

The composite of the effects of terrain and the signal variations caused by multi-path propagation is shown in Figure 2-15.

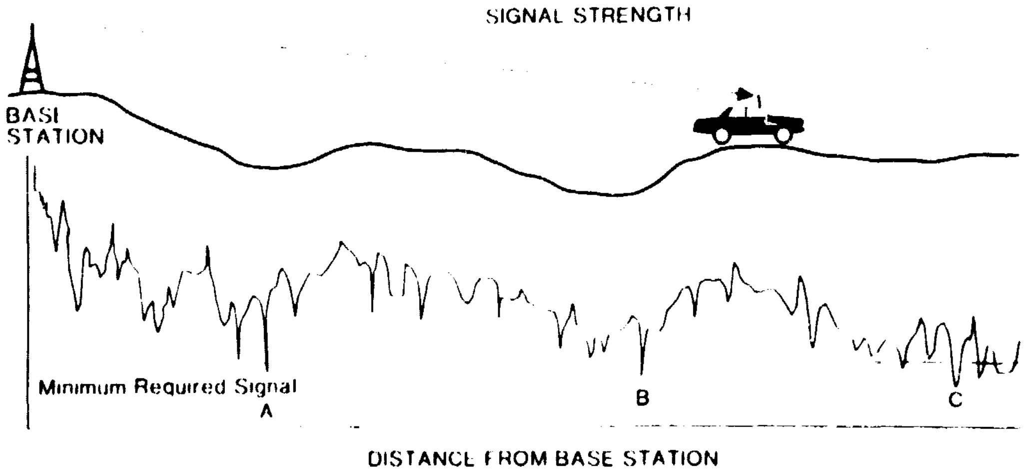

Figure 2-15. Strength of signal received by mobile unit moving away from base station at left.

The jagged line in the figure represents the strength of the signal received by a mobile as it drives away from its base station at the left. As long as the signal stays above the broken line, reception is acceptable. "Dead spots" are those locations where the signal level drops below the broken line. Actually, the minimum required signal is not a constant value, as drawn in Figure 2-15, but increases as the vehicle travels through noisy areas and decreases in quiet areas. Even the time of day may affect the minimum required signal, since noise levels in some areas drop off at night as traffic decreases and electrical apparatus is turned off.

For the first few miles from the base station the multi-path problem may be only a minor annoyance, although even close in, interruptions can occur if the user stops in a null area. In the null marked "a," he will have poor or no communication. Farther away, these dead spots become more and more frequent and last for longer periods of time.

At 800-900 MHz, rain and snow can greatly increase foliage loss, increasing the number of poor or no communication areas.

Already weak land-mobile signals are, therefore, further impaired by terrain and man-made features, by multi-path signal propagation and by weather. The system designer cannot arbitrarily raise power to make up the impairment; he is constrained by FCC regulations concerned with interference among systems and by economics.

Many users who utilize hand-held radios require operation in buildings, in vehicles, or in outdoor areas presenting severe propagation problems. The degree of difficulty this presents is dependent on the frequency range; higher frequency signals can penetrate some structures through smaller openings than longer wave signals. Even so, building penetration losses can range from a few dB (for wooden structures) to 60 dB or more. The medium value for city buildings with windows is 20 dB. In some cases in-building coverage can be provided only by special antenna and/or repeater systems inside the structure.

For the above reasons it is necessary for each mobile system to perform a detailed propagation analysis to assure that the signal quality in the coverage area will provide the required customer service and, in the case of public systems, meet FCC reliable service area regulations. The propagation analyses include the following factors:

System Coverage Parameters

The contours were constructed using the following system parameters.

1. Frequency Band
2. Base Station Characteristics
   - Transmitter Power Output
   - Antenna Type and Gain
   - Antenna Height Above Ground
   - Coaxial Transmission Line
3. Receive Losses
   - Duplexer, Filter
   - Multicoupler, Connectors
4. Transmit Losses
   - Duplexer, Filter
   - Combiner, Connectors

5. Average Terrain Variation
   Foliage Type and Density
   Weather Factors
6. Ambient Noise
7. Structures in Service Areas
8. System Design Reliability
   Egli Reliability Factor
9. Ground Conductivity (Mhos/Meter)
10. Permittivity (Dielectric Constant) (Electrostatic Units)
11. Mobile Transmitter Power
12. Mobile Antenna Height
13. Mobile Antenna Gain
14. Hand-Held Radio Transmitter Power
15. Hand-Held Radio Antenna Height
16. Hand-Held Radio Antenna Height and Gain

2.5.3 Simultaneous Transmission on One Radio Channel in Overlapping Coverage Areas

In many users' operations it is necessary or desirable to make a simultaneous transmission to all vehicles in a given jurisdiction. When FCC constraints or laws of radio propagation preclude providing the area coverage necessary to accomplish this from one base transmitter site the user has several options:

a. He can locate transmitters operating on a single frequency throughout his area of operations, arrange to control them from a central location, and energize them simultaneously. This will provide radio frequency energy over the entire service area, but in all areas where energy is present from more than one transmitter distortion and heterodynes will reduce the quality of the signal received by the vehicle, to the point of being unusable in many areas.

b. He can utilize the same system as above, but can make sequential transmissions, one or more non-overlapping transmitter at a time, until he has reached his vehicles in each transmitter coverage area. Although this technique will overcome the interference problem and make it possible for the central controller to transmit to all vehicles, it is time-consuming and makes no provision for all vehicles in the system to hear a transmission from a single vehicle in the half duplex or duplex system.

c. The transmitters could operate on separate frequencies and be energized simultaneously. This will overcome the interference problem and provide the desired coverage, but is wasteful of radio spectrum and may or may not be licensable by the FCC. Furthermore, special provisions would be required each mobile and in the system to avoid the nuisance of the mobile operator's having to switch channels in his mobile radio to correspond to the frequency in his immediate area of operation.

   This desired result could be achieved through the use of a special version of a trunking system, but it would be applicable only under circumstances that will permit appropriate apportionment of frequencies among sites and users; it may or may not make efficient use of radio frequencies or be licensable by the FCC.

d. From an operational and spectrum efficiency standpoint the best solution to the wide area coverage problem is a system properly designed to transmit simultaneously on the same frequency from several sites throughout the service area with acceptable distortion in the coverage overlap areas. The advantages of such a system are:

- Wide area coverage
- Simplified dispatch operations
- Efficient channel utilization

There are also disadvantages. The first disadvantage of simultaneous transmission is some degree of signal quality degradation in the overlap areas, resulting in some distortion even in optimized systems, and in "picket fence" sound even when the mobile or personal radio is stationary. This may be very noticeable in some parts of the service area and not present at all in others. Proper system design can minimize this problem.

The cost of simultaneous transmission is another disadvantage. One large cost arises from the requirement for an extremely close control of the offset of the frequencies of the transmitters comprising the simultaneous transmission system, necessitating the use of ultra-stable oscillators or rubidium-controlled synthesizers. As an example, in a large system it might be necessary to have six transmitters operating with carrier frequency accuracy of 2 Hz. This is a formidable challenge in commercial systems operating at 800 MHz, where the required accuracy may be one part in 10^{-10} per month.

In addition to the requirements for ultra-stability oscillators, it is necessary in a simultaneous transmission system to maintain the modulating frequencies to extremely close phase relationships over the entire audio passband at all base transmitter locations. To achieve this, complex and expensive audio phasing equipment is employed. Even so, maintaining the proper phasing is virtually impossible over leased telephone lines, and it is almost essential that radio radio links be provided between the participating stations. If the system is to have tone-coded squelch the subcarrier frequency must be generated at a central location and transmitted over microwave or other precisely controlled links to assure that the squelch tone will be of exactly the same phase at each base station location.

All of these considerations entail not only expense but also a high level of constant maintenance to assure that the frequency offsets and audio phasing are maintained properly.

Another consideration in the application of a simultaneous transmission system is operation during emergency situations, when control and audio links to the central location are broken. Special manual procedures must be instituted, and degraded performance must be accepted for the duration of the situation.

While there are cost and performance penalties in the utilization of simultaneous transmission technology, there are situations when these penalties are considered a reasonable price to pay for the operational benefits.

2.5.4 Radio Channel Trunking

Despite the opening up of the 800 MHz band for land-mobile use and the increasing use of data communications, radio spectrum scarcity remains the major factor limiting the growth of land-mobile radio and the provision of the level of service users desire. Working in conjunction with the FCC, manufacturers have looked to improving utilization of available radio channels by the use of "trunking" techniques. In a conventional land-mobile system, channels are pre-assigned to user groups, and means of optimally sharing these channels to make an idle channel available to the next user are not provided. If all users could, on a noninterfering basis, utilize whatever channel is free, operations could be speeded and more efficient use made of the radio spectrum.

The channel availability advantage of a properly operating trunking system is diagrammed in Figure 2-16, which shows expected waiting times in multi-channel systems. Notice that the waiting times are given as the number of service times (message units) that comprise the delay. An 80%-loaded channel in a single channel system will cause average wait times of two or three message units. In a mobile telephone system, where the conversations are typically long, these waits are often three to six (sometimes ten to twenty) minutes. In dispatch operations, the average message time is more in the range of five to thirty seconds, but average wait times can still be several minutes in a single-channel 80%-loaded system; this is an annoyance and hindrance to operations in any system, and may be unacceptable in an emergency system.

In a multi-channel system, the waiting time expected if any free channel of an 8 channel system were available to the next user is shown to be about 0.2 of a message unit, which in a dispatch system would be as low as one to six seconds. Reduced time to have a channel available is a major quality-of-service improvement for all users, and can be critically important in police systems, where many transactions are of an emergency nature. The major

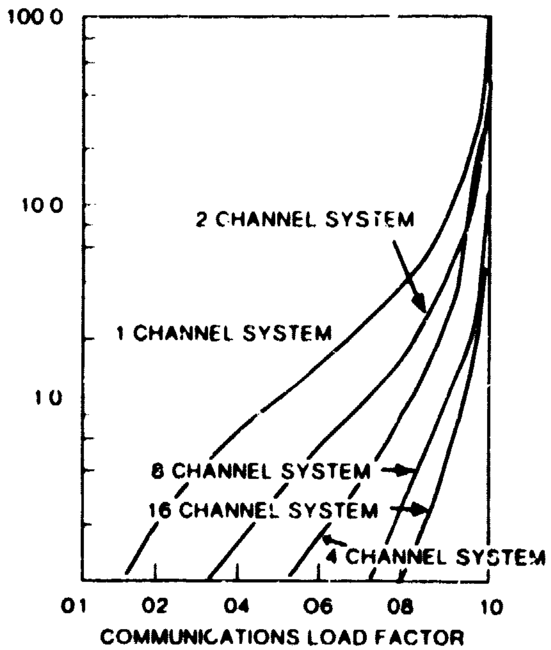

Figure 2-16. Expected waiting times in multichannel systems.

benefit, however, is the increase in channel utilization. Idle time on channels is reduced, with the result that a number of services can have high-quality communications with fewer radio channels. In a typical radio common carrier system, a two-to-one improvement in channel utilization is achieved.

Other major benefits offered by trunking in land-mobile systems are automatic redundancy in the event of base transmitter failure, communication privacy, and reduced interference between users within a system.

The opposing factors limiting application of trunking technology are equipment cost and the difficulty of grouping users in a radio coverage area. The FCC has spurred the use of trunking by special rules in the 800 MHz band, and the equipment manufacturers have made available effective trunking systems carrying only a moderate cost increment over conventional systems.

2.5.5 Position Location

A number of land-mobile system users have strong interest in a system to locate their vehicles in real-time. In cities, police departments and bus operators have emphasized their needs. A number of systems have been conceived, and the U.S. Department of Transportation has sponsored a series of experiments since 1978 to determine the technical and economic feasibility of several techniques.

Two basic types of location systems have potential for application:

a. Random route systems to locate vehicles (or, potentially, personnel) at any point within a design coverage area.

b. Fixed route systems to locate a vehicle along one or more pre-determined fixed routes.

Most location systems are limited to relatively small areas, such as a city, and cost, accuracy, and/or other factors have limited the application of the technology to only a few systems in the United States. Whereas the position location needs of a user in a city or other defined limited area can conceivably be met with available technology, no practical means has been found to accomplish random route location over large areas, such as a state or portion of the United States. Loran, the marine navigation system, has potential for use as a nationwide location system, but also has drawbacks:

a. Loran coverage is not provided in the U.S. mid-continent area, which includes all or part of at least 13 large states.

b. The Loran position information is collected by the vehicle, but must be sent from the vehicle to a central location for use and distribution. No commercially practical network of radio/land-line communication for this application exists.

c. The cost of on-vehicle equipment and the information collection, distribution, and utilization system may be prohibitively high for any one user.

The Department of Defense Global Positioning System (GPS) is under development for high-accuracy position fixing on land, sea, and air. Yiu, Crawford, and Eschenbach[1] describe its potential application to land mobile services. They anticipate that a GPS receiver of their design could "have a selling price of less than $2500" and that continued development could bring the price down to $1000.

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[1] (Yiu, Kai P.; Drawford, Richard; Eschenbach, Ralph "A Low-Cost GPS Receiver for Land Navigation." Navigation: Journal of the Institute of Navigation, Vol. 29, No. 3, Vall 1982, page 204.)

The GPS system, like other separate "navigation" systems, requires a receiver or other device separate from the mobile radio. Position fixes determined by the navigation device are sent to the dispatch office over the mobile communication link. A "surveillance" system is integral with the mobile communication system and enables the dispatch office to determine vehicle locations automaticaly by interrogation or by measurements on received signals. An example of surveillance system is a "Mobile Locator System for Metropolitan Areas," (Roy E. Anderson and Miguel Merigo, described in Patent 3,680,121). A short audio tone burst is transmitted by a vehicle. The difference in phases of the received tone at three or more receivers yields the difference in range from the vehicle to the three receiver sites. Hyperbolic lines of position are thus determined, and the intersection of the lines is the vehicle location. Figure 2-17 lists the presently available commercially practical vehicle location sytems.

2.6 STRENGTHS OF PRESENT LAND-MOBILE RADIO SYSTEMS

Land mobile system users place high expectations on the performance of their systems and on the competitiveness of the prices they will be asked to pay. Public service users demand excellent voice quality on a multiplicity of channels, reliable data communications, complex central control arrangements, and a high degree of availability of their systems (good coverage of their service area with low equipment failure rates and twenty-four hour repair service). Public service systems are military-like in their function, operation, complexity, and quality, and often include computer systems (DEC-11/70 to IBM-370 size) as dispatch and control aids. There have been occasional efforts to make mean-time-to-failure rates part of public service land-mobile equipment specifications. This has been discouraged, not because the equipment failure rates are unacceptable, but because the military-type quality control and manufacturing procedures for monitoring, logging, and reporting to this type of specification are inappropriate in this market. Instead, intense competition in the marketplace compels manufacturers to meet high quality standards at low prices.

In general, business users other than utilities do not require systems as complex as their public service counterparts; their control center is likely to be a microphone on a secretary's desk, and their mobile radios will have only one or two channels and few functional frills. They do, however, also require that they have reliable radio contact with their fleet, that equipment failure rate be low, and that repair service be readily available. Since business users have purchased their systems to increase their profits, they expect reliable performance, but also expect to pay reasonable prices.

Both public service and business customers frequently require communication service over extended areas, or odd-shaped areas. These applications require use of special techniques, including multiple sites, land-line or microwave links, and special control systems.

Land-mobile systems meet most of the challenging requirements of both the public service and business markets very well. The highly competitive nature of the market and the large dollar volume it represents have compelled manufacturers to provide rugged, latest state-of-the-art equipment and services at reasonable prices. The evolution of today's excellent mobile radio equipment has been driven by constant efforts to bring innovation and improvement to the market in response to users' needs and the availability of new technology. For example, when it was proposed to open up the UHF band (450-470 MHz) for land-mobile use, skeptics expressed concern about obtaining acceptable coverage with the shorter, line-of-site propagation and with competitively priced vacuum tube or solid-state devices. The required devices were produced, and coverage made adequate by system refinements. Similar concerns were expressed about the utility of the 800 MHz frequencies, but technology and techniques have made this band eminently satisfactory for a multitude of applications.

TECHNIQUES	LOCATIONS INSTALLED	ACCURACY 95%	ACCURACY 99.5%	ADVANTAGES	VEHICLE DATA* COSTS	VEH 1 CH RADIO COSTS (NON-VOICE)	CONTROL CENTER COSTS*	REMOTE SITE COSTS*
A. DEAD RECKONING								
• BOEING (FLAIR) WICHITA	ST. LOUIS	200'		·ACCURACY	$3750	$1250	$500K	MAY REQUIRE SOME "SIGN-
• E-SYSTEMS-ARLINGTON, KAN	BUENOS AIRES			·MINIMUM REMOTE SITE EQUIPMENT ·LARGE AREA COVERAGE	POSTS" RADIO			BEACONS
• MARCONI								
B. PROXIMITY								
(2) ·AVM SYSTEMS FT. WORTH BR SIGNPOST (2) ·FAIRCHILD-SHARP-SIGNPOST (1) ·RCA X-BAND ·NOVATEK INC-BURIED MAGNET WISMER BECKER, SACRAMENTO	HUNTINGTON BEACH	250'	450'	·SIMPLICITY ·ACCURACY FUNCTION OF # OF SIGN POSTS ·MIN. VEH. COST ·MIN. CALIBRATION ·SERVE MANY USERS	$1250 $3000	$1250	$350K	$300 ASSUME 2500 UNITS FOR 100 MI^2 AND 10,000 FOR 400 MI^2 IC ON 1000' GRID
C. RADIO LOCATION								
(1) ·SIERRA RESEARCH NARROWBAND (PHASE) (1) ·CUBIC CORP-WIDEBAND (PHASE)		1300' 2600'						
(2) ·HAZELINE-PULSE (TIME OF ARRIVAL ·RAYTHEON-FM (PHASE)	DALLAS	400'	800'		$1750	$1250	$500K	$800K FOR (3) TX SITES + CAL SITE
(2) (1)-TELEDYNE-LORAN C —MEGA PULSE LORAN C TRANSMITTER SYSTEM IF REQUIRED (TURNKEY-3 SITES + CAL. SITES)	NONE OPERATING	400'	600'	·CAN BE APPLIED TO LAND, AIR, AND SEA ·LARGE AREA COVERAGE				

* 1977 ESTIMATED COSTS

Figure 2-17. Presently available vehicle location systems.

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The strengths of land-mobile radio service can be summarized as follows:

- Effective and economical communications, particularly in limited coverage areas and over favorable terrain, to mobile and portable radios in automobiles, trucks, motorcycles, boats and aircraft, and to personnel with hand-held transceivers.
- Effective communications over extended areas, such as county-wide and state-wide, with some compromise in cost and/or absolute coverage as the areas increase in size and terrain becomes unfavorable because of hills, rivers, valleys, ravines, forests, and mountains.
- High degree of reliability
  - A properly designed land-mobile system will provide circuit merit 3 (see Figure 2-18) or better service over an agreed-upon percentage (90%, 95%, 99%, etc.) of the defined coverage area.
  - Cellular and other mobile telephone systems are required by FCC regulations to provide high-quality communications. 99% of the primary service area will have 22 dB over 12 dB SINAD signal. To achieve this the system will provide 3.5 microvolts at the mobile receiver input.
  - The equipment for both the public service and business radio market is reliable and rugged. Mean-time-to-failure rates are at the state-of-the-art for electronic equipment. Equipment is expected to last 10-15 years, although much of the duty is in unfavorable environments, including buses, military vehicles, and motorcycles.
  - Low cost. The competitiveness of the market and the high level of refinement of equipment design, components, and manufacturing result in good value in both the business and public service markets. In general, business market radios are considerably lower in price than those for public service, but basic quality may be essentially the same. The higher cost of public service radios results from users' specifications requiring higher power, greater special options capability, and additional system service expectations.
- Economy of radio-frequency spectrum
  - Narrow band operation
  - Frequent frequency re-use throughout the country
  - Sharing of repeater facilities and frequencies by a number of users
  - Channel trunking
- Data communications capability
  - The limited data capability of land-mobile systems meets the needs of most users in the present market.

This background of general satisfaction with land-mobile systems is not intended to imply that there are no limitations inherent in the present technology, nor that the needs of all potential users are met. The next section will deal with limitations and un-met needs in mobile communications service.

Circuit Merit Figure	Grade of Circuit Performance	Voice Frequency Signal-to-Noise Ratio	Typical Receiver Quieting
1	Unusable, Presence of speech barely discernible.	Below 8 dB	0 to 6 dB
2	Readable with difficulty. Requires frequent repetition. (Non-commercial)	8 to 16 dB	14 dB
3	Readable with only a few syllables missing. Requires occasional repetition. (Commercial)	14 to 22 dB	20 dB
4	Perfectly readable but with noticeable noise.	20 to 30 dB	25 dB
5	Perfectly readable; negligible noise.	Above 30 dB	Above 25 dB

Figure 2-18. Degrees of reliability for land mobile systems.

2.7 LIMITATIONS OF PRESENT LAND-MOBILE COMMUNICATIONS SYSTEMS

2.71 Spectrum Scarcity

For many users and would-be users of land-mobile communications, the primary limitation is not technological, but simply the lack of assignable frequencies for new or expanded service. In a given area there may be no frequencies available in the desired band. There are many laudable efforts under consideration and in use to extract maximum utility from the land-mobile assigned spectrum, including split (offset) frequency assignments, amplitude-compandored single sideband modulation, shared repeaters, trunking systems, and utilization of TV channels. Regardless of these measures, potential users either are unable to obtain channel assignment, or must accept frequencies that are technically deficient. For example, they may cause interference with other channels in a user's system, or with other systems nearby, requiring expensive and power-robbing filter systems. Frequencies might be available in the 800 MHz band, but the user may have an area of operations too large to be covered economically by these high frequencies. The extent to which this latter consideration can be a limitation is shown on Figure 2-19. On this figure are plotted predicted coverage above a minimum threshold for high-band, UHF, and 800 MHz frequencies. All predictions are based on the same transmitter power, antenna gain and height, and location. The coverage difference illustrated on this figure shows dramatically the problems a user may have if the only available frequencies for this system are in the high-frequency bands.

If the user requires coverage over an extended area and/or in irregular terrain, he will be compelled to use one or more of the system techniques addressed in Section 3, which will increase the cost of his system and/or may not be able to achieve the communication service he requires.

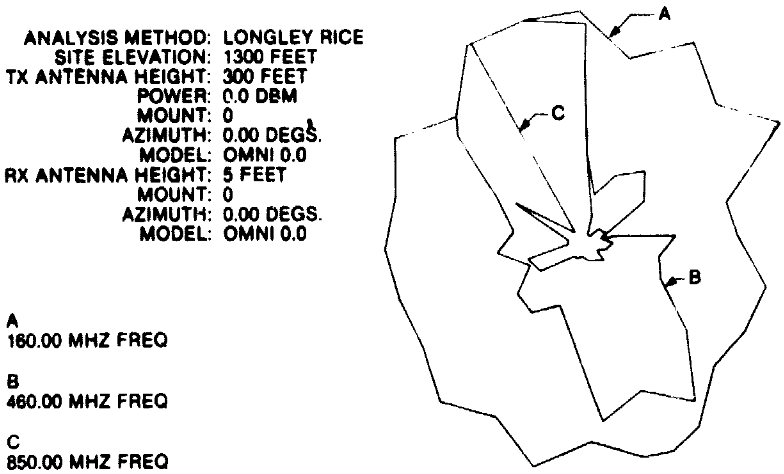

Figure 2-19. Comparison of coverage over typical terrain at 160 MHz, 460 MHz, and 850 MHz.

2.7.2 Service Area Limitation

As discussed earlier in this report, no land-mobile radio system will provide absolute coverage to vehicles or personnel over 100% of a typical service area 100% of the time. For example, in a normally good-quality commerical system calculations might show that a user could expect his 50 watt 150 MHz transmitter and a 100 ft high antenna to provide a usable signal to 90% of all locations within a 15 mile radius for 90% of the time. The remaining 10% of locations would have a usable signal less than 90% of the time.

As the service area increases in size, becomes irregular in shape, or includes terrain not conducive to good line-of-sight propagation, the percentage of the coverage area over which good-quality communications is possible will decrease although added system capability will be aimed at keeping the coverage as solid as possible.

2.7.3 Interference

In the real land-mobile world the density of system transmitters is high, and in typical areas strong signals on many frequencies will be in the environment, forming a basis for nuisance and destructive interference. Furthermore, a new system user will have little chance to select frequency assignments from the FCC that will minimize his inter-system and intra-system interference due to the scarcity of frequencies.

The importance of interference cannot be overemphasized in its effect on system propagation performance. The following brief description of interference in land-mobile systems will clarify this statement.

Sources of interference in a land-mobile system are as follows:

a. Ambient Noise

b. Transmitter Noise

The user's own land-mobile transmitter(s) and others emit a wide-band noise spectrum (Figure 2-20). Note that there is substantial noise power far from the desired output frequency.

c. Transmitter Spurious Signal Output

d. Transmitter Intermodulation

Intermodulation (IM) frequencies are generated when two or more frequencies mix in a non-linear element. The non-linear operation usually occurs in the transmitter power amplifier (transmitter IM) or in the receiver first converter (receiver IM). Transmitter intermodulation frequencies cause RFI when they happen to fall in the receiver's passband.

The effect of transmitter noise and intermodulation can be seen by reference to Figure 2-21, which shows the amplitudes of the undesired signals.

The significance of the interference problem in land-mobile systems is that special antenna configurations, complex cavity filters, and ferrite circuit assemblies must be employed to meet FCC requirements. Each time a cavity or circulator is employed to reduce the undesired signals some attenuation of the desired signal also occurs. In an extreme case, a system using an unfortunate assignment of frequencies in a crowded r.f. signal environment can utilize antenna combining and interference rejection equipment that will reduce 250 watt transmitter output power to less than 10 watts.

2.7.4 Low Height of Field Unit Radio

Many signal propagation problems in land-mobile radio are solved or relieved by using high base station transmitting antennas to extend the radio horizon and talk over obstructions. The field unit (vehicle or hand-held radio), however, is almost always at a height of six feet or less. When the terrain surrounding the field unit is flat, increasing the height of the base antenna will, up to limits, improve communication range to the field unit. When the terrain between the field unit and the base is irregular, however, raising the base station antenna may have little or no effect on the quality of communication with a field unit located directly behind an interfering terrain feature. This is illustrated in Figure 2-22. Increasing base antenna height at "A" from position 1 to position 2 will overcome the effect of terrain obstruction "B" on propagation in the area of "D," but will have little effect on improving communications with a field unit at position "C." Unfortunately, the situation depicted is often a practical reality, since roads and populated areas are often in long valleys, such as along river beds, and rising land on one side or the other of such a valley is geographically typical. The effect described here is, of course, worst on the highest frequency land-mobile bands. At 800 MHz the obstruction at "C" which is intefering with communication with the field unit is not necessarily a terrain feature; dense foliage could have a similar effect.

2.7.5 Environmental Considerations

The effects of the previously listed limitations are frequently exacerbated by environmental regulations. Many states, federal and state park management, and local governments severely restrict the nature of antenna and building structures within their respective jurisdictions. It is frequently impossible to locate antennas on the best location from a propagation standpoint, and in extreme cases no structure will be permitted that shows above the local

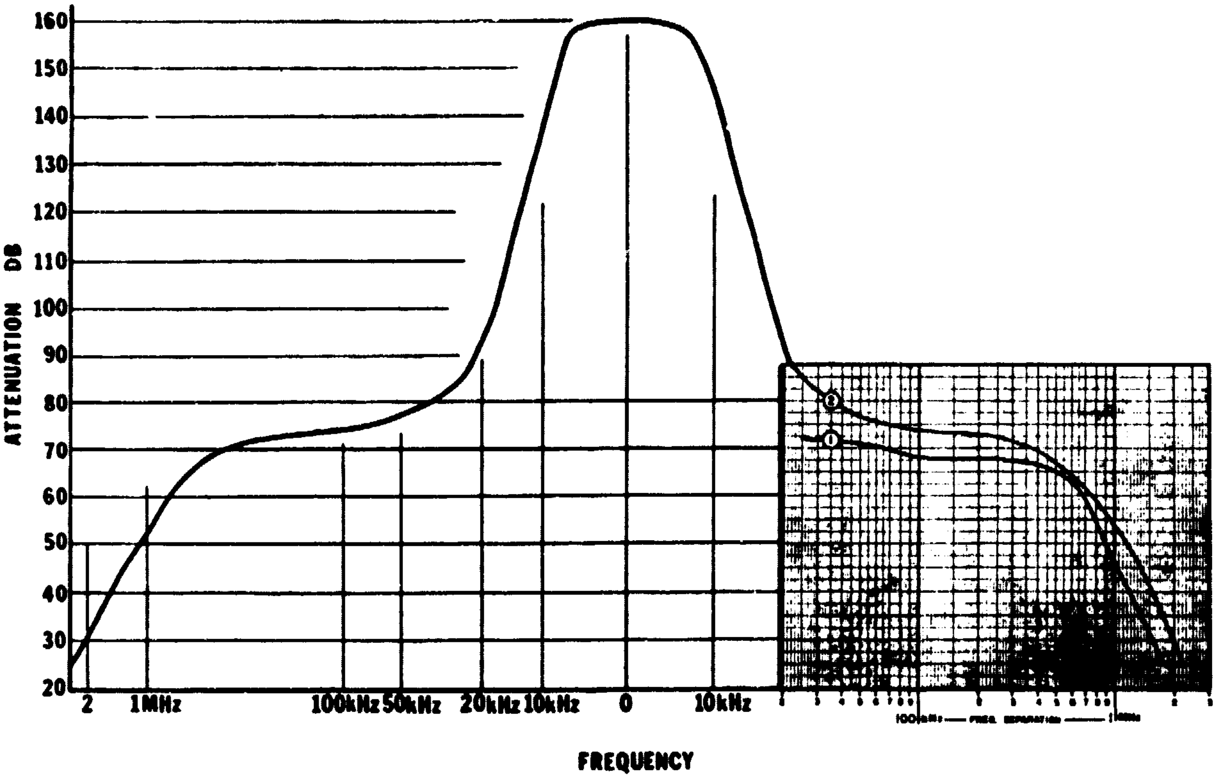

Figure 2-20. Transmitter noise spectrum.

trees. The effect of such a restriction on signal coverage in any frequency band can be serious; at 800 MHz it can present impossible barriers to achieving system goals.

2.7.6 Passband Width

Another limitation of present land-mobile systems is a deficiency in capability for high-speed signaling and data transmission. The AMPS-type of cellular system equipment achieves audio bandwidth of 12.5 kHz, for the purpose of attaining fast connect time with high-speed signaling. The normal land-mobile passband is 3000 Hz, which limits the data transfer rate to a range of 500 bps to 2400 bps, depending on the degree of falsing protection and recovery rate desired. To be safe in the system environments being addressed in this report, redundancy and error-correction should be employed, and data transfer rates of 500 to 1000 bps would then be typical.

This limitation, in combination with the FCC rule limiting the length of a data message in land-mobile service, severely restricts the amount of information that can be passed in data form over a land-mobile channel. The rate meets most of the requirements of present users for identification, status, and short message, but pressures are building to use land-mobile systems for much larger amounts of data. The Mobile Data Terminal (MDT) is a device for which there is potentially heavy demand. Since the MDT can transmit data at a 2400 bps rate for a two second period, it would seem that MDT's could make efficient use of land-mobile by transmitting 1800 messages per hour. Because of the protocols used in assuring transfer reliability with acceptable collision rates between terminals, and because of data overhead required to utilize the short transmission, optimum loading of MDT's on a channel is far less. A number of practical considerations reduce the actual number of MDT's that can operate

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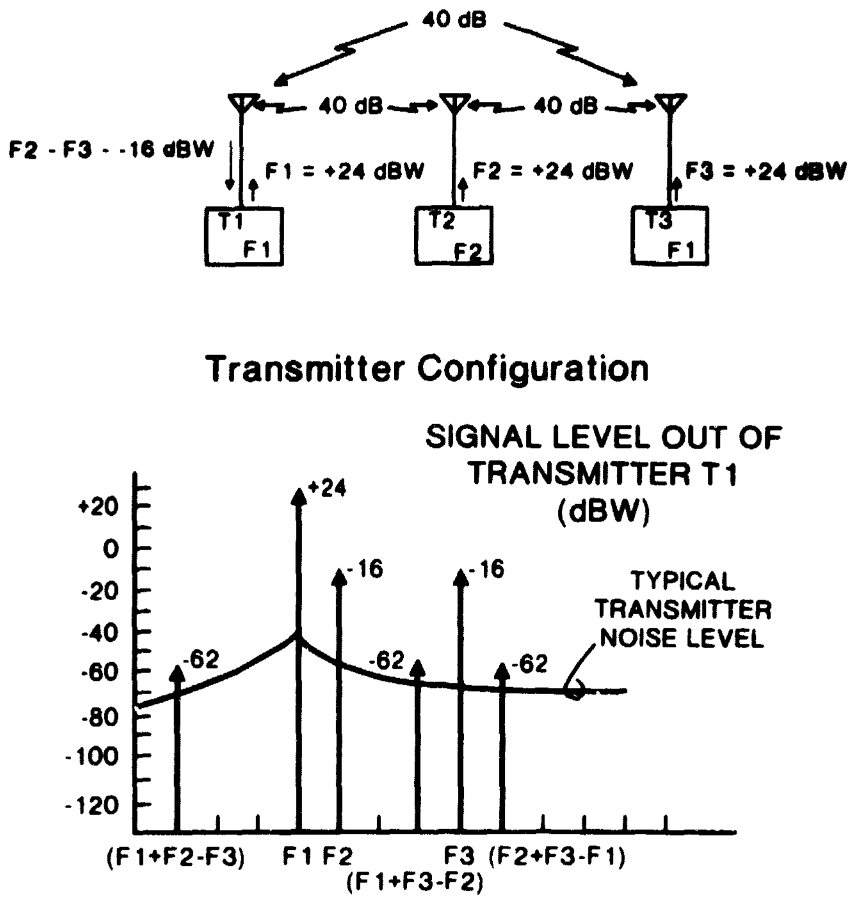

Figure 2-21. Three-transmitter internal frequencies present at the output of transmitter T1.

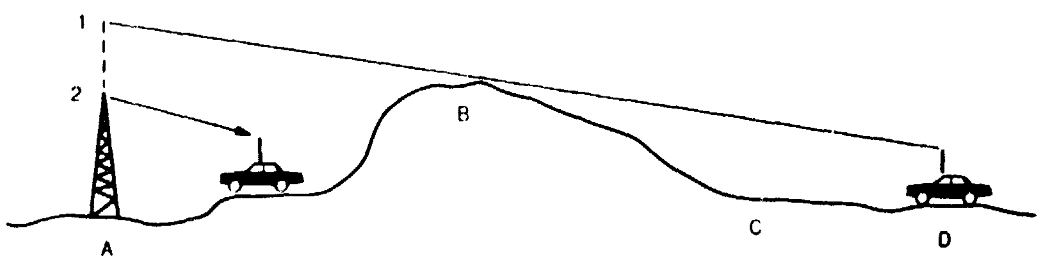

Figure 2-22. Relay antenna.

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successfully on a single channel. They are:

- The number of messages/hour will be sent between each vehicle and base
- The average length of the message
- The extent to which the MDT will be sharing the channel with voice traffic
- The quality of R.F. signal coverage
- User discipline

These factors limit the number of mobile data terminals that can operate on a single channel to 10 to 100.

Passband width of land-mobile radio systems will present a definite limitation in an increasing number of future applications, as increasing use is made of data communications to improve users' operations and make better use of the r.f. spectrum. There are technical and legal barriers to using a multiplicity of land-mobile channels in parallel to pass wider-band data. Data overhead to allow re-combining of the channels will result in lower data transfer efficiency than a single wide-band channel; intermodulation interference will be a major problem if the channels are adjacent or close to each other. At present such use in the land mobile spectrum is not licensable.

2.7.7 Compromises to Minimize Limitations

The close relationships between ideal propagation ranges, inter-system interference, and frequency availability reduce the options a land-mobile system designer has in meeting the required coverge ranges. This is particularly true if co-siting is a factor. In many cases the most desirable transmitting site(s) from a propagation standpoint may be heavily populated with other systems. The new system user has a choice of using a less populated site, with a perhaps unacceptable reduction in coverage range, or to select the least troublesome frequencies from those available, and design an antenna/interference reduction system that will produce acceptable levels of inerference. This approach may also cause sufficient attenuation of the transmitted signal to take the desired range unattainable, or unattainable with an economically acceptable system.

Rationalizing the above considerations with users' expectations for coverage sometimes requires that the designer call upon one or more of the technologies discussed in the previous section. Sometimes even employing all the system tools available, a completely satisfactory solution is impossible, and coverage or system operation, or both, must be a compromise. This is particularly true in statewide systems. in bus and truck transport systems where the trucks operate in large areas, and in mobile telephone systems when the user leaves the urban system coverage area.

In summary, the r.f. propagation ranges, multipath reception, and interference effects combine to comprise a major limitation in land-mobile systems. When combined with a scarcity of available frequencies, there are often severe compromises made in the land-mobile user's desired results. The problems are minimal in small area systems in flat terrain, but in statewide systems major concessions to cost and coverage must be made.

An illustration of the cost of no-compromise performance is the police/fire system serving the City of Indianapolis. To meet the police system requirement of UHF band radio coverage from hand-held radios over 99% of the police operations area requires 500 receivers located at 50 sites throughout the city and a large voting and switching complex (Figure 2-23) at the control center.

Figure 2-23. Switching complex.

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Section 3

NUMBER OF INSTALLATIONS FOR A UBIQUITOUS MOBILE TELEPHONE SYSTEM

The feasibility of implementing a terrestrial mobile phone system depends largely on the number of fixed installations required to cover the intended service area. The range of each installation depends on the propagation impairments in the area.

Path blockage due to irregular terrain is an important factor in limiting range. The distance between fixed stations is thus a function of terrain roughness. A study was conducted to determine the roughness of the terrain in different physiographic areas of the United States, and thereby predict the typical range that could be expected in these areas. A USGS map delineates the physiographic areas (Figure 3-1).

The procedure to determine the range of an installation is as follows:

a) Specify the percentage of the area to be serviced; e.g., 96%

b) Determine the terrain roughness from topographic maps; i.e., take 80% of the difference between maximum and minimum elevations along radials from the location of the installation. (See Figures 3-2 through 3-7)

c) Determine the height of the transmitter-receiver above the average terrain.

d) Specify the radio frequency, transmitter power, antenna gains and receiver sensitivity with appropriate fading margin.

e) Apply the graphs and formulas that relate the factors to range.

f) Compare the calculated results with results achieved in similar studies and installations.

The procedure was applied to sample areas taken from seven physiographic areas of the contiguous United States as defined by the U.S. Geological Survey (USGS). The result specifies the average range, hence the area served by a single installation in each of the physiographic areas. A USGS map delineates the physiographic areas (Figure 3-7). Dividing each physiographic area by the service area of a single installation yields the number of installations required in the area. Summing the numbers for all the physiographic areas yields the total number for all the contiguous states. Table 3-1 presents the results of the computation.

The average range is greatest where terrain is relatively flat. For the Atlantic Plains region of the southeastern United States, the average range is 20 miles. The Interior Plains region, including the Dakotas and the central plains southward to Texas, shows an average range of 10 miles.

The rugged Rocky Mountains are difficult to cover everywhere at 900 MHz, and the average dependable range is only 2 miles (fortunately the percentage area of the country is small, also, for such difficult terrain). The overall average range is about 5 miles, and increases to 6.5 miles if the Rocky Mountain System is excluded.

The total number of installations required to cover the contiguous United Stations completely is 40,098. Approximately half that number of installations is required to cover the Rocky Mountain System.

A sample power calculation is shown here to determine how much loss can be tolerated from base to mobile, and mobile to base stations.

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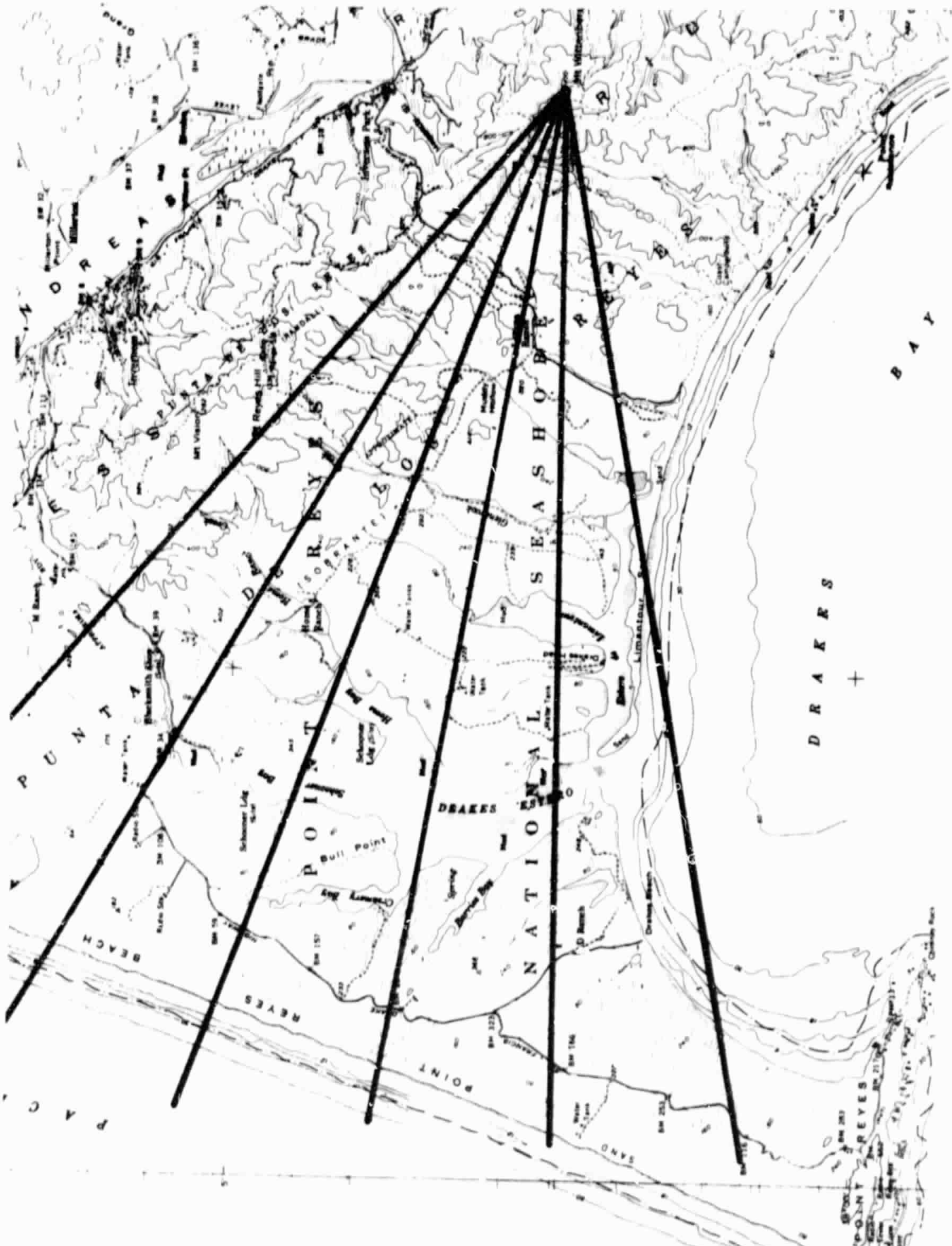

Figure 3-3 Topographic map — Pacific Mountains

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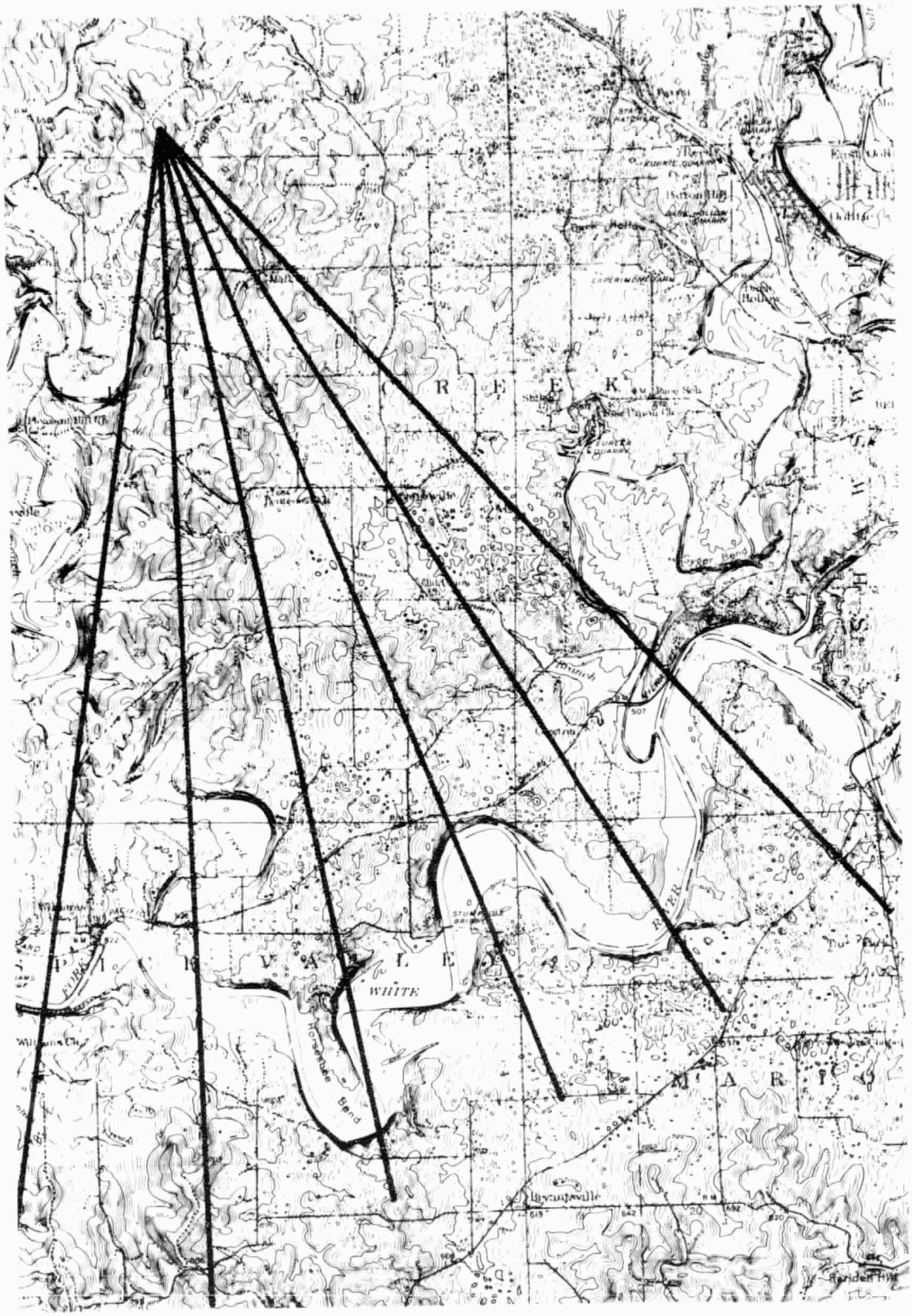

Figure 3-4. Topographic map — Indiana Interior Plains

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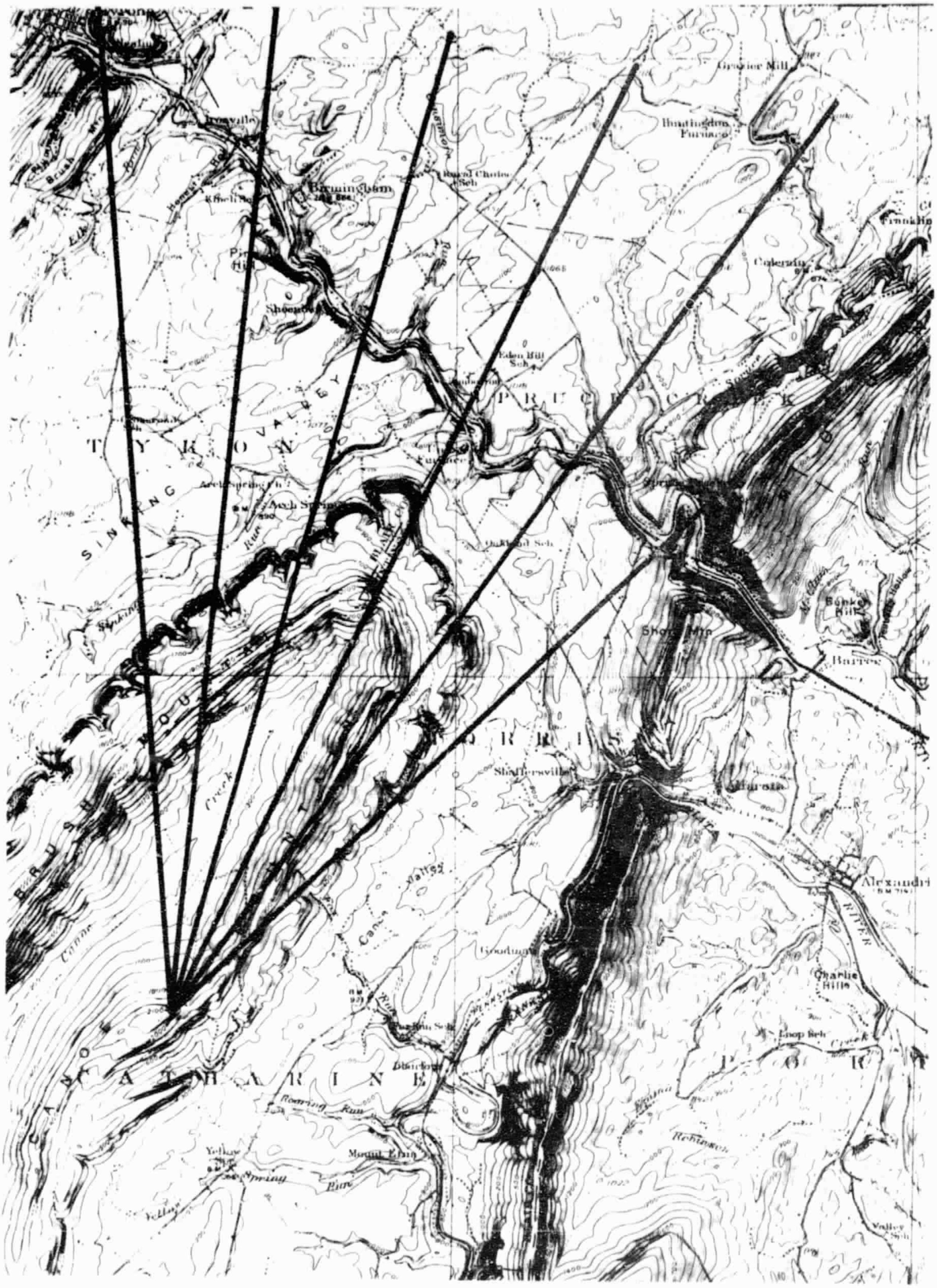

Figure 3-5   Topographic map — Appalachian Pennsylvania

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Figure 3-6. Topographic map — Wyoming Rocky Mountain System

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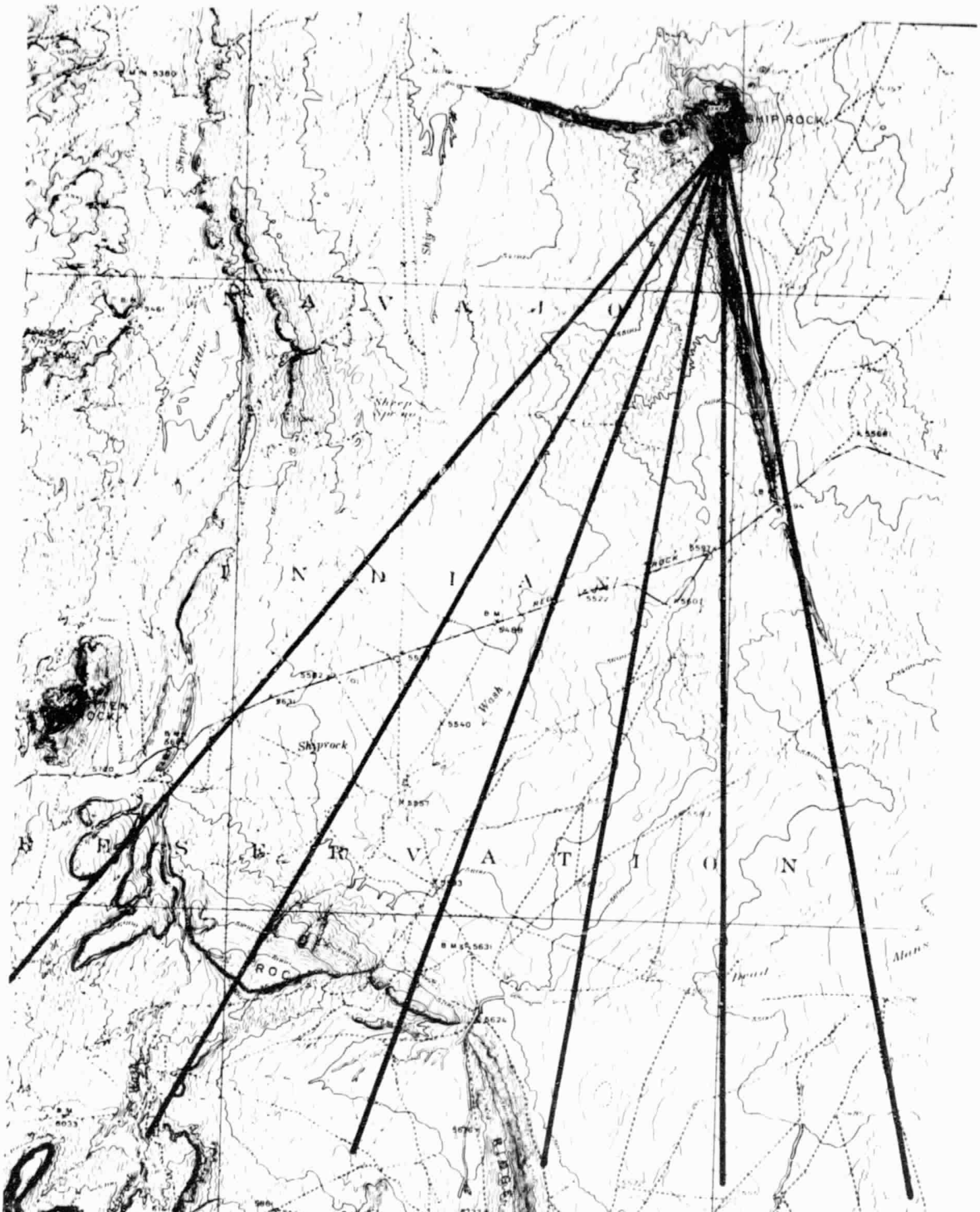

Figure 3-7. Topographic map — New Mexico Intermontane Plateau

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GIVEN:	
Effective Radiated Power (Base Station)	300 watts (+24.8 dBW)
Receiver Antenna Gain	2 dB
Minimum Signal for Receiver	.25 μV (for 12 dB SINAD)
BASE TO MOBILE:	
Power (Received at Mobile)	= 1.25×10^{-15} Watts
10 Log Power	= −149 dBW
Fading Margin	= +15 dB
Minimum Power at Receiver	−134 dBW
Effective Radiated Power	+24.8 dBW
Receiver Antenna Gain	+2 dB
Maximum Allowable Path Loss	160.8 dB
MOBILE TO BASE:	
Minimum Power at Receiver	−134 dBW
Effective Radiated Power	+4 dBW
Receiver Antenna Gain	+10 dB
Maximum Allowable Path Loss	148 dB

We assumed a transmitting antenna height of 150 feet and receiver antenna height of 6 feet. The 150 foot elevation was used based on the nominal antenna elevation for the AMPS system in Chicago. The expected range of elevation (100-200 feet) for the AMPS system was based on the cost vs. transmission quality. The path losses shown in Table 3-1 agree very well with the data in the Longley report on transmission losses over irregular terrain.

The range of the installations in the different areas was determined by the following method:

The maximum allowable path loss (from mobile to base) was previously determined to be 148 dB for a receiver sensitivity of 0.25 μV. By taking the terrain roughness from Table 3-1 and applying it to the chart in Figure 3-9, we can find the additional attenuation loss due to terrain variations. Subtracting this value from 148 dB yields the maximum plane earth loss for the terrain in a given area. Then by using the plane earth loss chart in Figure 3-8, we can find the range in miles for a specific area.

Figure 3-9 represents empirical data from three different sources. The Bullington data was used for this study.

Propagation studies by E.F. Johnson, Co. and data in the Bell System Technical Journal, (AMPS Studies in Chicago and Philadelphia), predict about the same order of transmission losses as we expect. Variations in EPR, receiver sensitivity, fading margin, and terrain obstructions account for range differences.

Analysis of propagation data in Japan by Akeyama et. al.[5] show variations in local values increase by 11 to 13 dB in mountainous terrain, requiring increased margins to be set for irregular topography.

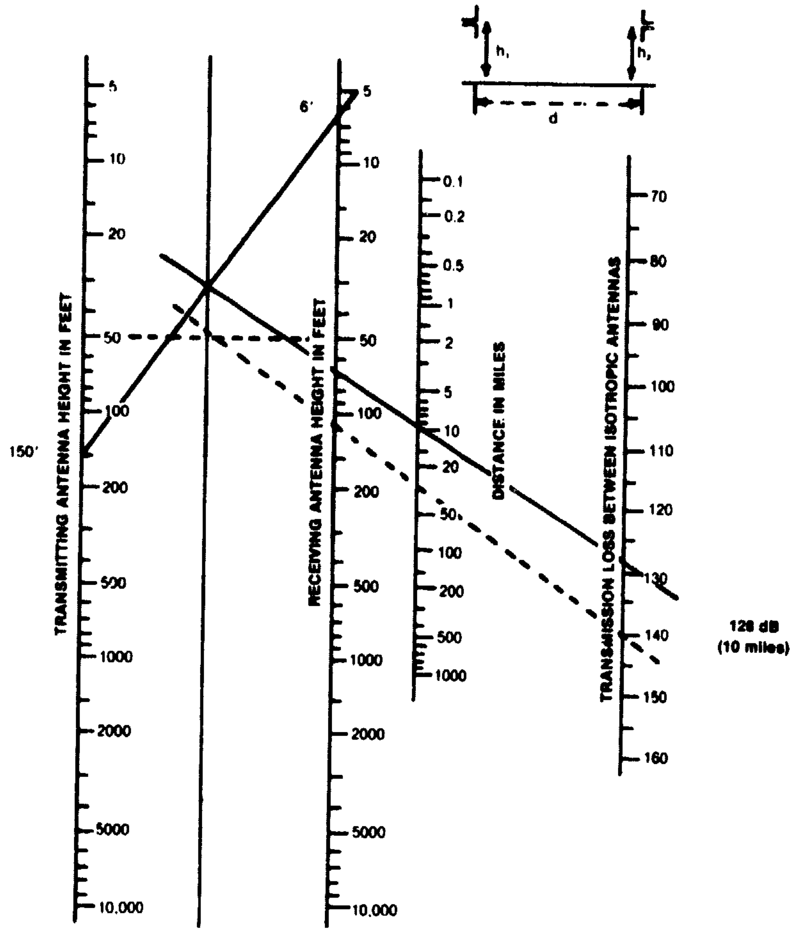

Figure 3-8. **Smooth earth propagation losses (after Bullington).**

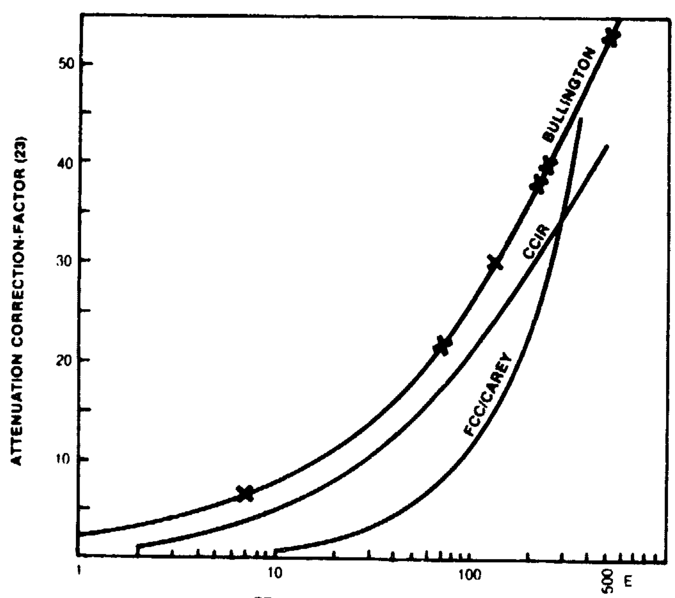

Figure 3-9. **Additional propagation losses at 900 MHz due to terrain roughness.**

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The AMPS simulation for Philadelphia predicts a cell radius of 8 miles for a S/N ratio of 18 dB over 90% of the area. The AMPS Developmental System in Chicago has a nominal cell radius of 10 miles for an S/N ratio of 18 dB.

References

1. "Radio Wave Loss Deviation and Shadow Loss at 900 MHz," by Neal Shepherd, IEEE Transactions on Vehicular Technology, Vol. VT-26, No. 4, Nov. 1977.
2. "Prediction of Tropospheric Radio Transmission Loss over Irregular Terrain, A Computer Method — 1968," A.C. Longley, et al.
3. "Computer Projections for Base Station Service Area Contours," by E.F. Johnson Company, Mobile Radio Department, Waseca, Minnesota, December 1979.
4. "Cellular Test Bed," Bell System Technical Journal, January 1979.
5. "Mobile Radio Propagation Characteristics and Radio Zone Design Method in Local Cities," A. Akeyama, et. al., Review of Electrical Communications Laboratories, Vol. 30, No. 2, 1982.

Figure 3-8 was originally published in the Bell System Technical Journal article, "Radio Propagation Fundamentals," by Kenneth Bullington in May 1957.

Figure 3-9 data from Neal Shepherd's report, Reference No. 1.

Section 4

NATIONWIDE TERRESTRIAL SYSTEMS

4.1 CONCEPTS RESTRICTED TO 800 MHz BAND

Four terrestrial system concepts were configured and analyzed from a business viewpoint to determine the minimum population density that can be served profitably by terrestrial means. Conclusions can then be drawn as to the population and communication needs left unserved.

The terrestrial non-urban systems that were considered use the 800 MHz frequency band and, to the extent possible, cellular-system-compatible technology. It must be recognized at the outset that the 800 MHz frequency band and the cellular system specifications are anything but optimum for a non-urban system. The cellular system was designed to provide telephone-quality communications in high-density population areas with a high percentage of mobile telephone users. For that application the 800 MHz band is the band of choice; the relatively short range of signal propagation and the rapid degradation of signal level at the radio horizon are exploited in the cellular telephone system to enable a graduated series of cell sizes to serve progressively heavier user loads. Within these cells the systems are designed to accept relatively high interference levels and employ high desired-signal levels which are generally readily attainable in the urban environment.

In the non-urban application, the situation is generally the reverse; user densities are low, desired signal ranges are long, and both the desired-signal levels and the interfering-signal levels are low over large portions of the service area. Under these application conditions the 800 MHz band is a poor choice, and the complex and expensive equipment required to accomplish cell division and hand-off are more burdens than necessities. The propagation limitation of the 800 MHz band relative to the lower frequency mobile bands is dramatically shown in Figure 2-19 Note that the reduction in area covered by 800 MHz is of such magnitude as to be a significant, possibly insurmountable, barrier to implementation of high-cost, cellular systems in areas of low user density.

Nevertheless, the 800 MHz band is used in the following terrestrial system designs for two reasons: First, attempting to clear for use the frequencies and locations that would be required for a continuous nationwide system on high-band (150 MHz) or UHF (450 MHz) would be a nearly impossible task; as stated earlier, frequencies are unavailable for present user and prospective user needs, and the task of reassigning lower-frequency band channels from present users to nationwide mobile telephone use would be formidable. The second reason for using 800 MHz frequencies in the non-urban system concept design is to enable subscribers to use their urban cellular mobile telephone transceiver in the non-urban system. Some modification of the mobile radio will be allowed in alternative economic analyses. This will be explained in later paragraphs.

Four system concepts are reviewed.

The signal propagation ranges specified for each concept are general figures based on Longley-Rice and other accepted methods of computation, modified by detailed prediction analyses and field experience with 800 MHz systems. It should be evident that no wide-area land-mobile system can provide 100% coverage of typical service areas. Terrain anomalies leave areas within defined cells unserved by a single central transmitter location. Complete coverage of those areas requires special system approaches, such as additional transmitters operating simultaneously with the primary transmitter, or remote receivers. The precise signal coverage predictions and detailed special designs to assure coverage to a specified percentage of each cell are far beyond the scope of this study.

4.2 FOUR SYSTEM CONCEPTS

4.2.1 "A" System

The System "A" uses FCC cellular signal quality specifications; i.e., 39 dBμV/m on the receiver antenna, 4 watt effective radiated power from mobile radio (EIA compatibility specifications), and FCC regulations applying to base antenna height and effective radiated power. These specifications result in essentially a balanced system; that is. approximately the same allowable talk-out and talk-in path loss.

TERRESTRIAL NON-URBAN SYSTEM PARAMETERS

TALK-OUT (BASE-TO-MOBILE)

Antenna Height (above average terrain)	100-200 ft
Effective Radiated Base Power (Product of transmitter power, antenna gain, cable and cavity losses)	100 W
Receiver Antenna Gain (Antenna Gain less Cable and Connector Losses)	0 dB
Minimum Field Strength at Mobile Receiver (per FCC Regulations)	39 dBμ (39 dB above 1 μ V/m
Minimum Signal at Receiver Antenna Terminals	3.54 μ V/m
Minimum Received Power at Mobile $\frac{(3.54\ \mu V)^2}{50}$ ohm	
Power at Receiver (minimum) 10 log (250×10^{-15})	-126 dBw
Effective Radiated Power (100 W)	20 dBw
Maximum Allowable Path Loss (Base to Mobile) [20 dBw $-$ (-126 dBw)] = 146 dB	146 dB

TALK-IN

Power at Base Receiver	-126 dBw
Diversity Antenna System Gain	+14 dB
Effective Mobile Radiated Power	+ 6 dB
Maximum Allowable Path Loss (Mobile to Base)	146 dB
Cell Control and Hand-off by the Mobile Telephone Switching Office (MTSO)	
No Hand-Held Mobile Telephone Service Guarantee	
Fully Cellular-Compatible Mobile	

Figure 4-1 is a cell cluster structure of System A. Twenty-four cells are used with each MTSO. At least 100 cells could be used in the cluster if it were not for the large geographical dispersion of the 100 cells. Figure 4-2 depicts the cell site configuration for System A, and Figure 4-3 depicts the Mobile Telephone Exchange at the MTSO.

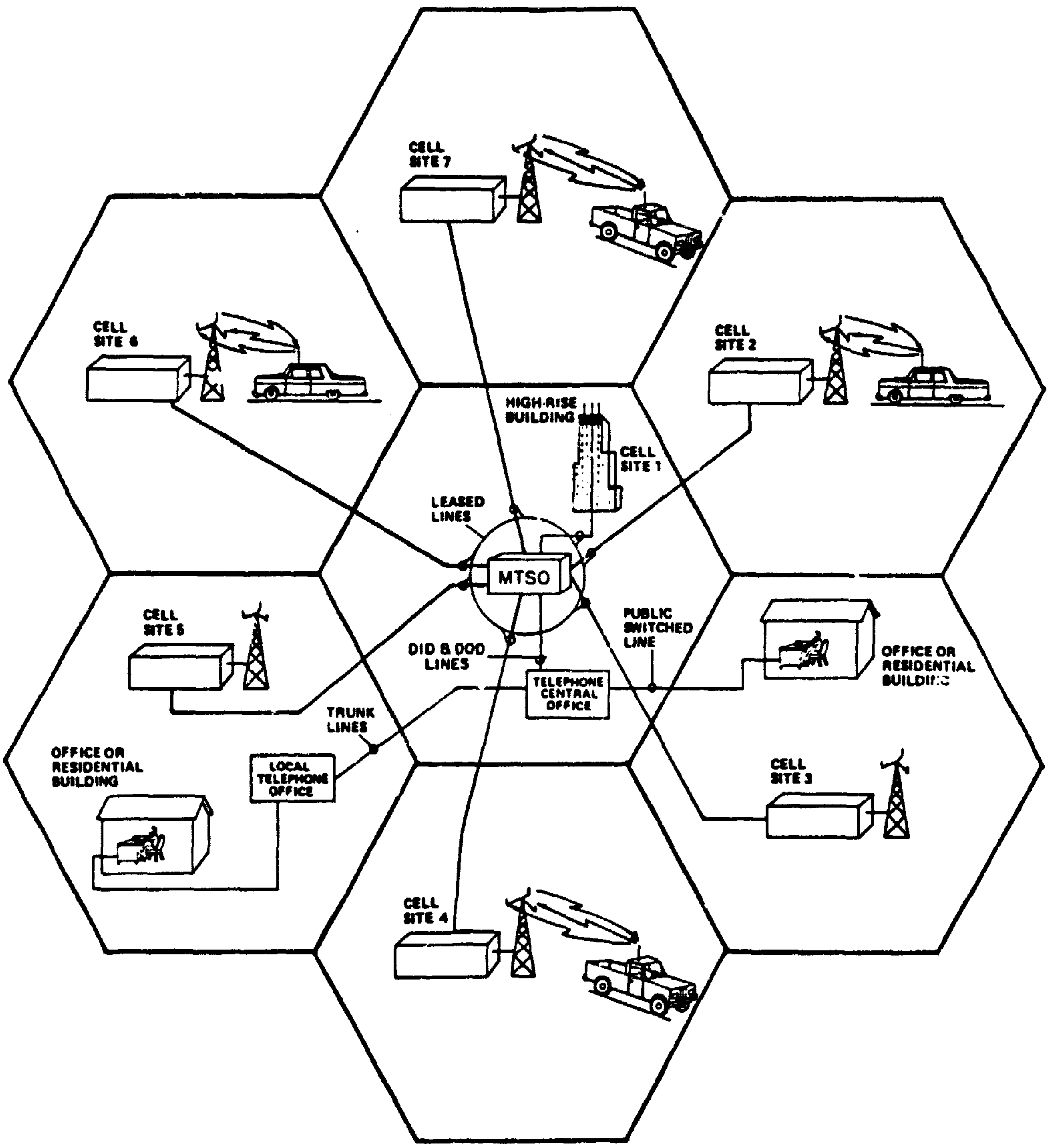

Figure 4-1. Cell cluster structure of System A.

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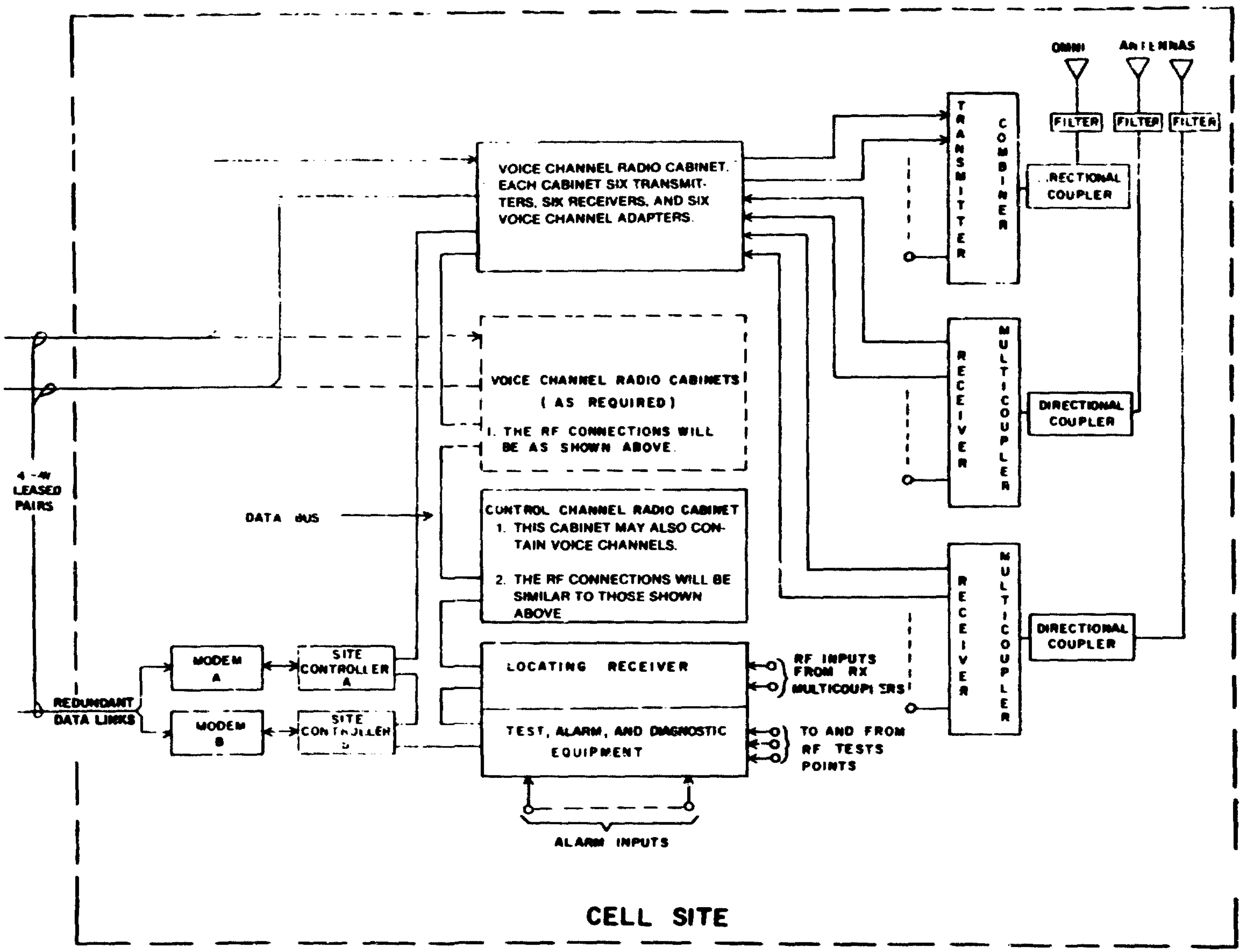

Figure 4-2. Cell site configuration for System A.

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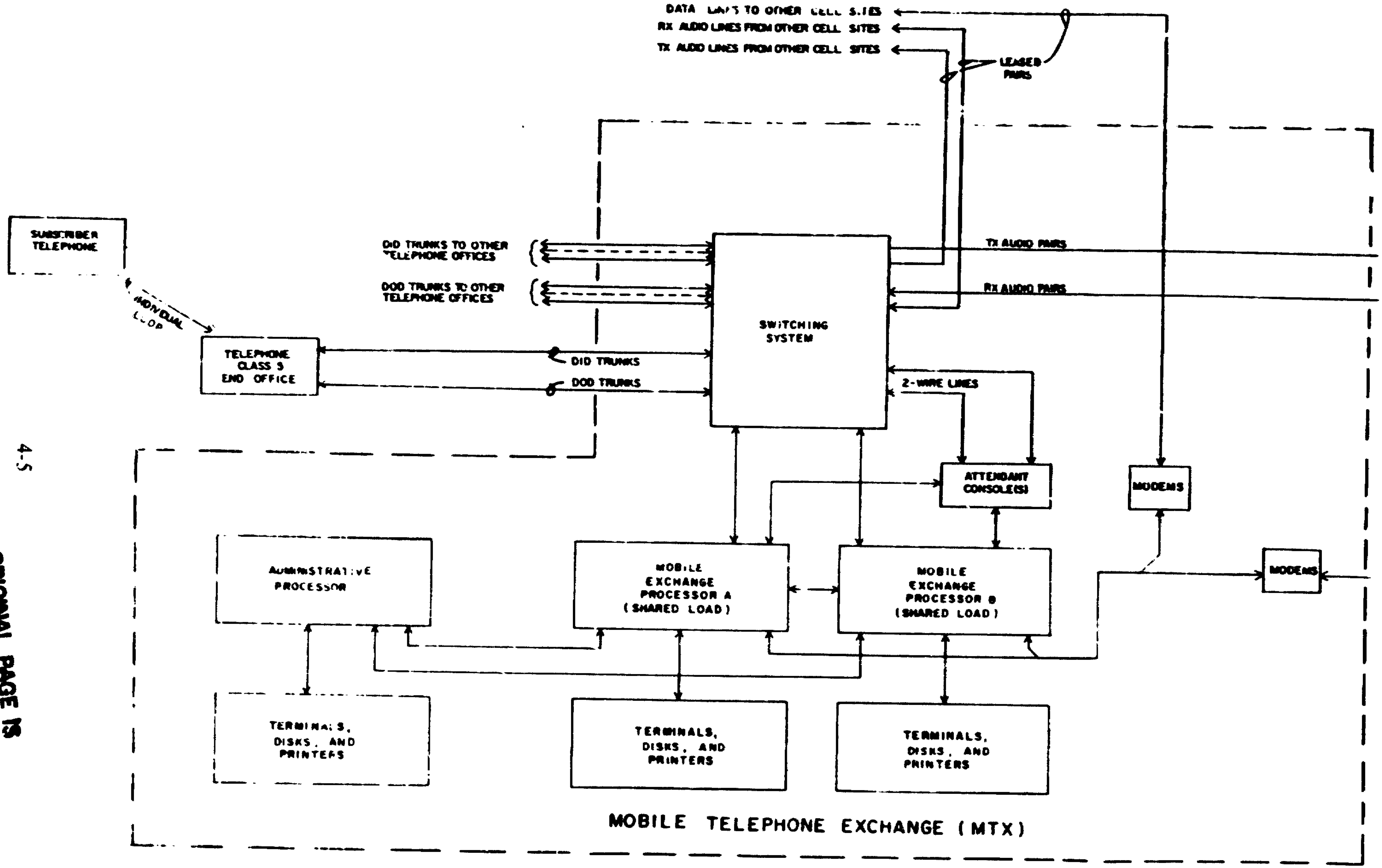

Figure 4-3. Mobile telephone exchange at the MTSO.

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Average cell radius across the continental United States is assumed to be 6 miles. This is slightly greater than the actual range predicted by the site analysis that shows 40,098 sites are required to provide coverage over 95% of the continental United States.

4.2.2 "B" System

Systems "B" is like System "A" except that it uses a simplified cell site structure. Each cell communicates directly with TELCO lines, using no MTSO. Fully cellular-compatible mobiles are used. Average cell radius is assumed to be 6 miles.

Inbound calls can be made by the user with a cellular mobile, connecting directly with TELCO lines. Calls can also be made to the mobile, but no provision is made to locate the mobile within the nationwide system. The basic system used is a stand-alone single cell system as diagrammed on Figure 4-4. It is a cellular version of the present Improved Mobile Telephone System (IMTS). There is no MTSO, no handover from one cell to another. It is assumed that the cost of cellular equipment will approach that of IMTS in the future, and that IMTS will be progressively phased out over the next decade or so, gradually forcing subscribers to switch to cellular systems.

Direct Inward Dialing (DID) and Direct Outward Dialing (DOD) leased lines are used for voice-associated communications; a dial-up line is used for periodic interrogation of the cell computer and disc storage for usage/billing information.

Redundancy is built into the terminal equipment, and one spare base station is provided per channel. The latter might not be required in all cells; either a temporarily higher blocking rate could be accepted when a transmitter fails, or a multi-frequency base station could be automatically switched to the failed channels.

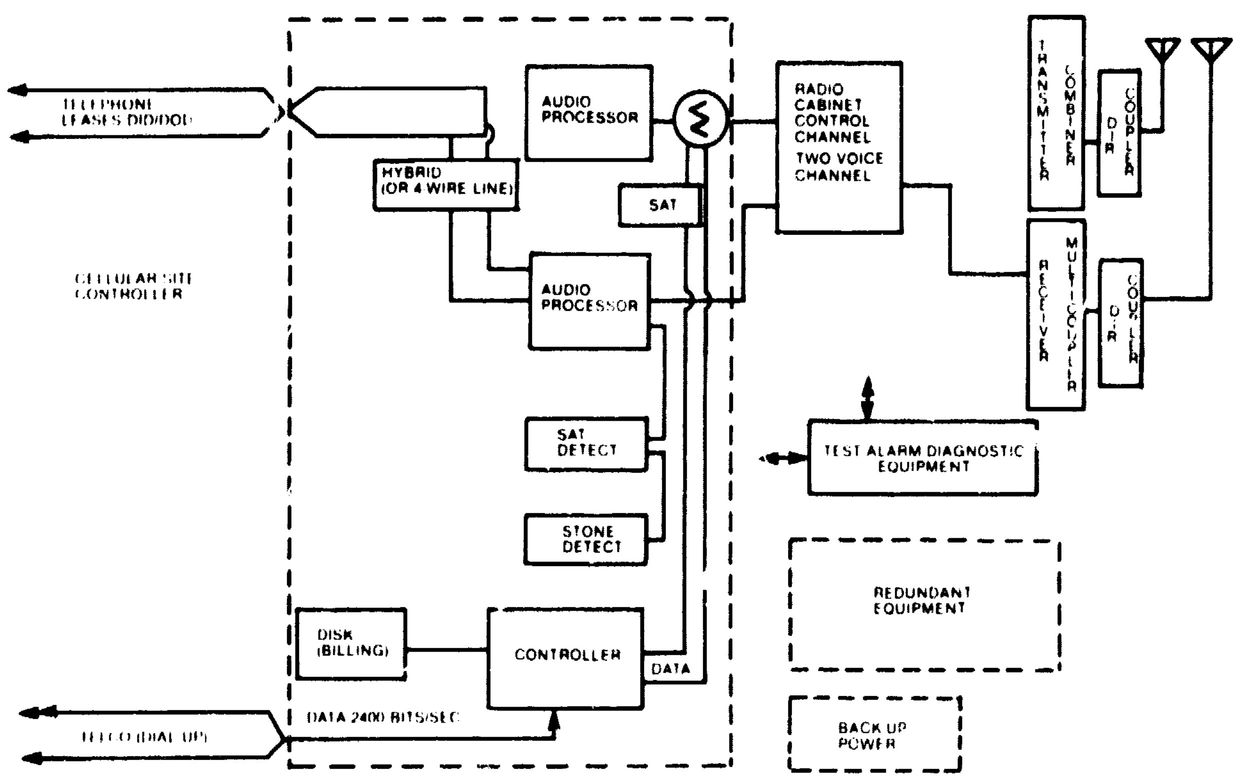

Figure 4-4. Stand-alone single-cell system.

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4.2.3 "C" System

System "C" is similar to System "B," but with specifications, on antenna height, base station Effective Radiated Power (ERP), mobile received signal level, and predicted coverage probability relaxed to those typical of 800 MHz systems other than cellular (15 mile radius) as follows:

> Base station power 90 watts
>
> Gain antenna at 500 ft height above terrain
>
> Remote receivers are located throughout a cell to extend the range of the cellular mobiles and provide for use of mobile hand-held telephone equipment. This system extends the average range from six miles to fifteen miles, and reduces the number of cell sites by almost an order of magnitude.

It is recognized that careful frequency planning, choice of base antenna site, and use of directional antennas will be required to prevent interference with urban cellular systems where the non-urban higher-power system adjoins an urban system. This is not considered to be a technical or economic barrier to use of this approach.

4.2.4 "D" System

The "D" system is like the "C" system except there are no remote receivers. Hand-held telephone service is not possible unless vehicular repeaters are used.

The mobile unit is the cellular mobile equipment, but with a 35-watt r.f. power amplifier switched on when the mobile is talking outside of the urban system coverage area. Provision is made either to switch the high-power amplifier off or to disable the mobile when within interfering range of an urban cellular system. This is a matter of system design and frequency coordination.

4.3 BUSINESS ANALYSIS

4.3.1 Cost Objectives

Each of the four systems is reviewed from a business standpoint. Based on the current average charge of $100 per month for mobile telephone service, an analysis is performed to determine the minimum user density (users per square mile) that is likely to attract investors in any of the four system concepts.

Analyses are performed on Systems A through D to determine (a) what the approximate user charge per month would be for each of the systems based upon the "Likely" market in the year 1990, and (b) what minimum population density can be served by the best candidate of the four systems. A market penetration rate of 1% of the total population in each case is assumed, that is, 1% of the population will utilize mobile telephone service. The value is obtained from the present penetration of Bell and entrepeneur IMTS service. Note that the analyses do not include use of the higher quantity potential market figures in the Market Study section of the project. The reason for this is outlined on Page 56, where it is concluded that only population densities over a value between 20 and 100 people per sq. mile can be profitably provided mobile telephone service. Based on the 1% penetration figure, there is no basis to conclude that mobile telephone service will increase in the proportion shown in subsequent years figures in the market study. Since the land mobile systems described in Task 3 cannot provide the other services in the Market Study, only mobile telephone service, and there is no reason to think that the penetration will exceed 1%, the population/penetration figures are concluded to be correct for the land mobile system.

The systems can be compared with present land-mobile telephone service, where an acceptable monthly charge is $100.00 per month. The elements that make up the cost vary among the system proprietors, but are typically made up as follows:

Base User Charge: $25.00/month

User Charge for Local Calls: $.27/minute

Average Use:

12 minutes/day, 5-1/2 days per week = 288 minutes/month

.27 = $77 per month call charges

Total Monthly Charge = $100.00 Average (not including vehicle radio)

(Plus long distance toll charges)

Based on this breakdown, an acceptable user (subscriber) base charge of $100/month is assumed for systems "A" through "D."

4.3.2 Analysis of System A

This analysis is based on fully cellular-compatible service to 95% of the continental United States. Equipment costs in this and the following analyses are based on catalog prices of 800 MHz base station equipment from major equipment suppliers and is in keeping with their pricing policies. Installation and project enginering costs are based on actual charges for similar installations. For the purpose of this analysis a cluster of twenty-four cells per MTSO has been chosen.

The analysis is shown on Tables 4-1, 4-2, and 4-3.

Table 4-1

EQUIPMENT/SYSTEM COST FOR NATIONWIDE CELLULAR-COMPATIBLE MOBILE TELEPHONE SYSTEM (SYSTEM A)

Site(s)	Radio Equip.	Switch/ Cell Site Control Equip	Ant System	Towers	Batt. Chgr Inv,	Install and System Test	System Eng/ Project Mgmt	Facility Prep	Telco Install.	Total Costs
MTSO	–	550K	–	–	75K	100K	125K	100K	–	950K
Each Cell (6 ch)	46K	1500K	10K	15K	25K	17K	60K	30K	–	353K
Cluster MTSO Plus 24 Cells	1.1M	4.15M	240K	360K	675Z	508K	1.57M	820K	–	9.43M
Total Nation Regional Systems	1.84B	6.93B	401M	601M	1.13B	0.849B	2.62B	1.37B	–	15.74B

Table 4-2

MAINTENANCE COST FOR NATIONWIDE MOBILE TELEPHONE SYSTEM "A"

Two bases for estimating maintenance costs yield approximately the same result:

I. Based on a percentage of equipment cost per cluster (MTSO + 24 cells)

Industry experience shows the percentage to be 16%.

- Equipment Costs — $6 Million
- At 16% = 1.2M/year (average of 48K/year/location)

II. Based on anticipated staffing/investment (5 yr) — 1M/year

- Personnel — 350/year
  - Manager (1) at 60K/yr
  - Secretary (1) at 20K/yr
  - System operator (3) at 45K/yr each — 24 hr manned
  - Technicians (3) at 35K/yr
  - Parts Supervisor (1) at 30K/yr
- Equipment — 600K/year
  - Vehicles — 75K investment ÷ 5 (15K/yr investment + 15K/yr maintenance)
  - Test equipment — 250K investment ÷ 5 (50K investment + 10K/yr maintenance)
  - Spares — 10% investment (initial inventory): 750K ÷ 5 = 150K/yr
  - Parts replacement at 5% = 375K/yr
- Facilities (leased + Utilities) — 50K/year

III. Total System Maint/Year Based on $1/M Cluster = $1.67B

Table 4-1 shows the equipment cost, with installation and project engineering, for a nationwide cellular compatible system based on the twenty-four cell cluster and 40,098 sites.

Table 4-2 shows anticipated maintenance cost for the equipment of Table 4-1, using both a percent (16%) of the equipment based on experience with such systems, and on a personnel and equipment build-up, Roman numerals "I" and "II," respectively. At first glance the figures for personnel may seem high, but the great size of the nationwide system and the complexity of operating a maintenance resource to serve it require a formal organization and staff.

Table 4-3 is a summary of the cost per subscriber based on a ten-year life expectancy of the equipment and a user base from the Volume 1.0 market analysis.

The results summarized in Table 4-3 show that the per user cost of *only the equipment and maintenance* in a nationwide cellular-compatible system are an order of magnitude too high.

Table 4-3

COST OF EQUIPMENT WITH MAINTENANCE, UBIQUITOUS SYSTEM

SUMMARY – EQUIPMENT COST WITH MAINTENANCE, SYSTEM A

Total Equipment Cost	$15.74 Billion
Based on 10-year Amortization	$ 1.574 B/year
Maintenance	$ 1.67B/year
Total	$ 3.244 B/year
Total Potential Users	744,000
Equipment and Maintenance Cost/User	$4,360/year $ 363/mo

With a result so far from the subscriber cost objective, even large changes in the estimates of the costs would not bring them near the objective.

No further analysis of the System A was performed, since capitalization, telephone line, land cost, and administration would increase this value even further. It would be unreasonable to attempt to estimate the cost of sites, telephone lines, power systems, and maintenance for this system, since attempting to place a grid of 40,000 sites across the United States would entail placing sites in areas completely undeveloped and without access or facilities. In the case of a large number of sites, therefore, it would be necessary to estimate the cost of installing telephone line or satellite terminal systems in undeveloped areas, building access roads to sites, supplying power by means of new transmission lines or solar, wind, or petroleum-driven generators, etc. Such an analysis would require individual call loading figures for each site before estimates of facilities could be started.

For the purpose of this study, it should be sufficient to state that System A is a practical impossibility from physical as well as economical viewpoints. The already too-high costs of just the equipment/maintenance could be increased as much as an order of magnitude if all associated costs could be computed.

4.3.3 Analysis of System B

It becomes evident from the analysis of the System A that a practical non-urban mobile telephone system will require modification in quality of services provided and the area served to bring it into commercial viability. Therefore, the requirements for System B have been modified. The primary requirement is that the owner of a cellular mobile radio will be able to use it outside of his home system area to place a call from his vehicle. The average service area of each cell is the same six-mile radius as in System "A." Hand-off of the subscriber from cell-to-cell has been eliminated, providing the user with service similar to that provided by the present widespread IMTS systems, with the exception, of course, that IMTS service is provided on high-band and UHF frequencies (152 MHz to 158 MHz and 454 MHz to 460 MHz). Use of 800-900 MHz frequencies greatly reduces maximum range, and with it the number of potential users per cell. The reduced coverage is evident from Figure 2-19, which compares typical signal coverage on the three frequency bands.

****

1. THE CUSTOMER BASE IS 22 SUBSCRIBERS.
2. THE GRADE OF SERVICE IS P 20 (20 % BLOCKED CALLS).
3. THE CELLS ARE 6 MILES IN RADIUS.
4. THE MOBILE-TO-LAND ORIGINATE RATIO IS 2 : 1.
5. THE CALL DURATION IS 120 SECONDS.
6. EACH SUBSCRIBER WILL MAKE .5 CALL(S) DURING THE BUSY HOUR.
7. THE DAY-TO-BUSY HOUR RATIO IS 10 : 1.
8. THE MAX NO. OF VOICE CHANNELS PER CELL IS 47
9. MOBILE-MOBILE CALLS ACCOUNT FOR 10 PERCENT OF TRAFFIC

****

POPULATION OF SERVED AREA IS .22E+07
AREA SERVED, IN SQUARE MILES, IS 90

****

THE AREA OF A 6 MILE CELL IS 93.53 SQUARE MILES AND
THE NO. OF CELLS IS 1 , DISTANCE BETWEEN IS 10.3923 MILES.
THE RADIUS TO EXACTLY MATCH COVERAGE AREA IS 5.88567

****

THE FOLLOWING IS A CELL BY CELL DESCRIPTION OF THE SYSTEM:

****

CELL NO.	CELL TYPE	DESIRED PROB	ACTUAL PROB	CELL DENSITY	NET MIGRA	VOICE CHAN	ERLANGS PER CEL	SUB PER
1	0	0.200	0.057	% 100	0.00	2	0.37	22

****

CELL NO.	CELL COORDINATES		SW CELL	TELCO CELL	CONN TYPE
1	6	6	1	1	0

****

****
*   SYSTEM SUMMARY   *
****

THE SYSTEM CONTAINS 1 SWITCH(ES), CONTROLLING 1 CELLS
6 MILES IN RADIUS, WITH A TOTAL OF 2 VOICE CHANNELS.

THE INTERCONNECT TO THE TELCO OFFICE WILL REQUIRE 2 DIDS
AND 3 DODS ASSUMING A 2 TO 1 MOBILE ORIGINATE RATIO
AT A .001 PROBABILITY OF BLOCKING IN THE TRUNK LINES
AND AN AVERAGE CALL DURATION OF 120 SECONDS.

THE TOTAL MILEAGE IN FOUR-WIRE LINES CONNECTED TO THE TELCO
WITHIN THE SWITCHING CELL IS 0 AND THE TOTAL MILAGE

FROM THE SWITCHING CELL TO OTHER CELLS CONTAINING TELCOS
IS 0 MILES.

THERE ARE 60 SUBSCRIBERS IN THE SYSTEM GENERATING 30
CALLS DURING THE BUSY HOUR (FOR A TOTAL OF 1 ERLANGS
OF TRAFFIC.)
****

Figure 4-5. System B description.

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The system parameters set out in the System B description on previous pages result in the cell description shown in the computer printout, Figure 4-5. The computer program that generated Figure 4-5 is used by a major mobile system supplier as an aid in design of IMTS and similar systems.

For comparison with Systems C and D, the following analysis has been prepared on per site basis for population densities of 20 persons/sq. mile, resulting in a predicted customer monthly charge for service, not including rental or purchase of the mobile radio. It should be noted athat the same comments regarding the physical and economic practicability of implementing a nationwide System apply also to System B. The per site analysis is shown on the basis of implementing only *selected* sites where practical (estimated to be where population density is 20 persons/sq. mi. or more)

Characteristics and Assumptions:

- Cellular-compatible mobile
- 6 mile average radius
- 20 persons per square mile (minimum capacity installation)
- 1% of population are subscribers
- 22 subscribers/cell
- blocking rate 20%

(2% blocking rate for System "A," 20% for "B," "C," "D" to reduce number of channels and cost)

EQUIPMENT/SYSTEM COST FOR NATIONWIDE CELLULAR-COMPATIBLE MOBILE TELEPHONE SYSTEM (SYSTEM B)

Site(s)	Radio Equip.	Switch/ Cell Site Control Equip	Ant System	Towers	Batt. Chgr Inv,	Install and System Test	System Eng/ Project Mgmt	Facility Prep	Telco Install.	Total Costs
MTSO	–		–	–					–	
Each Cell (3 ch)	75K	40K	10K	15K	25K	32K	60K	25K	–	282K
Total Nation 40000 sites	3.00B	1.6B	400M	600M	1.	1.28B	2.4B	1.00B	–	11.28B
Maintenance at 16% of equipment										.896B

COST OF EQUIPMENT WITH MAINTENANCE, UBIQUITOUS SYSTEM (B)

Total Equipment Cost	$11 28 Billion
Based on 10-year Amortization	$ 1.128 B/year
Maintenance	$ .896B/year
Total	$ 2.024 B/year
Total Potential Users	744,000
Equipment and Maintenance Cost/User	$2,720/year $ 227/mo

I. Implementation Costs (Non-Recurring) for Minimum Capacity (3 channel) Cell

1) Equipment Costs

– Radio Tx/Rx (3 channels with redundancy)	$ 75K
– Cell Site control (like IMTS)	40K
– Antenna System	10K
– Tower (including installation)	15K
– Battery/Charger	25K
– Test and Diagnostics Equipment	10K
Equipment Subtotal	$175K
2) Installation/System Test/Site Management	$ 32K
3) System Engineering/Project Management	60K
4) Facilities Preparation	25K
TOTAL IMPLEMENTATION	$292K

II. Recurring Annual Costs

1) Leased Land Costs	$ 12K
2) TELCO Costs	12K
3) Maintenance Costs	24K
4) Administration Costs at 227/subscriber	5K
TOTAL RECURRING COST	53K

III. Capital Cost – 5 year Payback 105.1K

Year	Balance	Capital Payback	Interest at 12%
1	292 K	58.4K	35.04
2	233.6K	58.4K	28.03
3	175.2K	58.4K	21.02K
4	116.8K	58.4K	14.02K
5	58.4K	58.4K	7.0K
		TOTAL	105.1K
	Annual Cost of Capital		21.0K

IV. System Cost per Subscriber

Assumes 5 years to recover implementation cost of $29K i.e., ≈58,400/year.

1. Total non-recurring	$58,400/year
2. Total recurring	$53,000/year
3. Capital Cost	$21,000/year
	$132,400/year (cost only)

4. System B Cost per Subscriber:

$132,400/22 = $6018/year = $502/month

(No profit, no nationwide architecture)

V. Breakdown of TELCO Costs — 20 miles average distance to Central Office

3 Direct Inward Dialing Lines $70/line/month	$ 210
+ $4/mile/line/month	240
4 Direct Outward Dialing Lines $60/line/month	240
+ $4/mile/line/month	320
	$1010/mo.

Total = $12K per year

VI. Breakdown of Implementation Manpower Costs

(a) Based on 9-month project
(b) 3-month installation and check-out

1. System Eng'g/Project Mgmt.

   3 man months project management
   3 man months system engineering
   — propagation
   — outside plant
   equipment configuration
   6 man months at $10,000/month = $60K

2. Installation/System Test/Site Management
   Based on 3 month period

   2 man month site management
   1 man months installation
   1 man month system test
   1 man month system test
   4 man months at $8,000/month = $32K

4.3.4 Analysis of System C

The analysis of System "B" shows that leasing a non-urban mobile telephone system on full cellular specifications results in an unacceptable subscriber rate even if a simplified system aproach is used, unless application is limited to relatively high population density areas. Since this limitation causes the system to fall far short of the original goal of $100/month subscriber charge for low population densities, the alternative of modifying system specifications was selected. These specifications are similar to those applying to SMR 800 MHz systems.

Characteristics and Assumptions

- Cellular-compatible mobile
- 15-mile range outbound to mobiles
- remote receivers inbound from mobiles
- 20 people per square mile
- 1% of population are subscribers

  141 subscribers/cell

I.	Implementation Costs (Non-recurring) System C	
	1) Equipment Costs	
	– Radio Transmitters and Receivers (7 channels with redundancy)	$ 90K
	– Remote Receivers – 6 at 10K each	60K
	– Cell Site Controller	40K
	– Antenna System	20K
	– Tower (including installation)	15K
	– Battery/Charger	25K
	– Test and Diagnostics Equipment	10K
	2) Installation/System Test/Site Mgmt	22K
	3) System eng./Project Mgmt	60K
	4) Facilities Prep	35K
	TOTAL IMPLEMENTATION	$377K
II.	Recurring Annual Costs	
	1) Leased Land Costs	10K
	2) TELCO Costs	64K
	3) Maintenance Costs at 16 percent of Equipment Cost	36K 36K
	4) Administration Costs at $200/subscriber	28K
	TOTAL RECURRING	$138K
III.	Cost of Capital	$136K 5 yrs = 27K/year

IV. Cost/Subscriber – System C

Assumes 5 years to recover implementation cost of $377K i.e., $75,400/year.

1. Total non-recurring	$ 75,000/year
2. Total recurring	$138,000/year
3. Capital Cost	$ 27,000/year
TOTAL	$240,000/year

4. Cost per subscriber:
$\frac{\$240,000}{141}$ = 1700/year = $142/month

· (No profit, no national architecture)

IV. Breakdown of TELCO Costs

Remote Receivers to Cell Site Center

– 6 lines to each	
– Av. 10-mile length	
– $65/line/month =	$2340
– $4/mile/line/month =	$1440
	$3780/month

V. Cell Site Center – 20 miles to Central Office

DID's = 5	
– $70/line/month	350
– $ 4/mile/line/month	400
DOD's = 6	
– $60/line/month	360
– $ 4/mile/line/month	480
	$1590/month

Total = $5370/month = $64K/year

Note that the subscriber monthly charge is approaching the goal of $100. At $142.00, however, the cost is still too high. It is apparent that the remote receiver system that allows a 4-watt vehicle radio or a 2-watt hand-held talk back over the 20-mile outbound range of this system is too costly at low population densities.

4.3.5 Analysis of System "D"

System D eliminates the remote receiver system (and, therefore, hand-held telephone coverage), and adds a switchable 35 watt r.f. power amplifier to the output of the mobile radio. The cell description is the same as for System "C."

Characteristics and Assumptions:

- High power mobile
- 15 mile radius
- 20 people per square mile
- 1% penetration
- 141 subscribers/cell

I.	Implementation Costs (Non-Recurring)	
	1) Equipment Costs	
	– Radio Transmitter-Receiver (7 channels with redundancy)	$ 90K
	– Cell Site Controller	40K
	– Antenna System	20K
	– Tower (including installation)	15K
	– Battery/Charger	25K
	– Test and Diagnostics Equipment	10K
	Equipment Sub-Total	$200K
	2) Installation/System Test/Site Management	$ 22K
	3) System Eng./Project Management	60K
	4) Facilities Prep	25K
	Total Implementation	$307K
II.	Recurring Annual Costs	
	1) Leased Land Costs	$ 12K
	2) TELCO Costs	28K
	3) Maintenance Costs	28K
	4) Administration Costs at $299/subscriber	28K
	TOTAL	$ 96K
III.	Capital Costs at 12%	$111K

IV.	Cost/Subscriber – System D	
	Assumes 5 years to recover implementation cost of $307K; i.e., $61,499/year.	
	1. Total Non-recurring	$61,400/year
	2. Total Recurring	$96,000/year
	3. Cost of Capital	$22,100/year
		180K/year
	4. Cost per subscriber System D	
	$\frac{\$180{,}000}{141}$ = $1273/year – $106/month plus cost of mobile power amplifier at $10/month	
IV.	TELCO Costs (20 miles to TELCO Switch)	
	5 Direct Inward Dialing Lines	
	$70 line/month	$350
	+ $4 mile/line/month	400
		$750/month
	6 Direct Outward Dialing Lines	
	$60/line/month	$360
	+ $4/mile/line/month	480
		$1590/month
	Total = $2540/month, $28K/year	

Note that the subscriber monthly charge is approaching the target of $100/month, but no profit or nationwide architecture is included, and no service is offered to population densities under 20 persons/sq. mile.

4.3.6 Adaptations of System "D"

All of the preceding analyses are based on mobile telephone service to population densities of 20 people per square mile (minimum) and a user penetration rate of 1% of the population. The market analysis of Volume I shows a radio telephone user base of 745,000 for unmet needs in three categories. Another analysis, based on the assumptions in Table 4-4, has been prepared using this user base with the site costs of simplified Systems B and D. The resulting average users per site are shown. Since the 745,000 user base used in Table 4-4 encompasses mobile telephone service, new services (except for high-rate oil and gas data), and public service, each of the sites will be somewhat more complex than the mobile telephone-only sites used in the Systems B, C, and D analyses. Additional radio channels and telephone lines for direct inward and outward dialing may be required to separate the services, since some may use an "unfair" share of channel time during certain use periods. Note that no interconnecting land-line/microwave system has been incorporated in the System D design, and the system is, therefore, of local rather than nationwide architecture.

One additional test was given to System D. This analysis is shown in Table 4-4. Note that the table and the following analysis of System D with a population density of 100 people per sq. mile lead to an important conclusion: Although on a nationwide basis with 745,000 users the cost is shown to be approximately $100/month, this is an *average* cost. The correct conclusion, therefore, is that normal market drives will provide service only to non-urban population in a density somewhere between 20 and 100 people per sq. mile, and that densities below this figure will not be served, regardless of the "average" user charge shown in Table 4-4. This conclusion is borne out by the present IMTS service provided by Bell and en-

Table 3.4-4

SYSTEM B/SYSTEM D PARAMETERS BASED ON COMPLETE U.S. NON-URBAN COVERAGE

Cell Spacing	# Sites	Cost Per Site (Year)	Total Site Cost	User Base	Users Per Site	User Cost (Year)	User Cost (Month)
12 Miles	100 × 208 = 20,800	$132,400	$2,753,920,000	745,000	35	$3,696	$308
30 Miles	40 × 84 = 3360	$180,000	$ 604,800,000	745,000	223	$811	$67 plus

Mobile power amplifier cost of $10/mo. No profit, no nationwide architecture. Mobile telephone service only.

trepreneurs. In order to determine the population density at which the lowest cost system (System D) comes within the subscriber base charge goal of $100/mo., a system was designed for a density of 100 people per square mile. The cell description is as shown in Figure 4-7.

The business analysis for this cell follows.

SYSTEM D-2

High-Power Mobile
- 15 mile radius
- 1 % penetration
- 100 people per square mile
- 584 subscribers

I.	Non-Recurring Cost	
	1. Equipment Costs	
	– Radio Transmitter-Receiver (18 ch)	$83K
	– Cell Site Controller	52K
	– Antenna System	30K
	– Tower (including installation)	15K
	– Battery/Charger System	25K
	– Test and Diagnostics Equipment	15K
	Subtotal	220K
	2. Install/System Test/Site Management	23K
	3. System Eng'g/Proj. Management	70K
	4. Facilities Preparation	30K
	Subtotal	$123K
	Non-recurring Total	$323K
II.	Recurring Cost – Annual	
	1. Leased Land	12K
	2. TELCO	42K
	3. Maintenance Costs at 10 of Equipment	14K
	4. Administration Cost at $100/subscriber	50K
	Total Recurring	$118K
III.	Capital Cost at $12% interest	23K/year
IV.	Cost/Subscriber	
	Assumes 5 years to recover implementation	
	$705K – $141,000/year	
	1. Total non-recurring (annual)	65K
	2. Total recurring (annual)	118K
	3. Capital cost (Annual)	23K
	Total Cost	206K/year

Cost per Subscriber
206K/584 – 353/yr – $30/mo*

NOTE:	These are basic costs, without the following:	
	Profit	$ 6/mo
	High Power Mobile Power Amplifier	$10/mo
	Nationwide architecture –	

Cellular mobile –

System D Base Service Charges per Subscriber	$46 (with 20% profit but without equipment charges for standard mobile cellular radio)

TELCO Cost

12 Direct Inward Dialing Lines	
$70/line/month	$840
+ $4/line/month/mile (20 miles to TELCO switch)	960
	1700
18 Direct Outward Dialing Lines	
$69/line/month	1080
+$4/line/mile/month (20 miles to TELCO switch)	1440
TOTAL TELCO	$4320/mo

Capital Cost – 5 Year Payback

Year	Balance	Cap. Payback	Int. at 12%
1	$323K	$64.6K	$39K
2	258K	64.6K	31K
3	194K	64.6K	23K
4	129K	64.6K	15K
5	64.6K	64.6K	8K
			116K
			$23K/year

****

1. THE CUSTOMER BASE IS 1 % OF THE SERVED AREA POPULATION.
2. THE GRADE OF SERVICE IS P 20 (20 % BLOCKED CALLS).
3. THE CELLS ARE 15 MILES IN RADIUS.
4. THE MOBILE-TO-LAND ORIGINATE RATIO IS 2 : 1.
5. THE CALL DURATION IS 120 SECONDS.
6. EACH SUBSCRIBER WILL MAKE .5 CALL(S) DURING THE BUSY HOUR.
7. THE DAY-TO-BUSY HOUR RATIO IS 10 : 1.
8. THE MAX NO. OF VOICE CHANNELS PER CELL IS 47
9. MOBILE-MOBILE CALLS ACCOUNT FOR 10 PERCENT OF TRAFFIC

****

POPULATION OF SERVED AREA IS 59400
AREA SERVED, IN SQUARE MILES, IS 594

****

THE AREA OF A 15 MILE CELL IS 594.57 SQUARE MILES AND
THE NO. OF CELLS IS 1 , DISTANCE BETWEEN IS 25.9808 MILES.
THE RADIUS TO EXACTLY MATCH COVERAGE AREA IS 14.9927

****

THE FOLLOWING IS A CELL BY CELL DESCRIPTION OF THE SYSTEM:

****

CELL NO.	CELL TYPE	DESIRED PROB	ACTUAL PROB	CELL DENSITY	NET MIGRA	VOICE CHAN	ERLANGS PER CEL	SUB PER
1	0	0.200	0.149	% 100	0.00	14	9.73	584

****

CELL NO.	CELL COORDINATES		SW CELL	TELCO CELL	CONN TYPE
1	0	0	1	1	0

****
* SYSTEM SUMMARY *
****

THE SYSTEM CONTAINS 1 SWITCH(ES), CONTROLLING 1 CELLS
15 MILES IN RADIUS, WITH A TOTAL OF 14 VOICE CHANNELS.

THE INTERCONNECT TO THE TELCO OFFICE WILL REQUIRE 10 DIDS
AND 15 DODS ASSUMING A 2 TO 1 MOBILE ORIGINATE RATIO
AT A .00% PROBABILITY OF BLOCKING IN THE TRUNK LINES
AND AN AVERAGE CALL DURATION OF 120 SECONDS.

THE TOTAL MILEAGE IN FOUR-WIRE LINES CONNECTED TO THE TELCO
WITHIN THE SWITCHING CELL IS 0 AND THE TOTAL MILAGE
FROM THE SWITCHING CELL TO OTHER CELLS CONTAINING TELCOS
IS 0 MILES.

THERE ARE 584 SUBSCRIBERS IN THE SYSTEM GENERATING 292
CALLS DURING THE BUSY HOUR (FOR A TOTAL OF 9.73333 ERLANGS
OF TRAFFIC.)

****

Figure 4-6. System D description. Population density 100 persons/mi.^{2}.

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Section 5

ALTERNATIVE COST ANALYSIS OF FOUR SYSTEM CONCEPTS

The previous sections have described the operational features of terrestrial systems and associated costs. A business analysis was presented which is typical for this industry, particularly the smaller radio common carriers, which is based on rapid write off of the invested capital. The motives for this business strategy relate to other ancillary investments and overall tax strategies which are too numerous and complicated to relate here. Alternatively, a business strategy is considered that is similar to that described for the space system and gateways, based on investment, return on investment, and taxes over the system life, which is assumed to be an *average* of 10 years, with zero salvage at the end.

Table 5-1 summarizes the appropriate system financial characteristics, described in previous sections, and Table 5-2 summarizes the monthly subscriber charges for rates of return of 20% and 40%, with 46% tax rate using the methodology described in Section 4.4.1.

Table 5-3 converts these charges to call minute charges assuming all subscribers are either radio, telephone, or dispatch subscribers with calling rates of .03 and .01 erlangs peak, in the busy hour.

Since it cannot automatically be assumed that the subscriber is communicating with his home base, e.g., that the base station is located at the local exchange serving his home or business, additional dial up telephone charges are appropriate. Such charges are likely for most subscriber calls. These are listed in Table 5-4 for call minute charges and for a monthly charge based on call rates of .03 and .01 erlang during the busy hour for radio telephone and dispatch subscribers respectively.

Considering both equipment costs and incidental telephone charges, the subscriber charges are substantial, this grade of service is poor and the system relatively inflexible. The latter results from the relatively low number of subscribers per site, which means that the system can not respond to seasonal or local peak demands without a considerable added expense in extra equipment. For example seasonal traffic variations due to proximity, to resorts and other recreational facilities, seasonal agricultural activities, or peak local traffic perturbation caused by storms, accidents, etc.

Table 5-1

TERRESTRIAL SYSTEM CHARACTERISTICS

	System Description	Investment	O&M Per Year	Subscribers
A	95% CONUS Coverage, 40098 sites (24 call cluster) or 1670 regional systems. Cellular-compatible, 6 mile coverage radar, grade of service = .02	$15740M Total or $9.425M per region	$1670M Total or $1M/region	744.000
B	Similar to IMTS (no handover) 6 mile coverage radar, grade of service = 0.2	292k/site	$53k/site	22/site
C	Same as B except 15 mile radius grade of service = 0.2 remote "satellite" receivers extend grade of service = 0.2	$377k/site	$138k/site	141/site
D	Same as C except mobile 35 watt PA and no "satellite" receiver grade of service = 0.2	$307k/site	$96k/site	141/site

Table 5-2

MONTHLY SUBSCRIBER COSTS
COST, DOLLAR PER MONTH PER SUBSCRIBER

System	i = 0.2	i = 0.4
A	815	1389
B	596	956
C	155	227
D	121	181

Table 5-3

CALL-MINUTE CHARGES FOR THE FOUR SYSTEMS
Call Minute Charges, Cents Per Minute

System	i = 0.2		i = 0.4	
	Radio Telephone	Radio Dispatch	Telephone	Dispatch
A	124	372	212	635
B	91	272	146	437
C	24	71	34	103
D	18	55	28	83

Table 5-4

TYPICAL CALL MINUTE CHARGES
FOR TELCO, BAND 2

	Typical TELCO Charge	
	Call-Minute	Month
Radio Telephone	$.60/min	$394
Dispatch	$.60/min	$1321

Appendix A

PROPAGATION OF TERRESTRIAL MOBILE RADIO SIGNALS

Terrestrial mobile radio systems designs are dominated by the propagation characteristics of signals in the mobile radio bands. Volume II discusses the propagation characteristics in detail as they affect the range, coverage, performance and costs of terrestrial systems. The characteristics are summarized here as a basis for comparing terrestrial and satellite signalling characteristics.

Radio waves at frequencies higher than approximately 30 MHz are not reflected or refracted by the ionosphere as much as signals at lower frequencies. Frequencies below 30 MHz are used for long distance communication by reflection from the ionosphere. Above that frequency they are generally limited to "line of sight" ranges. There are exceptions. High power transmitters and high gain, directive antennas are used for tropospheric propagation over hundreds of miles. Signals are scattered over the horizon by cells of varying refractive index caused by turbulence in the atmosphere. Frequencies in the range of 1 GHz are used for tropospheric scatter propagation. Ducting, caused by temperature inversions in the atmosphere, can be used to propagate VHF (30 - 300 MHz) and UHF (300 - 3000 MHz)signals over distances exceeding a thousand miles under unusual conditions. Reflections from meteor trails and auroras can also be used to popagate VHF and UHF signals far beyond horizon distances. Occasional reflections from the ionosphere cause VHF signals to "skip" hundreds or thousands of miles.

The usual propagation range for VHF and UHF signals over smooth terrain is 4/3 the line-of-sight distance between the transmitter and receiver. The range is greater than the geometrical range because refraction in the lower atmosphere bends the signal paths beyond the horizon. A convenient rule of thumb to calculate the range is:

$$R = (2H)^{1/2}$$

Where R = range in miles, H = tower height in feet.
Figure 2-11, Section 2.0, plots the actual range as a function of tower height, but the rule-of-thumb is quite accurate.

The line-of-sight range limitation is used to advantage in local mobile communications systems. A channel can be used simultaneously in many communities. It is the usual practice of the FCC to license a channel for reuse in communities separated by 70 miles or more.

The line-of-sight range limitation above approximately 30 MHz is a severe disadvantage for mobile applications that require long range communications. No satisfactory long distance radio propagation means are available using terrestrial radio installations. Use of the 2 - 30 MHz band for mobile use by ionospheric reflection is cumbersome and unreliable. Channel capacity is extremely limited in that band, and its use for commercial mobile applications is negligible.

The line-of-sight range limitation is at once an advantage for local systems and a disadvantage for long distance systems. Impairments in terrestrial signal propagation are:

- Path blockage by structures, terrain, or foliage.
- Rayleigh fading.
- Co-channel interference.
- Adjacent channel interference.

When the direct path between a base and a mobile is blocked, the direct signal may be completely cut off. Diffraction around the edges of the blocking object reduces the sharpness of its shadow and can provide a useful signal in a portion of the area behind the object. Diffraction is a function of wavelength. It is more effective in filling in the shadowed area at lower frequencies than at higher frequencies. Reflections by other objects in the region also help to fill in shadowed areas. Communications coverage in urban areas and in hilly terrain is improved by using much higher transmitter power than is needed to overcome the inverse square spreading loss of the radio signals. The higher power improves the strength of the signals that are diffracted and reflected into the shadowed areas. The improvement is very much greater in the 150 MHz mobile band than it is in the 800-900 MHz band.

Reflections are always present in terrestrial mobile communications. Reflected signals combine at the receiving antenna with the direct signal. They differ in phase, may be as large, or sometimes larger in amplitude than the direct signal. The phasor sum of the "multipath" signals can have any amplitude from zero to larger than the direct signal. Motion of the vehicle or of reflecting objects cause the amplitude of the received signal to change rapidly with time. The fading pattern has a Rayleigh-like distribution. Fading amplitudes of 30 dB are typical. In terrestrial systems the ground is an important reflector that cannot be avoided because of the low elevation angle from mobile to base antenna.

Co-channel interference results when signals from another source are present in the channel that a mobile is using. Urban cellular systems in the 806-890 MHz band are co-channel limited. Signals on the same channel from other cell sites in the same city are the limiting background in the mobile receiver, not the receiver's own input noise. As the desired signal experiences deep Rayleigh fading, the co-channel interference is heard during the brief, rapid fades. The avoidance of co-channel interference imposes limits on power and antenna siting for cellular compatible systems in smaller communities separated from urban centers.

Co-channel interference occurs in mobile systems in all bands. The ionospheric, ducting, and troposcatter propagation effects can cause interference, most frequently in the 30 and 150 MHz bands. Siting of antennas on mountain tops and the use of high power transmitters can cause interference to mobile systems hundreds of miles from the source of the interference. Careful frequency coordination is necessary to avoid the interference.

Adjacent channel interference occurs when a nearby transmitter on an adjacent channel is transmitting while a receiver is listening to a more distant transmitter. The strong nearby signal, after attenuation in the receiver's filters, is still comparable in strength to the desired signal. A related difficulty is receiver desensitization by a strong nearby transmitter on any channel within the band in use. One reason for central power control of each mobile in a cellular system is to avoid having a cell site receiver desensitized by a mobile that is transmitting very close to the cell site receiver. Desensitizing the receiver would cause all of the signals that it is receiving to be reduced in amplitude.

Appendix B

EXPERIMENTAL CONFIRMATION OF TERRESTRIAL SIGNALLING RANGE CALCULATIONS

The results achieved in wide-area terrestrial mobile radio systems confirm the calculated ranges and the numbers of installations that are required for terrestrial cellular compatible systems and for dispatch systems operating in the 800-900 MHz band. One system of interest is the province-wide mobile radio telephone system of Alberta Government Telephone (AGT).

Uppal and Edwards[1] describe measurements made to determine the comparative ranges achievable in the frequency bands 150, 410, and 850 MHz for the purpose of estimating the feasibility of increasing the capacity of the existing 150 MHz Alberta AGT system by adding channels in the two higher frequency bands. Their results could be used to estimate the numbers of terrestrial installations that would have to be added because the ranges are shorter at the higher frequencies.

The province of Alberta has an area of 660,902 km^2. The AGT mobile radio telephone system serves three quarters of the area of the province, or 495,677 km^2, with 115 installations. On that basis we determine that the average service area of an installation is 4310 km^2. Average range is thus about 37 km or 23 miles. The service areas and ranges are achieved with an average antenna height of 52 m (170 ft) and an effective radiated power of 43 watts.

The authors describe the test measurements they made along roads through wooded areas. Receivers in a test vehicle measured the strengths of signals at the three frequncies as the vehicle moved, averaging the signal strengths over distance increments of 135 m (411 ft). They report: "The dB differences between the three bands from the 1981 tests...at 30 km [range] are as follows:

4 dB between 150 and 410 MHz at 30 km.
15.5 dB between 410 and 850 MHz at 30 km.
19.5 dB between 150 and 850 MHz at 30 km.

In order to use the 410 MHz band for the new automatic mobile telephone system, a combination of increased antenna height and base station ERP would be necessary to compensate for the 4 dB difference between the two bands. The maximum usable ERP, however, may be limited by the mobile transmit path toward the base station when considering reciprocal coverage, since it is hard to obtain mobiles with as high a transmitter output power as is available in base stations.

From the above dB difference comparison at 30 km, it can be seen that a total compensation of 19.5 dB would be required in order to go from the 150 MHz band to the 850 MHz band. This may be very difficult to do in practice.

This means that a lot of additional sites will have to be developed to provide coverage comparable to the existing 150 MHz mobile system."

Since 115 installations are required in the AGT 150 MHz system to serve 495,667 km^2, (191,377 mi^2), it is evident that 1764 similar installations would be needed to serve an area the size of the contiguous states if the terrain were like that of Alberta. A very much larger number of installations would be needed at 850 MHz because of the 19.5 dB greater propaga-

[1] Uppal, R. and Edwards, G. "Comparison of Signal Coverage for Mobile Radio Systems in the 150, 410 and 850 MHz Bands," *Proceedings of the 32nd IEEE Vehicular Technology Conference,* May, 1982.

tion loss and the lower power of the mobile transmitters. The nearly 100 times greater propagation loss at 30 km range indicates that the number of installations would have to be increased by a factor between one and two orders of magnitude, thus adding credence to the estimate that 40,000 installations would be required for the contiguous states.

1. Report No. CR-168063	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MOBILE RADIO ALTERNATIVE SYSTEMS STUDY TERRESTRIAL SYSTEM CONCEPTS		5. Report Date June 1983
		6. Performing Organization Code
7. Author(s) Norman Cromwell, Howard L. Lester, Roy E. Anderson		8. Performing Organization Report No. 83SRD038
9. Performing Organization Name and Address General Electric Company Corporate Research and Development Schenectady, New York		10. Work Unit No.
		11. Contract or Grant No. NAS3-23244
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address NASA-Lewis Research Center Cleveland, Ohio		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Volume I of the Mobile Radio Alternatives Systems Study describes the markets for mobile radio services in non-urban areas of the United States in the years from 1985 to 2000. This volume of the study report examines terrestrial mobile radio systems for satisfying the markets.

Results of the terrestrial systems study are presented as follows:

- Present day mobile communication technologies, systems and equipment are described fro background in evaluating the concepts generated in the study.
- Average propagation ranges are calculated for terrestrial installations in each of seven physiographic areas of the contiguous states to determine the number of installations that would be required for nationwide coverage.
- Four system concepts are defined and analyzed to determine how well terrestrial systems can fulfill the requirements at acceptable costs.

Nationwide dispatch, telephone and data services would require terrestrial installations in many locations where they would be used infrequently and would not recover their investment. Access to a roaming vehicle requires that the vehicle location be known within the range limit of the terrestrial installation in which the vehicle is present at the time of the call. Access to that installation must be made through the public switched telephone network, usually inviolving a long-distance toll charge, and requiring costly means to track or locate the vehicle as it moved through the network of installations.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Mobile radio communications, Non-urban mobile radio systems concepts, Non-urban mobile radio technology	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
none			

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)