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COMMUNICATION SYSTEMS FOR DUAL MODE TRANSPORTATION

R.E. Eaves
R.D. Kodis

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FINAL REPORT

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16. Abstract

The communications requirements of dual mode transportation systems are discussed for both the on-guideway and off-guideway modes. Candidate communication systems are classified according to their principle of operation, and the characteristics of the systems are described. The suitability of these systems is assessed on the basis of dual mode requirements, FCC restrictions, and physical and electrical limitations.

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PREFACE

The Urban Mass Transportation Administration is presently engaged in a program to develop and demonstrate transportation systems based on vehicles which are capable of automatic operation on special guideways and manual operation on conventional roads. Such a dual mode concept offers great potential for meeting the transportation needs of metropolitan areas, but adequate and reliable communications to and from vehicles are essential for its success. The following report treats this important aspect of dual mode transportation. The aim in writing it has not been to give quickly outdated details of conventional technology, but to provide a perspective consistent with the breadth of the dual mode concept.

Most of the waveguide techniques for waveguide-vehicle communications described in this report were developed with the support of the Advanced Systems Division of the Federal Railroad Administration.

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TABLE OF CONTENTS

Section Page

1. COMMUNICATION SYSTEMS FOR DUAL MODE TRANSPORTATION... 1

1.1 Dual Mode Concept.... 1
1.2 On-Guideway Communications.... 1

1.2.1 Command and Control.... 1
1.2.2 Emergency Voice Communication.... 2
1.2.3 Service Vehicle Voice Communication.... 2
1.2.4 Remote Fault Monitoring.... 2

1.3 Off-Guideway Communications.... 2

1.3.1 Communication with Vehicle Operator.... 2
1.3.2 Digital Data Link.... 2

1.4 FCC Regulations.... 3

2. CANDIDATE COMMUNICATION SYSTEMS.... 5

2.1 Communication Through Electromagnetic Fields... 5

2.1.1 Radiating Electromagnetic Fields.... 5

2.1.1.1 Localized Radiation Sources.... 5
2.1.1.2 Line Radiation Sources.... 9

2.1.2 Communication Through Nonradiating Fields.... 13

2.1.2.1 Inductive Fields.... 13
2.1.2.2 Surface-Wave Fields.... 22

2.2 Closed-Circuit Communication Through Mechanical Contact.... 26

3. CONCLUSIONS.... 29

3.1 On-Guideway Communications.... 29
3.2 Off-Guideway Communications.... 32

REFERENCES.... 35

APPENDIX.... 39

LIST OF ILLUSTRATIONS

Figure		Page
1.	Classification of Communication Systems for Ground Transportation	6
2.	Propagation from a Single Cell	7
3.	Frequency Re-Use Plan for Small-Zone System	8
4.	Leaky Coaxial Line Similar to That Developed by Sumitomo with Dimensions Typical of 400-500 MHz Region	10
5.	Leaky Circular Waveguide Similar to That Developed by Sumitomo with Dimensions Shown	12
6.	Parallel Wire Inductive System	14
7.	Pairs of Inductive Wires	16
8.	Quadruplets of Inductive Wires	18
9.	Cross Section of Sumitomo Helical Inductive Cable	19
10.	Multiple Antenna Arrangement for Inductive Lines	20
11.	Coaxially Shielded Transmission Line	21
12.	Sumitomo Alternating and Shielded Transmission Line	21
13.	Cross Section of Transmission Line Investigated by Wheeler Laboratories	22
14.	Cross Section of Goubau Line with Typical Dimensions	24
15.	Cross Section of Dielectric Line Investigated by General Applied Science Laboratories	24
16.	Cross Section of Dielectric Line Investigated by Honeywell	25
17.	Cross Section of Dielectric Line Investigated by TSC	25
18.	Hierarchical Control of the On-Guideway Communication System	31

1. COMMUNICATION SYSTEMS FOR DUAL MODE TRANSPORTATION

1.1 DUAL MODE CONCEPT

Dual mode transit seeks to incorporate the best features of scheduled and demand-responsive bus systems with those of automated transit. The two primary modes of such a system are an operator-controlled mode on surface streets and an automatic mode on guideways. A dual mode system offers the high arterial capacity attainable only with automatic control and the passenger convenience of bus pickup. Both are achieved without the need for passengers to change vehicles.

To realize the full potential of such a transportation system, reliable communications are needed for both the on-guideway and off-guideway modes. Since the dual mode concept as considered by the Department of Transportation (DOT)[1] is not a specific system but a broad category of systems, it follows that the communications requirements must be stated rather broadly.

1.2 ON-GUIDEWAY COMMUNICATIONS

1.2.1 Command and Control

High capacity, short headway operation requires highly reliable automatic command and control. This is clearly the most important function which the communication system supports. Furthermore, it is a time-critical function in that its communications link must be immediately available at all times.

The data rate required for command and control depends upon mechanical aspects of the vehicle and dynamical aspects of its motion.[2] It also depends upon the degree to which detection and computation functions are performed on board the vehicle, rather than at the wayside. Typically, data rates range from several hundred to several thousand bits per second.

1.2.2 Emergency Voice Communication

Although on-guideway voice communication is not used ordinarily, it is important that emergency voice communication be provided for passengers. In the event that the vehicle becomes disabled, such communications can be used to give directions and assurance to anxious passengers. It also provides a means for passengers to report problems (e.g., injury, fire), and can thereby act as a deterrent to crime on the vehicle.

1.2.3 Service Vehicle Voice Communication

It is desirable to provide voice communication with operators of service vehicles, such as those for removing snow or towing disabled vehicles. If the portion of the guideway being serviced is not being used by a passenger vehicle, the passenger emergency voice channel can be used for this purpose.

1.2.4 Remote Fault Monitoring

A desirable safety feature is the continuous monitoring for vehicle faults from a remote central location.

1.3 OFF-GUIDEWAY COMMUNICATIONS

1.3.1 Communication with Vehicle Operator

Coordination of vehicles entering and departing from the guideway area will require a voice communication link to the operator. In the case of dial-a-ride service, a voice link must be provided throughout the off-guideway vehicle range.

1.3.2 Digital Data Link

It is anticipated that some functions can be partially or fully automated through a digital data link. For example, such a system would permit a vehicle operator to enter data at his convenience, so that it would be automatically transmitted when a radio channel became available. It could also hold incoming data until the vehicle operator is free to accept it.

1.4 FCC REGULATIONS

The Federal Communications Commission (FCC) regulations relevant to the communication systems which will be discussed are given in Reference 3. Contact with the FCC[4] has clarified the interpretation of these regulations, and a summary is given below.

Communication devices which operate through radiated fields require licensing regardless of the field strengths employed, with the exception of those occupying several low power communication bands (10-490 kHz, 510-1600 kHz, 26.97-27.27 MHz). Systems operating in these public bands are vulnerable to interference from general use and, consequently, are too unreliable for dual mode communications. Therefore, it is assumed that any radiating system employed will not be operating in these public bands and will require licensing.

Communication devices which employ conduction or guided wave fields, rather than radiated fields, do not necessarily require licensing, even though some radiation may incidentally occur. The principal restriction which must be satisfied to avoid the need for licensing is that the electric field should not exceed fifteen microvolts per meter at a distance of $\lambda/2\pi$ from the device.

There is serious doubt that this criterion is appropriate for modern technology. The specification of a field limit at a distance of $\lambda/2\pi$, or roughly one-sixth the wavelength, is not a proper measure of radiative interference at high frequencies. In the case of surface-wave devices, such as those which will be discussed in Section 2.1.2.2, the distance $\lambda/2\pi$ is only about 2cm. At this close distance the electric field is quite intense and in gross violation of the FCC restriction, even though the structure causes essentially no radiative interference whatsoever. It should also be pointed out that atmospheric noise alone exceeds the 15 μV electric field limit.

The FCC recognizes that regulations sometimes require modification and does consider requests for revision accompanied by justification. It is expected that this action will eventually be taken with regard to the regulation of nonradiating devices.

2. CANDIDATE COMMUNICATION SYSTEMS

In this section candidate communication systems for ground transportation will be presented by category (Figure 1), and each will be described in sufficient detail for them to be compared. Their suitability for dual mode use will be considered in Section 3. A classification of communications in some contemporary ground transportation systems is given in the Appendix.

2.1 COMMUNICATION THROUGH ELECTROMAGNETIC FIELDS

2.1.1 Radiating Electromagnetic Fields

The systems described in this section rely upon radiated electromagnetic fields for their operation. Therefore, all of them require licensing by the FCC.

2.1.1.1 Localized Radiation Sources - The category of localized radiation sources includes the common method of radio communication in which a central base station broadcasts to mobile units. Such operation requires licensing by the FCC, and past policy has been to make frequency assignments around 50 MHz and 450 MHz. However, the spectrum in these regions has become overcrowded, due in part to the practice of making bloc assignments of frequency. This has resulted in wasteful situations such as channels in New York City being reserved for forestry service. As an initial step to relieve spectrum crowding, the FCC is allocating a 115 MHz band in the 900 MHz region for mobile communications, and it is anticipated that assignments for dual mode vehicles will be made there. However, more far-reaching changes in frequency management will be required to provide adequately for future mobile communication needs.[5,6]

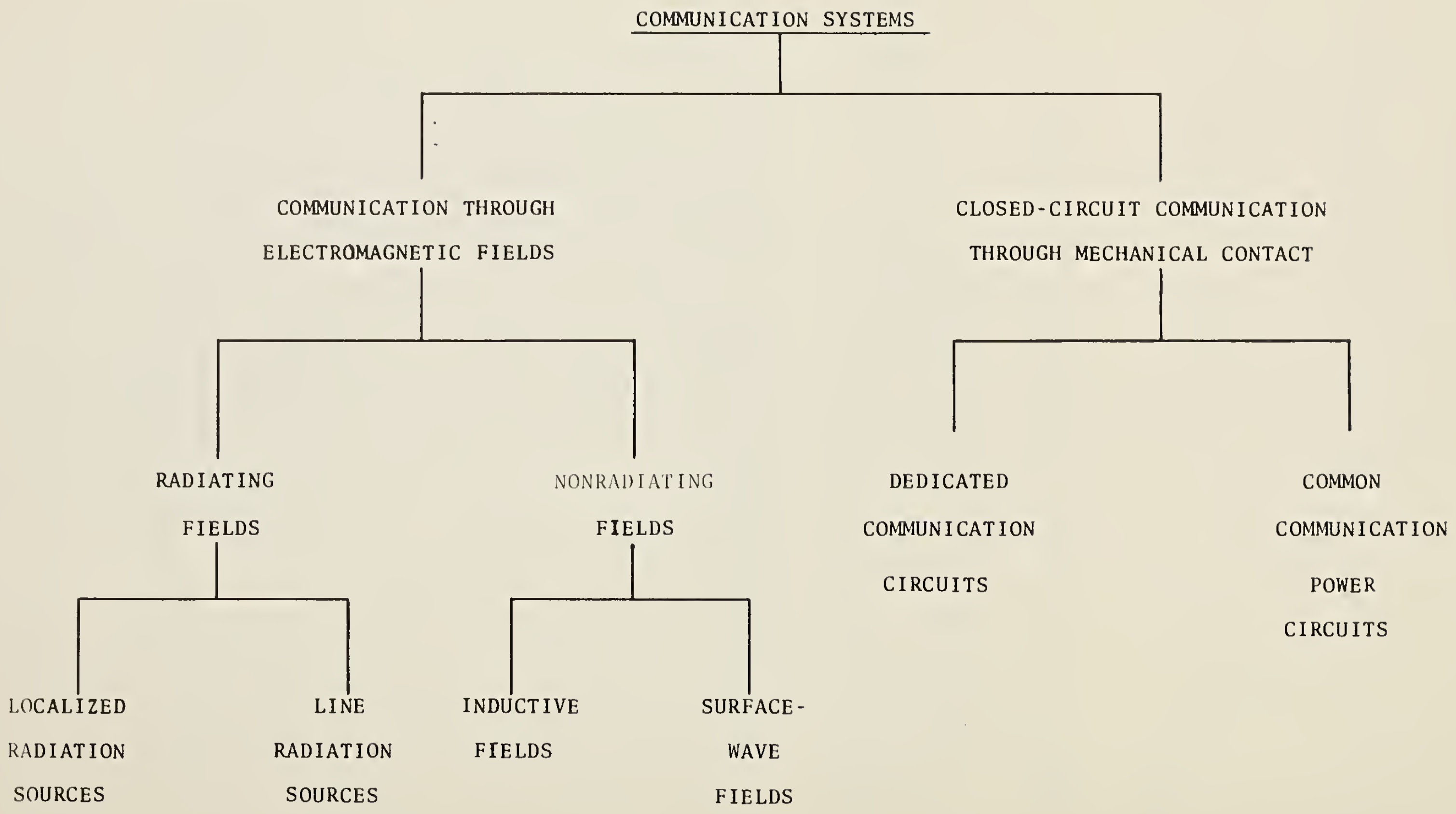


Figure 1. Classification of Communication Systems for Ground Transportation

The inefficiency of spectrum use is apparent from a consideration of current mobile communication systems. Since the dispatcher at the base station does not know the location of the mobile unit, an omni-directional signal must be broadcast with enough strength to cover all possible vehicle locations.

If the dispatcher knows the location of the vehicle, it would be necessary to broadcast only over a small region using an antenna near the vehicle. By dividing a region into small cells or zones, each with its own base station, the same frequency could be used simultaneously in different sections of a city. Each base station requires limited radiating power and is linked to a central processing unit through a microwave link or a land line, such as an existing cable TV line.(7)

In reusing a frequency in other cells, buffer zones must be allowed between zones of the same frequency to assure that interference is eliminated. If a two-ring buffer is needed (Figure 2), then the frequency of the central cell can not be repeated in any

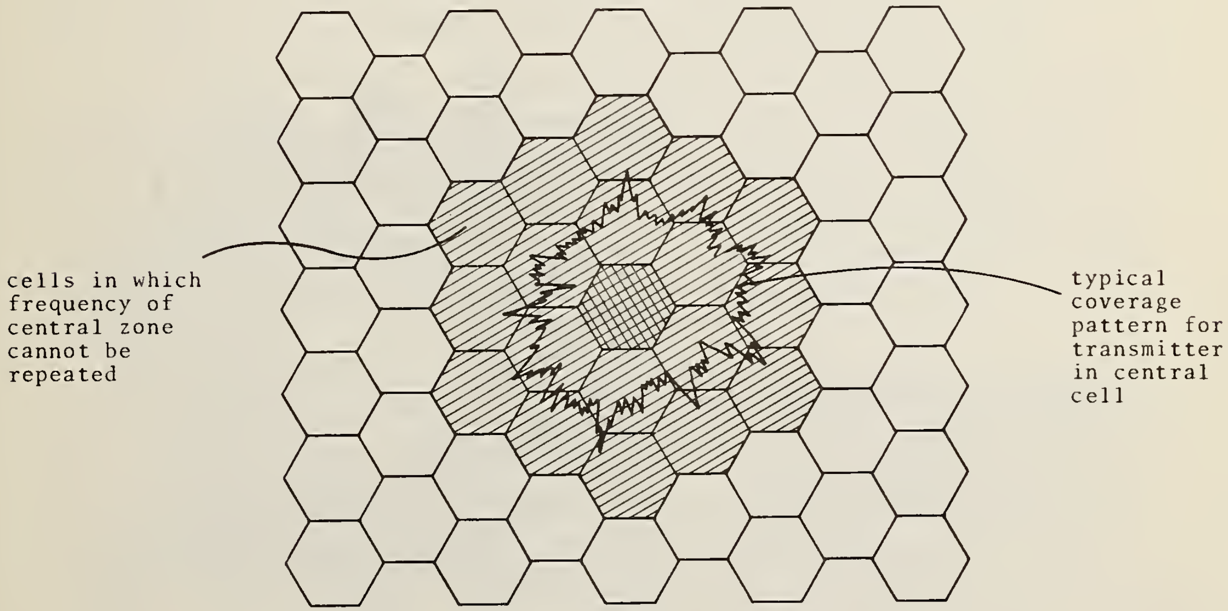


Figure 2. Propagation from a Single Cell

of the surrounding eighteen cells. It should be pointed out that a vehicle location subsystem must be provided in order for the small cell system to function. However, the vehicle position information gained thereby is valuable in itself for dispatch service. Another advantage of the small cell concept is that adjacent channel interference is reduced. This problem occurs when an adjacent frequency band is being broadcast from a base station much nearer than the one broadcasting the desired band, so that the adjacent channel is not adequately rejected. However, this does not occur in small cell systems since an adjacent channel signal comes from the same base station or the base station of an adjacent zone.

Perhaps the most obvious approach to assigning channels to zones is the fixed frequency method, in which each zone is assigned a fixed group of channels. Outside the buffer region groups may be reused, so that the required number of channel groups, m, will depend on the size of the buffer region. Figure 3 illustrates that m=7 in the case of 19-zone or 2-belt buffering. The total number

The number in a cell identifies its frequency group.

1. identifies frequency group 1
2. identifies frequency group 2
.
.
.
7. identifies frequency group 7

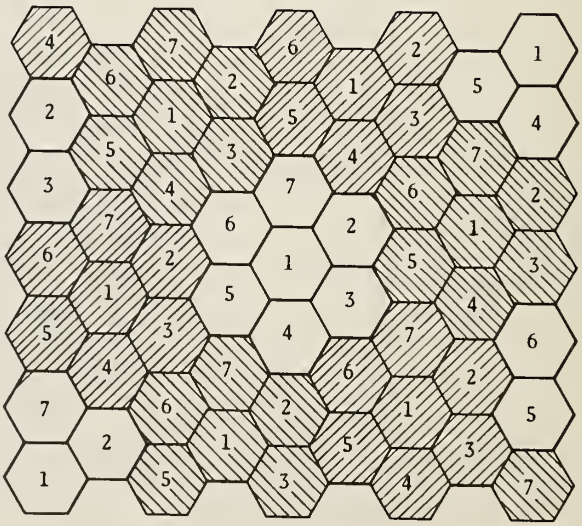


Figure 3. Frequency Re-Use Plan for Small-Zone System

of frequency allocations required in the system is mj. An advantage of the fixed-frequency approach is that each base station requires equipment only for j of the mj frequencies. However, the disadvantage is that each mobile unit requires equipment for at least m frequencies to assure the ability to communicate in all zones and if the need to reduce the waiting time for a channel requires k available channels in each zone, then each mobile unit must be equipped for mk frequencies.

A dynamic-frequency assignment approach permits the complexity of the mobile equipment to be reduced at the expense of increasing that of the stationary equipment. In such a scheme, each mobile unit requires equipment for only one frequency, while each base station can operate at all frequencies. The central station remembers the frequencies in use by mobile units and base stations and assigns channels on a dynamic basis. If it is desired that mobile units be equipped for more than one channel, the increased number of channels need not be in multiples, as in the fixed frequency approach. In dynamic frequency assignment, the reuse scheme indicated by Figure 3 still represents the densest possible frequency assignment at any moment, although the system will not always be in this configuration limit.

In this section, communication system design has been presented in terms of distinct choices: central coverage versus zonal coverage, fixed-frequency assignment versus dynamic-frequency assignment. In fact a continuous range of systems exists between these idealized choices and conversion from one to the other can be accomplished in evolutionary fashion.[8]

2.1.1.2 Line Radiation Sources - A localized omni-directional antenna is an inefficient technique if radio coverage is needed only along a narrow corridor, such as a road or a guideway. Localized directional antennas can be a reasonable solution if the guideway is relatively straight. But in general the most satisfactory coverage of a narrow corridor can be obtained through a leaky transmission line installed along the guideway and designed to radiate slightly throughout its length. Such a structure may be thought of as a combination transmission line and antenna, and provides essentially cylindrical coverage with the guideway as an axis. It requires licensing by the FCC as do conventional antennas. In tunnels or other confined regions, coverage through localized antennas may be virtually impossible. This application has simulated the development of leaky transmission lines and is the most important need they fill.

The most thoroughly investigated form of leaky transmission line consists of a standard coaxial line with slots or holes cut in the outer conductor[9-11] (Figure 4). It is desirable that such a line be designed so that[12,13]

$$|\beta + 2\pi m/p| > k_o \quad \text{for one value of integer } m, \text{ e.g., } m = -1 \qquad \text{(Eq. 1a)}$$

and

$$|\beta + 2\pi n/p| < k_o \quad \text{for all integer } n \neq m, \qquad \text{(Eq. 1b)}$$

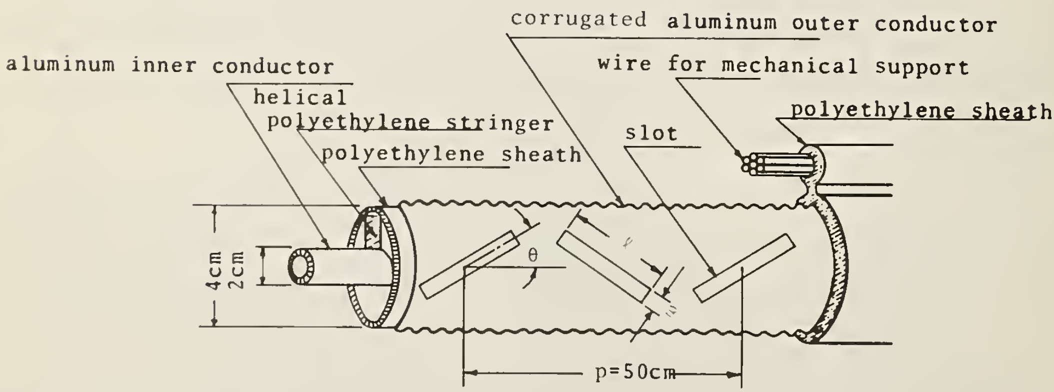


Figure 4. Leaky Coaxial Line Similar to That Developed by Sumitomo with Dimensions Typical of 400-500 MHz Region

where β is the transmission line propagation constant, k_o is the free space propagation constant, and p is the periodicity of the slot array. This assures that only one harmonic mode will satisfy the slow-wave condition (1a) required for radiation, avoiding the large fluctuations in coupling characteristics which can result from multiple radiation modes. The angle of radiation is given by $\arcsin|(\beta + 2\pi m/p)/k_o|$, and the intensity and polarization of radiation can be controlled by adjusting the length, angle, and position of the slots. Since leaky coaxial lines operate at wavelengths much longer than the circumference, very little directional control can be attained in the transverse plane, but this has the advantage that slot alignment is not critical.

Radiating line sources, such as the slotted coaxial line, produce fields which decay with radial distance as $r^{-1/2}$. This variation is milder than those experienced with the wayside lines that will be considered in Section 2.1.2. For this reason the lateral tolerance in installation is also not very critical.

For ease in manufacture some leaky coaxial lines are made with closely spaced holes. Such a design satisfies the fast-wave condition (1b) for all harmonic modes; and, consequently, the structure, if perfectly constructed and uniformly installed, does not radiate. In practice, irregularities in manufacture and installation cause the line to radiate. Clearly a line which relies upon such random features does not result in optimal design and may be unreliable.

The vehicle coupling antenna for leaky coaxial lines may consist of a simple half-wave dipole or a more elaborate but more effective slotted traveling-wave structure.(13) In practice, the problem of detection is complicated by the irregularity of the fields along the length of leaky coaxial lines. Typically coupling levels may vary ± 10 dB over distances of several feet. In enclosed areas, such as tunnels, these problems can become more pronounced due to standing-wave patterns which result from reflections. Therefore, it may become necessary to employ space-diversity or frequency-diversity techniques to effect statistical averaging, or to employ a direct form of signal processing (such as automatic gain control), so that an acceptably uniform signal is obtained.

The leaky coaxial line is most commonly used in the VHF band and the lower part of the UHF band, particularly the 400-500 MHz region. Problems can be expected in adapting the leaky coaxial line to the 900 MHz region reserved for future mobile communications. Coaxial line losses increase with frequency, and smaller dimensions and tolerances may be required to prevent the propagation of higher modes. These considerations indicate that leaky coaxial lines may not be as successful for long distance transmission in the 900 MHz band.

Another type of radiating line source which has been investigated is a leaky circular waveguide (Figure 5) operating in the TE mode at around 9 GHz[12,14,15] The potential benefits in terms of low loss and wide bandwidth are considerable, but the system demands great care in construction and installation to avoid the problems of over-moded operation. In particular, the necessary rigidity of the structure makes it difficult to allow for bends and thermal expansion without causing unacceptable

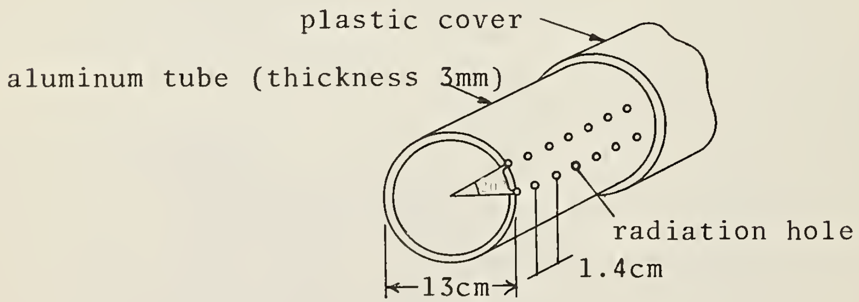


Figure 5. Leaky Circular Waveguide Similar to That Developed by Sumitomo with Dimensions Shown

distortion from mode conversion and reflections. Consequently, a circular waveguide system would be considerably more expensive than a leaky coaxial line system and could be justified only if long distance, wide bandwidth communication were an absolute requirement.

2.1.2 Communication Through Nonradiating Fields

The systems described in this section do not rely upon radiated electromagnetic fields for their operation, although radiation may incidentally occur. Provided the electric field does not exceed 15 $\mu v/m$ at a distance of $\lambda/2\pi$, they do not require an FCC license.

2.1.2.1 Inductive Fields - The most elementary form of inductive system consists of wire loops along the road or guideway coupled inductively to a wire loop on the vehicle.[16,19] Usually a guideway loop is so long that it is essentially a parallel pair of wires, as shown in Figure 6. As current in the parallel pair changes, the associated magnetic field also changes and a voltage is induced in the nearby loop on board the vehicle (loosely referred to as an antenna, although no significant radiation may be involved). Conversely, input signals to the vehicle loop can be detected from the parallel wires.

The coupling configuration in Figure 6 detects changes in the vertical component of the magnetic field between the parallel wires, but other arrangements have been investigated.[2] For example, separate vertical loops can be positioned directly above each wire to detect changes in the horizontal component of the magnetic field. However, this configuration is more sensitive to lateral vehicle motion. Regardless of the position of the coupler, loops with multiple windings or ferrite cores can be employed to make the vehicle antenna more sensitive or to allow reduction of its physical size.

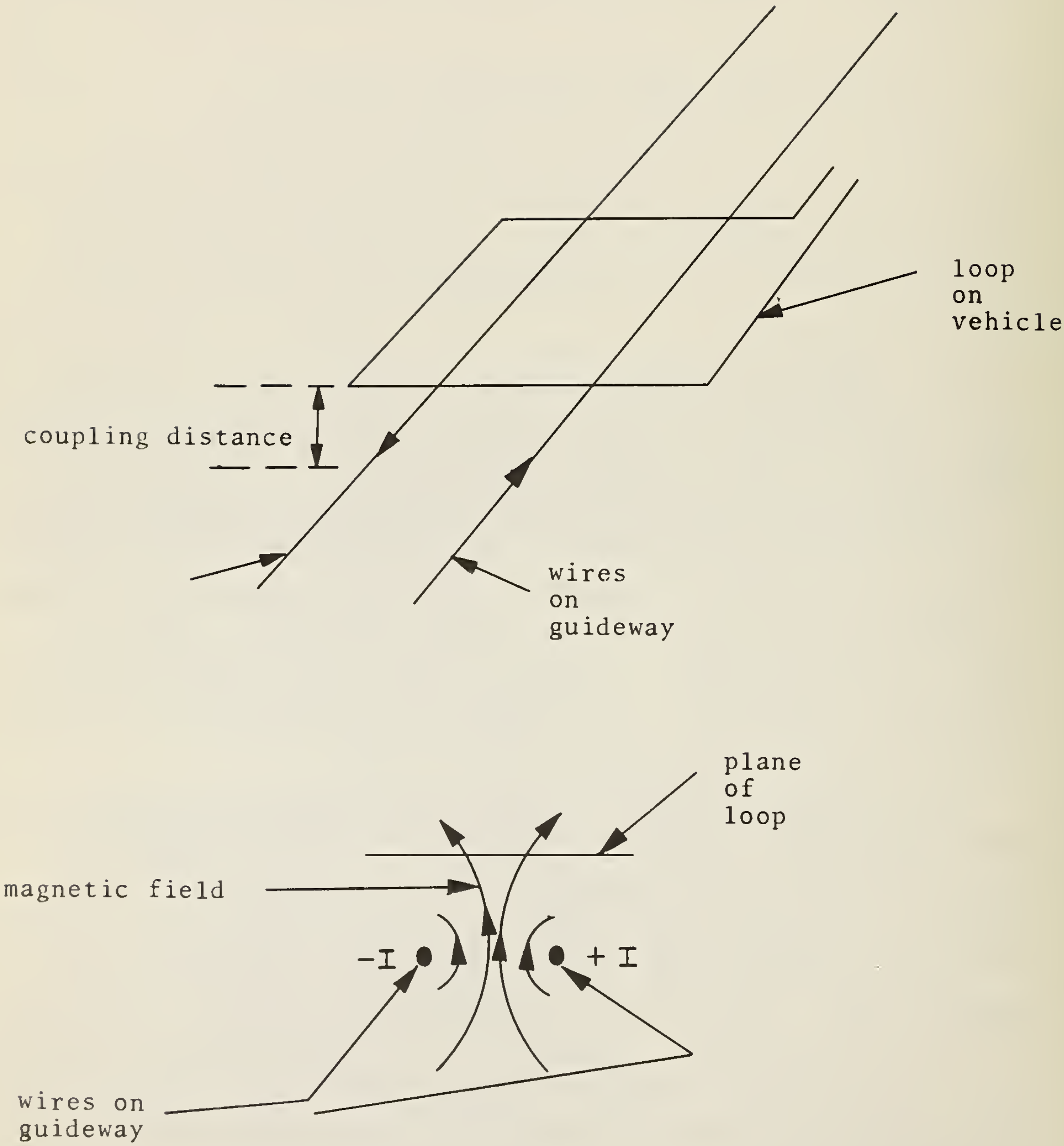


Figure 6. Parallel Wire Inductive System

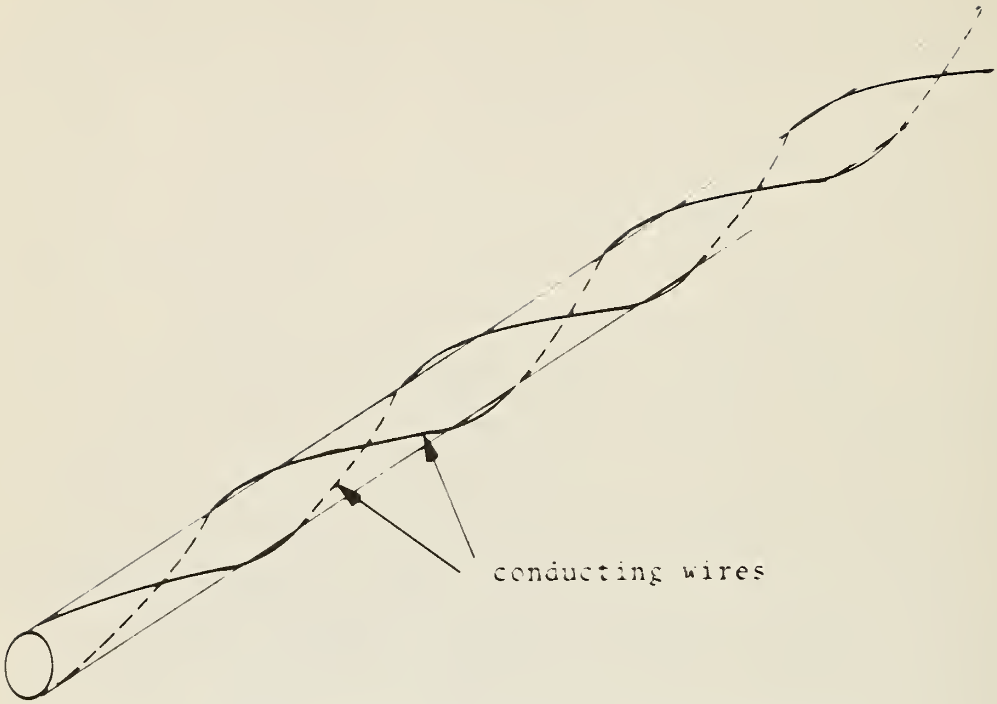
Parallel wire inductive systems are limited by their tendency to radiate excessively as the frequency is increased. As a result, attenuation becomes intolerable at high frequencies, and the radiation fields may exceed FCC limitations; at the same time, the line becomes more susceptible to external radiation. For these reasons the characteristics of the line are more favorable at lower frequencies. For example the restriction that the wavelength should be much greater than a kilometer of electrically visible line requires a frequency of 30 KHz or less. However, at these low frequencies, environmental noise, especially atmospheric noise, becomes excessive, so that transmission is reliable only for very low data rates. At somewhat higher frequencies, up to several hundred kilohertz, there is less environmental noise, but the noise susceptibility of the line is increased, so that data rates are still limited. In order to increase capacity, it is necessary to incorporate a means of suppressing the noise and improving the performance at higher frequencies where environmental noise is less severe.

The well-known electromagnetic technique of twisting wires to reduce their susceptibility to noise and to extend their frequency range can be adapted to inductive systems[18] by means of either a helical winding on a cylindrical surface (Figure 7a) or by a planar alteration of position (Figure 7b). In either case, the design criterion is

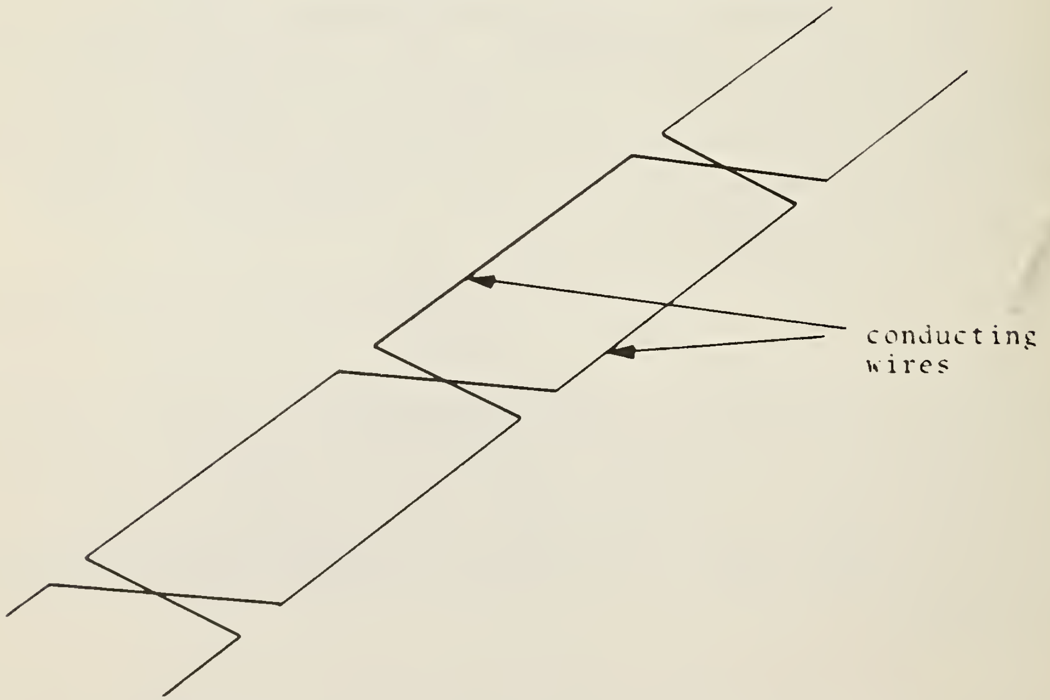
$$d \ll p \ll \lambda \tag{2}$$

where d is the distance between the wire pair, p is the periodicity distance, and λ is the signal wavelength. Radiation is thereby suppressed because one half-period section tends to cancel the adjacent section. The alternating wire arrangement is also helpful in suppressing the effects of external inductive noise, provided

$$d \ll p \ll D \tag{3}$$



a. Helical Pair of Inductive Wires



b. Alternating Planar Pair of Inductive Wire

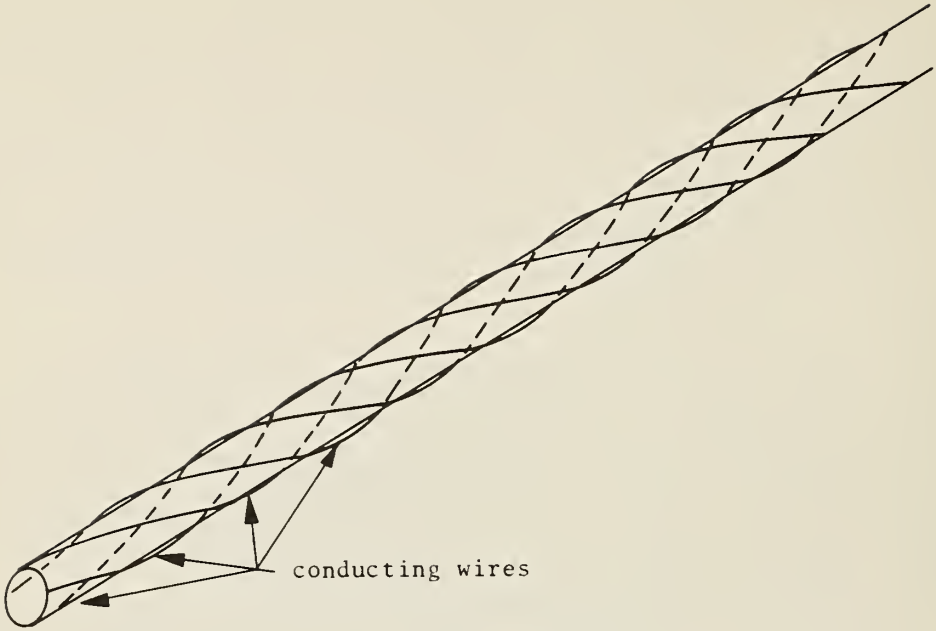
Figure 7. Pairs of Inductive Wires

where D is the correlation length of noise along the line. If condition (3) is fulfilled, noise will be relatively uniform over several sections and its effects will tend to cancel. Further improvement can be realized by extending this technique to a helical quadruplet (Figure 8a) or planar quadruplet (Figure 8b). The helical quadruplet has been constructed in a particularly compact form[18] (Figure 9). A typical frequency range for such structures is 50-250 KHz.

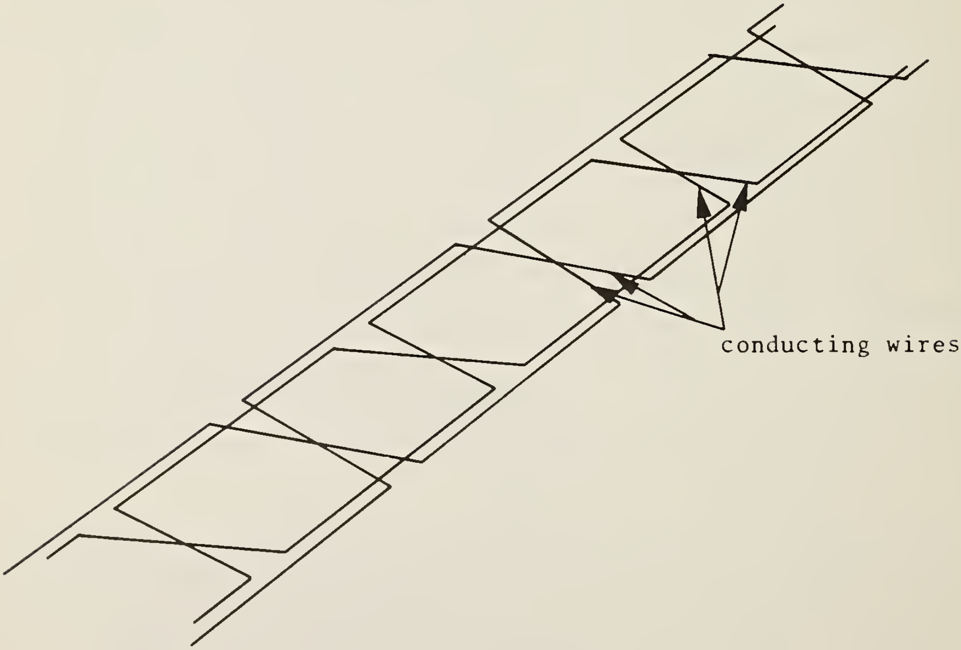
The signal levels produced by an alternating pair are severely nonuniform, with nulls at wiring crossings. The situation is somewhat improved with the alternating quadruplet, but nonuniformity may still be unacceptable. For this reason, multiple receiving antennas are used with proper spacing to provide a uniform detected signal (Figure 10).

In addition to radiation losses, attenuation can be caused by lossy material near the wires in regions of strong field. This effect may occur when moisture with impurities accumulates to form a medium of lossy dielectric in a region of strong electric field. Such losses are considerably reduced through the use of thick insulation to keep moisture away from the dense field immediately surrounding the wire. Another approach which virtually eliminates these losses is to shield each wire with a coaxial conducting sheath (Figure 11). Most of the electric field is confined within the coaxial shield, but a magnetic field is still generated outside the structure due to current flowing on the outer surface of the shield and on the short-circuiting conductors. Attenuation can still be caused by conductor loss in the inductive structure itself and by lossy magnetic material, such as structural steel, but the influence of environmental moisture is virtually eliminated.

Sumitomo Ltd. has demonstrated an inductive line which combines conductive shielding with alternating wire position.[19] The design (Figure 12) consists of insulated wires held in grooved metal frames, which provide a partial conducting shield.



a. Helical Quadruplet of Inductive Wires



b. Alternating Planar Quadruplet of Inductive Wire

Figure 8. Quadruplets of Inductive Wires

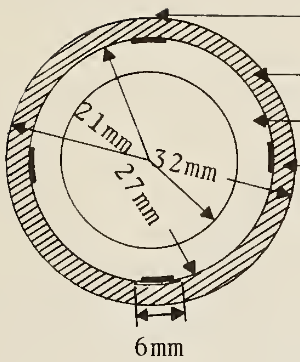
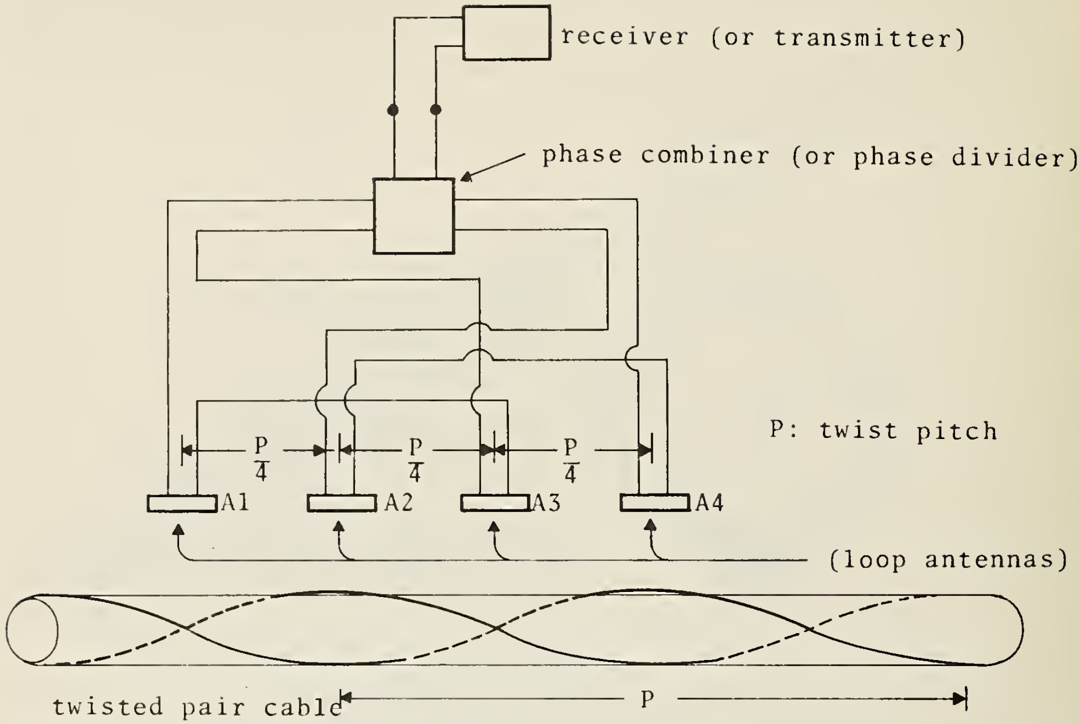


Figure 9. Cross Section of Sumitomo Helical Inductive Cable

An interesting possibility for inductive line design is a two-conductor transmission line with one of the conductors forming a partial shield for the other[20] (Figure 13), thereby reducing radiation. Lines of this type are still in a developmental stage, and extensive data is not available. Nevertheless, such configurations promise to push the capability of inductive lines well into the megahertz region. However, the design shown in Figure 13 suffers serious mechanical disadvantages due to its rigidity and unwieldy size, and designs have been proposed which may eliminate the mechanical problems while retaining desirable electrical characteristics.

With inductive wire systems, both parallel and alternating, the magnetic field is predominantly that of a two-dimensional dipole, so that the field decreases with transverse radial distance as r^{-1}. However, the shielded inductive line shown



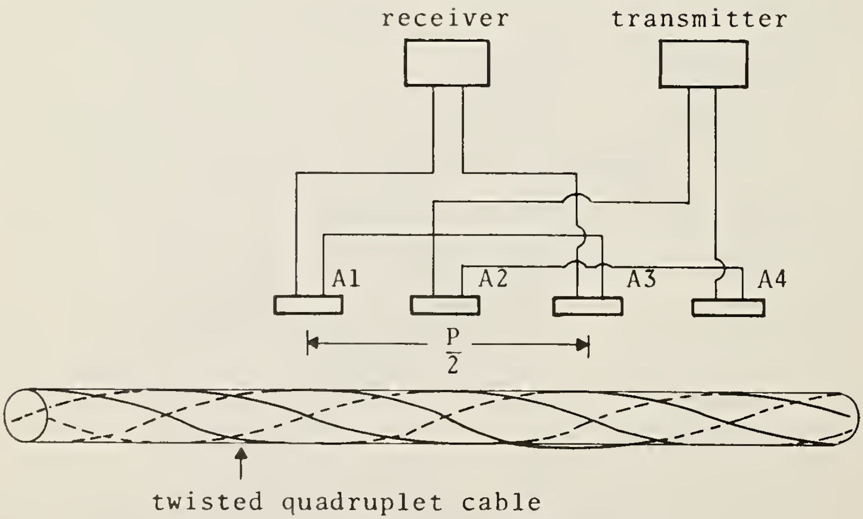
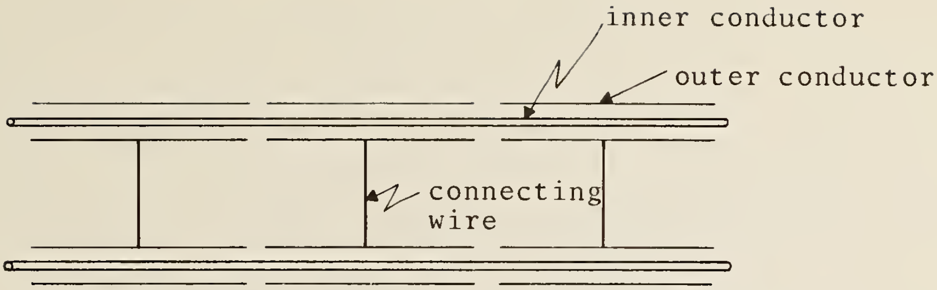
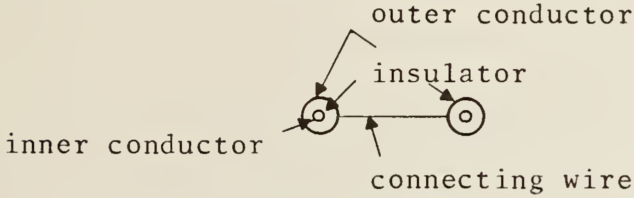


Figure 10. Multiple Antenna Arrangement for Inductive Lines



(a) Plane view



(b) Cross-sectional view

Figure 11. Coaxially Shielded Transmission Line

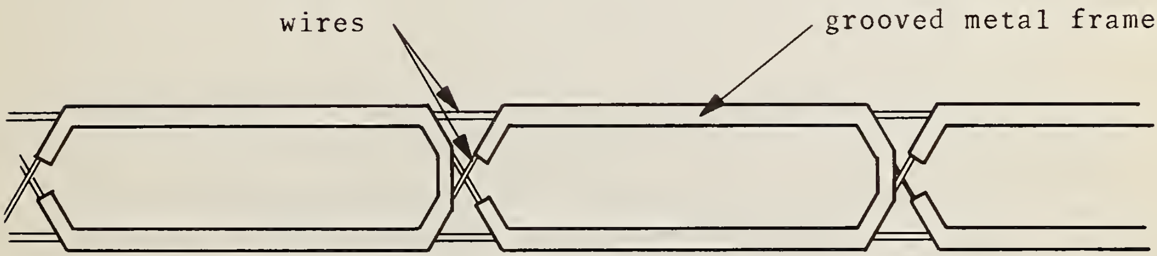


Figure 12. Sumitomo Alternating and Shielded Transmission Line

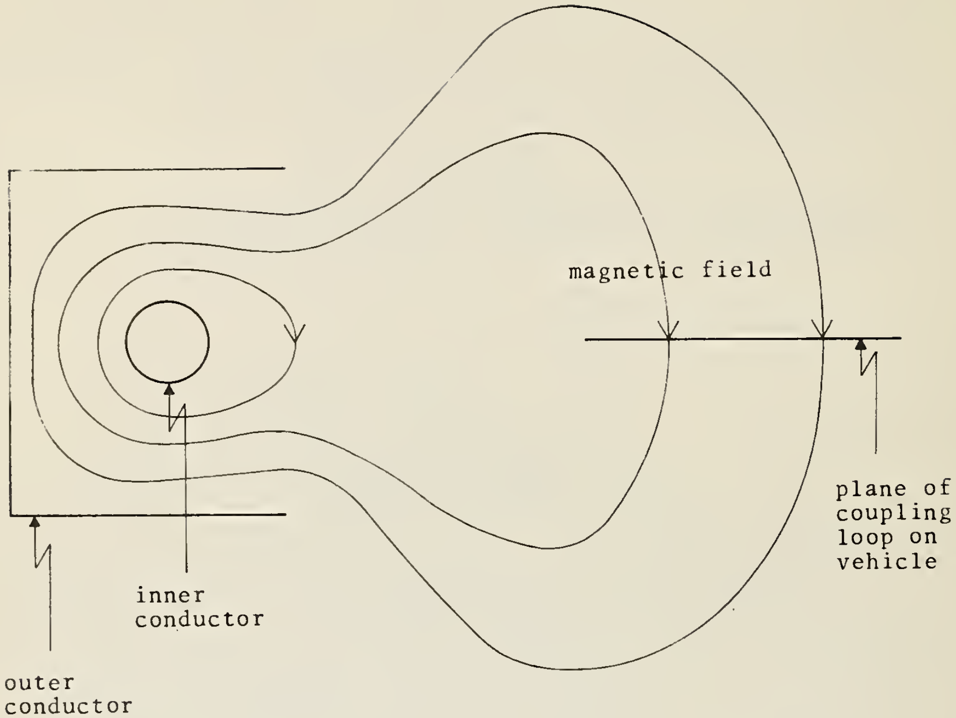


Figure 13. Cross Section of Transmission Line Investigated by Wheeler Laboratories

in Figure 13 is oriented so that the dipole field vanishes at the coupler, and hence the variation is that of a quadrupole, r^{-2}. In either case, the fields decay algebraically. Therefore, while variation in coupling distance is somewhat more important than for a radiating line source, it is not so critical as to exclude moderate lateral vehicle motion.

2.1.2.2 <u>Surface-Wave Fields</u> - Open waveguides which support surface - waves have recently received considerable attention as a means of communicating from wayside to guideway-confined vehicles.[21] Most commonly, such waveguides incorporate dielectric material to guide electromagnetic waves along the structure without containing them. The electromagnetic fields extend a short distance into the surrounding space, but the field energy is propagated directly down the waveguide, so that no energy is lost in radiation if the structure is perfectly uniform. In principle, a transfer of energy takes place only at a vehicle equipped with a coupler, which usually consists of a short length of surface waveguide similar to the wayside structure and positioned near it. In practice the wayside structure will deviate from uniformity at curves, expansion joints, and other irregularities, and consequently some radiation will occur.

Perhaps the most frequently discussed surface waveguide for ground communications is the Goubau line[22] (Figure 14) which typically operates in the 500-1000 MHz region. However, the structure suffers serious disadvantages which cast doubt on its usefulness. Its geometry requires that any mechanical support extend into regions of intense field where scattering results in energy loss, signal distortion, and possible violation of FCC regulations. Furthermore, the structure is difficult to shield from precipitation and other environmental effects which degrade its performance.

Several alternative dielectric waveguides incorporate a conducting shield to isolate the supports from the dielectric and thereby avoid the problems of the Goubau line. One configuration, which has been studied in some detail, is a modified image line[23] with dielectric of essentially semicircular cross section (Figure 15) operating at about 4 GHz. Other configurations which have been suggested are shown in Figures 16 and 17 and are also intended to operate in the region of several gigaherz. An entirely metallic structure of periodic conducting teeth has been investigated by Sumitomo for use around one gigahertz.[28] It is included here with dielectric surface-waveguides because the comb-like array acts as an artificial dielectric and supports a fast wave ($V_p > c$). All of these structures are necessarily rigid and require a means to allow for thermal expansion. This might be accomplished by expansion joints with negligible electrical reflectance or by installing the line under tension. However, neither of these alternatives has been adequately explored.

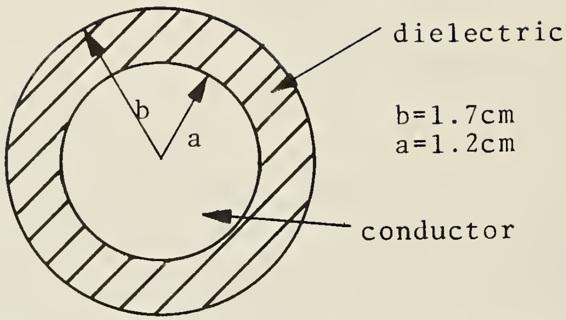


Figure 14. Cross Section of Goubau Line With Typical Dimensions

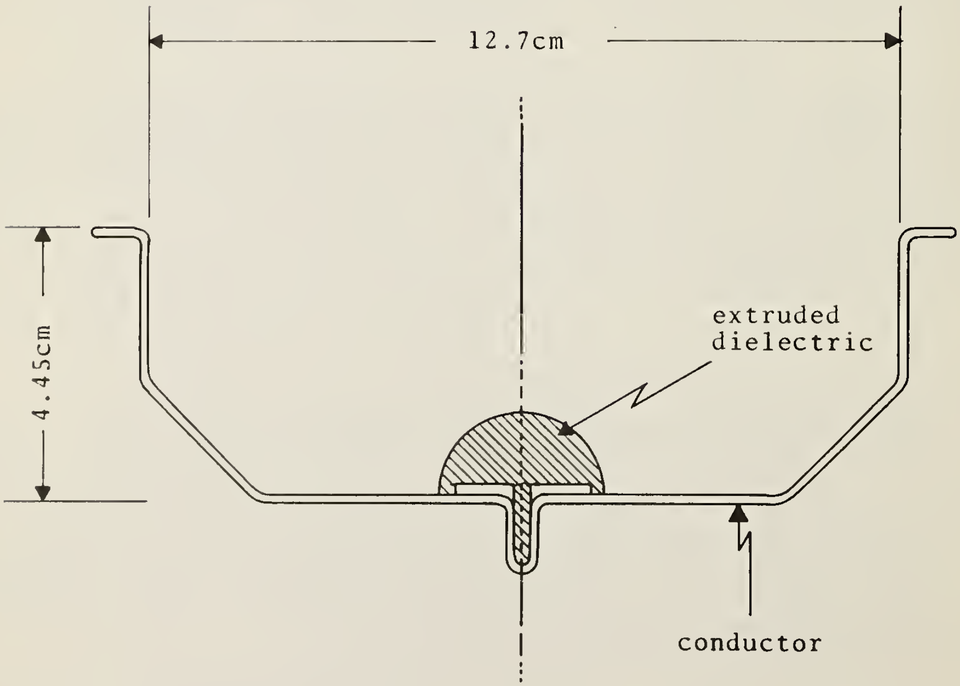


Figure 15. Cross Section of Dielectric Line Investigated by General Applied Science Laboratories

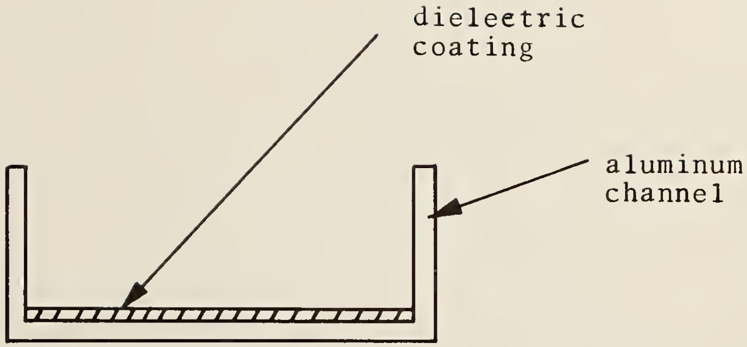


Figure 16. Cross Section of Dielectric Line Investigated by Honeywell[24,25]

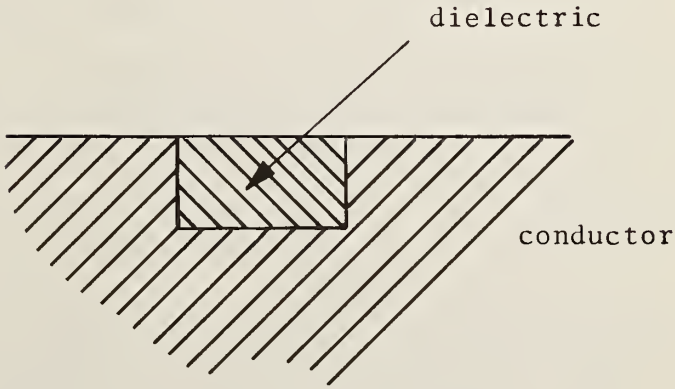


Figure 17. Cross Section of Dielectric Line Investigated by TSC[26,27]

Characteristically, the electromagnetic fields surrounding a surface waveguide decay with transverse radial distance in an exponential manner, as $e^{-\alpha r}$, where α is a constant which determines the rate of decay. This steep decrease places rather stringent limits on the lateral motion which can be tolerated if the coupler is to experience a relatively uniform field level. Specifically, if lateral vehicle motion causes the coupling distance to vary by Δd, the resulting power variation at the coupling distance will be $8.68\alpha\Delta d$ decibels. Clearly, this variation can be reduced with a structure which exhibits a small α, corresponding to a shallow rate of decay. The allowable lateral motion and power variation thus place an upper limit on α. However, as α becomes small, the field energy is less tightly bound to the waveguide and more energy will be lost at curves and discontinuities. For this reason the severity of curves and other deviations from uniformity place a lower limit on α. Any useful surface-wave structure must have an α which lies between this lower limit set by curves and the upper limit specified by variations in coupling distance. If the system includes tight curves or requires considerable lateral freedom, the lower limit on α may exceed the upper limit. In this case, surface-wave structures would not be acceptable for wayside-to-vehicle communications.

2.2 CLOSED-CIRCUIT COMMUNICATION THROUGH MECHANICAL CONTACT

The category of communication links dealt with here includes closed wire circuits between vehicle and wayside maintained during vehicle motion by a sliding or rolling contact. Conducting wires or rails running along the guideway provide a path for signals, which are transmitted or received aboard the vehicle through a contact arm or other extension. Such a system has few advantages over inductive wires and suffers some notable disadvantages. Exposed signal rails are susceptible to radiation and inductive interference as are parallel inductive wires, but the corrective technique of twisting or alternating conductors can not be applied. Furthermore, signal rails or wires can not be shielded from the environment as effectively as inductive wires, since the vehicle contact must have access to the conducting surface.

Peculiar to contact links are problems originating in the mechanical contact itself. A momentary break in the contact which may be insignificant in the case of power transmission can be totally unacceptable in communications, especially for digital transmission where bit times are commonly on the order of several milliseconds or less. The specific cause of the break in contact may be unevenness in the line or the motion of the vehicle, or may be due to an accumulation of residue on the line. That effect, in the form of oxidization has been identified as a cause of problems in the BART system.[29] Perhaps the only significant performance advantage of contact systems is that the signal coupling between wayside and vehicle does not vary with lateral vehicle motion, provided a good contact is maintained.

Although unexceptional in performance, a contact communications link can sometimes be implemented inexpensively through existing equipment. An obvious example is the use of the rolling contact between vehicle and track in a conventional train.[30] Such track circuits were first used in 1872, and today over 110,000 miles of main line track in the United States are used as circuits in block signal control.[31] In a strict sense, track circuits usually serve only as a means of detection rather than communication. That is, they are employed to detect the presence of a train within a block of track, but no exchange of information between vehicle and wayside is involved.

In cases where a supporting structure already exists for a power rail or catenary, it may be used as a convenient and economical means of support for a separate signal rail or wire. Such an arrangement requires separate points on the vehicle pickup arm for power and communications.

Another approach which utilizes existing equipment more fully is to transmit communication signals over rails used for power. The complexity and expense of such a system lies in the heavy duty filtering equipment needed to separate direct current or low frequency power from higher frequency communication signals.[32] This equipment must be provided not only on board the vehicle, but at nodal interconnections of the wayside system where power and communications must be separated. The lowest frequency available for communication is determined by the problem of filtering. Clearly a frequency band must be allowed for isolation of the power and communications spectra. The size of this isolation band is determined by the voltage and frequency of power transmission and the sharpness of the filter characteristics. With regard to these considerations, transmission of power and communications over common rails or wires is more practical for direct current power systems of relatively low voltage.

As transmission media, signal rails in a contact system and parallel wires in an inductive system are essentially the same; the systems differ principally in the method of coupling from vehicle to wayside. Consequently, the frequency range of each is limited in the same way by susceptibility to noise and attenuation resulting from radiation.

3. CONCLUSIONS

3.1 ON-GUIDEWAY COMMUNICATIONS

Command and control for vehicles on the guideway is the most critical function which the communication system supports, and it requires a highly reliable link which is always available. For this reason radiating systems in the land mobile frequency band are unsuitable for command and control, since the limited number of licensed channels would force vehicles to wait for an opportunity to communicate. Sufficient spectrum space may be available at higher frequencies, such as the nine GHz region employed by the circular waveguide (Figure 5), but the equipment and precision installation required may be needlessly expensive. Consequently, the possible communication links are narrowed to nonradiating and contact systems within the FCC limits for unlicensed devices.

Nonradiating systems of the surface-wave type are suitable only if rather stringent limits on lateral vehicle motion and guideway turning radius are satisfied. The restriction on lateral vehicle motion is unlikely to be satisfied, except for tightly confined vehicles on tracks; and the restriction on guideway turning radius is sure to be violated in all cases. Therefore, surface-wave structures can be eliminated as serious candidates, leaving inductive and contact systems for consideration.

Communication through direct contact with a signal rail is generally justified only for systems in which the supporting structure for the rail and the vehicle contact arm have an independent reason for existence. Such systems include those in which vehicles are powered from a wayside rail and those which employ an arm in lateral control. The technique of superimposing communication signals on the power rail is likely to be prohibitively expensive because of the large number of vehicles and nodal points which require filtering equipment.

Inductive lines are not required to withstand the mechanical stresses encountered in contact systems, and their installation does not demand as much precision. Consequently, if supporting structures are counted as a part of the system, inductive systems can be expected to be less expensive than contact systems. Most commonly, inductive lines used for communications are buried in the roadway; and, if the command and control system employs inductive fields to detect lateral vehicle motion, it is sometimes possible to satisfy the detection and communications functions with the same inductive lines.

For low data rates, a simple parallel wire inductive system may be adequate if electrical noise is not severe. However, an alternating configuration (Figures 7b and 8b) can be implemented for a moderate additional cost which is justified by the improved noise immunity. Regardless of the configuration, the wires should not be installed in immediate proximity to ferromagnetic material, e.g., steel reinforcement, to avoid magnetic losses and field distortion. Imbedding the wires within the guideway provides some protection from environmental moisture losses, but concrete is not impermeable and therefore the wires should be thickly insulated. While still more protection from moisture losses is afforded by the metal frame construction shown in Figure 12, there is doubt that the additional cost is justified.

An alternative to the planar configuration in Figure 8b is the helical cable shown in Figure 9, which offers the same immunity from noise and losses in a compact unit. The cable itself is somewhat more expensive than separate wires; but installation is less expensive, and this usually predominates over equipment costs.

Wayside transmission lines are integrated with a central control in hierarchical fashion,[2] such as that shown in Figure 18. A wayside control unit is directly linked to the four adjacent sections of wayside transmission line, two for each direction of motion. A local control then has responsibility for a number of wayside controls, which are limited in their separation by transmission loss on the wayside line. Similarly, local controls are integrated with a region control, and regional controls with a central control.

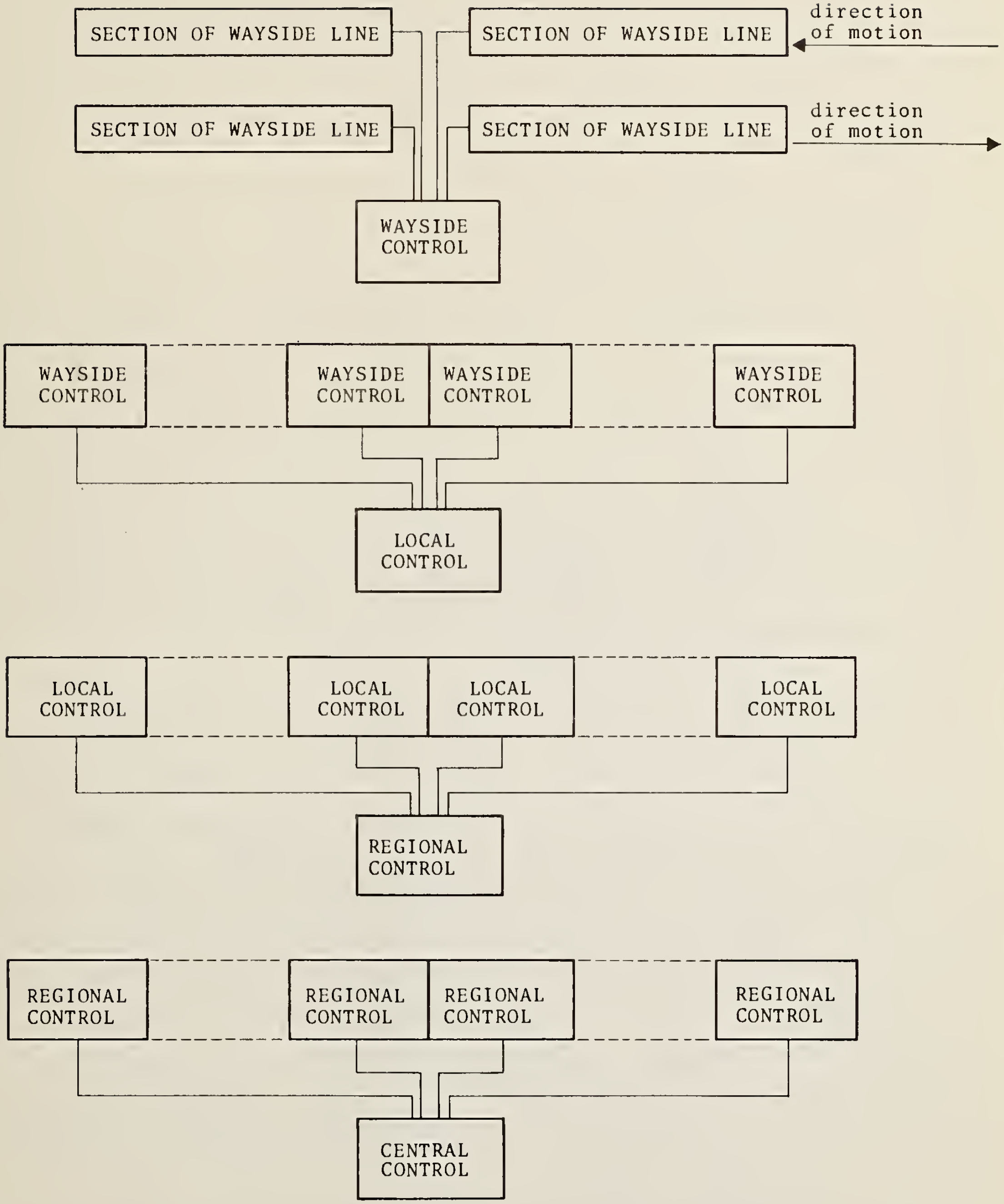


Figure 18. Hierarchical Control of the On-Guideway Communication System

Induction and contact systems are capable of handling both digital and voice communications on the guideway. However, emergency calls and service vehicle calls are the only on-guideway voice communications and are a relatively infrequent occurence. Therefore it may be possible to handle these functions through off-guideway frequency allocations (see Section 3.2) without noticeably increasing the load on these channels.

3.2 OFF-GUIDEWAY COMMUNICATIONS

In the off-guideway mode, vehicles are not confined to a relatively small number of arteries, but rather can range throughout a metropolitan area with the freedom of other traffic. Consequently, a communications system with broad coverage is needed. Nonradiating systems can be excluded because they provide communication only over a narrow path. Radiating line sources installed along all possible routes may be technically feasible, but are an inefficient and expensive means of general coverage. Clearly, the best method of providing off-guideway communications is through conventional localized antennas.

There should be no unusual problems in the implementation of a voice link adequate for the initial stages of the dual mode program. A standard mobile radio link would employ frequency modulation and operate throughout the dual mode service area on frequency assignments in the VHF-UHF region, with no attempt to realize a small-cell approach. The system should incorporate known techniques of vehicle antenna design to minimize the Rayleigh fading experienced in an urban environment, which is caused by variations in intensity due to reflected waves. Since minima and maxima of electric fields tend to be out of phase, a composite antenna of electric and magnetic dipoles will have a smoothing effect. Improvement can also be achieved through diversity techniques, such as spacing antennas a wavelength apart.

Off-guideway communications requirements will increase with the demand for service and the growth of the system, and it will become necessary to make more efficient use of the limited spectrum space in the 900 MHz region allotted to dual mode transportation. This will most probably mean an evolution of the off-guideway communications system through various forms of the small-cell approach. The course of development which should be taken will depend upon the dual mode system employed and details of the metropolitan area, such as geography, user patterns, obstructions to radio propagation, and the radio noise environment. Therefore, each case must be considered individually through a statistical trade-off study. As an illustration of the kind of choices involved, consider a fixed-frequency system in which each of the seven frequency groups (Figure 3) contains j frequencies, so that 7j frequencies are used in the system. Any given vehicle requires equipment for only seven frequencies, i.e., one from each group, in order to communicate from all locations. However, as the communications load increases, the waiting time for a channel may become unacceptable. One possible way to handle the increased load would be to leave stationary equipment unchanged but equip all vehicles for k channels in each zone, or a total of 7k channels. An alternate approach would be dynamic-frequency assignment, in which base station equipment is expanded for operation on any frequency and central processing equipment becomes more complex, but vehicle equipment can be unchanged or even simplified to one-frequency operation.

Although radiating line sources are not suitable as a means of general coverage, they are useful for providing an adequate signal in tunnels or other corridors where reception is poor. The most appropriate line source is a leakly coaxial cable with dimensions properly chosen for the 900 MHz region and with radiation characteristics graded along its length to produce a relatively uniform signal level. It can be installed along the wall of a tunnel and connected at the mouth of the tunnel to a standard antenna through an amplifier.

At a more advanced stage of dual mode, consideration should be given to automating much of the information exchange through a digital data link similar to that which has been demonstrated for aircraft.[33] In the case of dial-a-ride service, time and location of the next passenger pick-up could be printed on a screen in view of the driver. After the pick-up has been completed, the driver would press a button to acknowledge successful pick-up and cause the next destination to be shown. Other functions, such as request for guideway entry, could be similarly automated to achieve more efficient use of spectrum space and to ease the work load of the operator.

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APPENDIX: COMMUNICATIONS IN SOME CONTEMPORARY GROUND TRANSPORTATION SYSTEMS

		Direct Contact	Induction	Radiating Source	Surface-waves
Dual Mode	Rohr	presence detection, command and control		voice communication, off-guideway communications	still in a developmental stage
	GM		presence detection, command and control, on-guideway voice communication	off-guideway communications, emergency on-guideway voice communications	
	TTI		presence detection, command and control, on-guideway voice communication	off-guideway communications	
TRANSPO PRT	Rohr Monocab		presence detection, command and control	voice communication	
	Ford		presence detection, command and control	voice communication	
	Bendix Dashaveyor		presence detection, command and control	voice communication	
	TTI		communication only in stations	presence detection at optical frequencies	
	BART	presence detection	command and control	voice communication (radiating line within tunnels)	
	Morgantown		presence detection, command and control	voice communication	
	AIRTRANS (Dallas-Ft. Worth Airport)	presence detection, command and control		voice communication	